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Solidification mechanism of austenitic stainless steels solidified with primary ferrite

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ABSTRACT

The solidification mechanism of austenitic stainless steels solidified with primary ferrite is clarified in terms of crystallography. The formation of austenite was expected to take place by the peritectic/eutectic reaction in the interdendritic region of the primary ferrite, but no unique orientation relationship was confirmed between the primary ferrite and the austenite. The austenite was found to keep growing along its <100> direction, independently of the primary ferrite, even after the primary ferrite changed its growth direction. This was confirmed by solidification experiments with changing heat flow directions, and was supported by the observation that the austenite forms crystallographic domains different from those of the primary ferrite in the final microstructure. Thus, it is concluded that the austenite is not crystallographically restricted by the primary ferrite, and that the growth of the primary ferrite and that of the austenite are crystallographically independent of each other.

1. Introduction

Most austenitic stainless steel weld and cast metals are designed so to solidify with the primary ferrite and secondary austenite in order to minimize the occurrence of hot cracks. This solidification mode is known as the ferritic-austenitic solidification mode (FA mode) [1–3], where the formation of the austenite takes place following the primary ferrite by the eutectic or peritectic reaction. Fig. 1 shows the vertical section of phase diagram for the 70 mass% Fe-Cr-Ni ternary system calculated using ThermoCalc [4] with SSOL database and the alloy used in the present study is indicated by an arrow. In this 70%Fe psudobinary section, the austenite seems to be formed by eutectic reaction after the primary ferrite solidification, but there are reports insisting of the formation of austenite by peritectic reaction [5], and thus the mechanism of the austenite formation is still unclear. Many researchers have studied the solidification process [6–12], but the understanding of the solidification sequence leading to the final weld or cast microstructure is still insufficient [13–15]. Since properties of austenitic stainless steel welds and casts, such as cryogenic toughness [16,17] and corrosion resistance [17,18], are significantly affected by their final microstructure, particularly the content and morphology of retained ferrite, better understanding of the evolution of the primary ferrite and the secondary austenite and sequence to the final microstructure is quite important [14].

In this context, the solidification mechanism of austenitic stainless steels solidified with primary ferrite was investigated in this study. Welding process was employed to examine the behaviors of the primary ferrite and the secondary austenite under changing heat flow direction during the solidification or with changing growth direction induced by the change in heat flow direction.

2. Experimental procedures

The material used in the present study is an austenitic stainless steel containing 19 mass% Cr and 11 mass% Ni. Chemical compositions of the steel are given in Table 1, in which alloying elements other than Cr and Ni are reduced as low as possible. The steel was laboratory-melted and cast into a 25 kg ingot, which was then hot-rolled to a 5 mm thick plate and solution annealed at 1373 K for 3600 s.

Autogenous welding without filler metal was performed using a gas tungsten arc (GTA) welding process with a current of 150 A, a voltage of 12 V and a travel speed of 1.67 mm/s. To measure the cooling curve of the weld metal, a 0.5 mm-diameter platinum-

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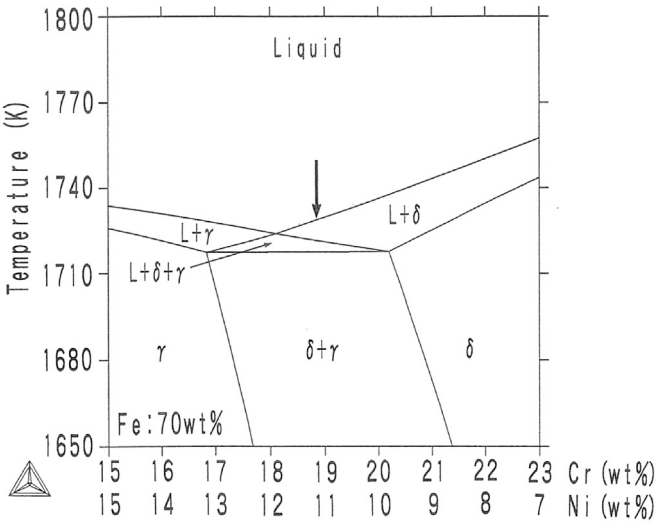

Fig. 1. Vertical section of the phase diagram for Fe-Cr-Ni alloy at 70 wt% Fe, calculated using ThermoCalc, showing the location of the present material with an arrow.

Table 1
Chemical compositions of material used (mass%).

C	Si	Mn	P	S	Cr	Ni	N	O
0.0034	0.01	0.01	0.001	0.0004	18.82	11.20	0.0022	0.0030

rhodium thermocouple was inserted into the molten weld pool. Temperature of a location of interest was determined using the cooling curve measured and the velocity of solidification front estimated by the travel speed of the molten pool. Liquid-tin quenching of the weld molten pool [19] was used to quench and examine the solidification front.

The identifications of phases and their crystallographic orientations were performed using a scanning electron microscope (SEM) equipped with an electron backscattering diffraction (EBSD) analyzer with an accelerating voltage of 20 kV and a step size of 0.2 μm. The specimen for EBSD was mechanically polished with 1 μm diamond paste, then further polished by electropolishing in a solution of 15% perchloric acid in ethanol in order to remove surface strain and finally electroetched in a 10% oxalic acid aqueous solution.

3. Results and discussion

3.1. Microstructural change during solidification

Fig. 2 shows microstructure around the solidification front in the weld metal, obtained by the liquid-tin quenching method. Heat flow is from the left to the right in the figure and primary dendrites of the ferrite (δ) grow from the right to the left. It is seen that the austenite (γ) starts to form in the interdendritic regions about 50 μm behind the ferrite dendrite tips. Fig. 3 shows an area where the austenite starts to form, which shows cellular morphology of the austenite. It is not clear by this figure whether the austenite forms as a result of the eutectic reaction or by the peritectic reaction between the melt and the primary ferrite, but since interfacial energy between liquid and bcc (ferrite) is usually expected to be lower than that between liquid and fcc (austenite) [10,20], one possibility is that the cellular morphology of the austenite observed seems to be a result of the peritectic reaction, as suggested in ref. [21] where the cellular morphology of austenite is needed to balance the interfacial energy at the liquid-bcc-fcc triple point. Another possibility is that the austenite grows in an independent manner of the ferrite in the inderdendritic liquid, and the cell tip is located simply at the melting point of the austenite which is lower than that of the ferrite. This explains the cell tip of the austenite is about 50 μm behind the ferrite dendrite tips.

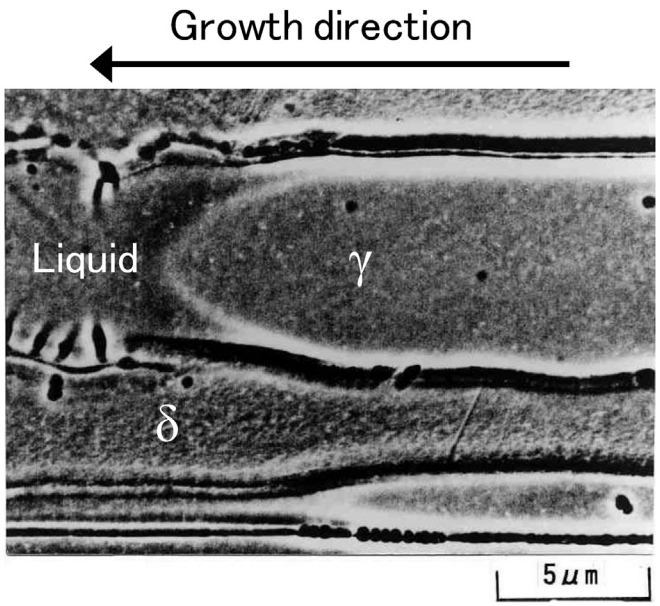

Fig. 3. Growth front of the interdendritic austenite during primary ferrite solidification.

3.2. Crystallographic orientation relationship between ferrite and austenite during solidification

Fig. 4 shows the crystallographic orientation of the primary

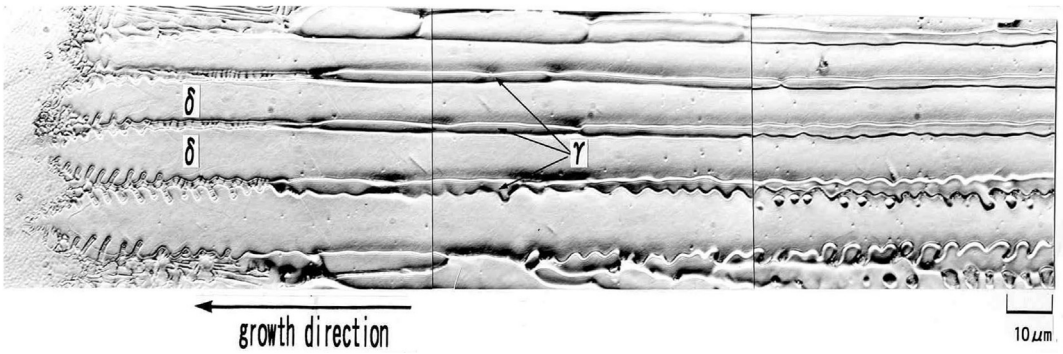

Fig. 2. Growth of the primary ferrite dendrites and the evolution of the austenite in the interdendritic region, obtained by the liquid tin quenching method.