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Clarification of Solidification Behaviors in Austenitic Stainless Steels Based on Welding Process

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Abstract

Solidification morphologies and the formation mechanism of vermicular and lacy ferrite observed in the austenitic stainless steels solidified with primary ferrite (FA mode) were clarified in terms of crystallography. The austenite in the interdendritic regions is not crystallographically restricted by the primary ferrite during the growth. The growth manner of the primary ferrite and secondary austenite is named as "independent two phase growth". The ferrite morphology is decided by both the crystallographic orientation relationship between ferrite and austenite established at the stage of ferrite nucleation and the relationship between the welding heat source direction and the preferential growth directions of ferrite and austenite.

1. Introduction

Most austenitic stainless steel weld and cast metals are designed to solidify to give primary ferrite and secondary austenite to minimize the occurrence of hot cracks. This solidification mode is known as the ferritic-austenitic solidification mode (FA mode)[1-3]. **Fig. 1** shows the typical microstructures of as-solidified weld metal solidified in FA mode, which consist of primary ferrite at the center of solidification cells engulfed by austenite. Often, two types of ferrite morphology are observed; one is known as 'vermicular' and the other is 'lacy'. And its structural characteristics have significant influence on its properties; various papers reported that the difference in the morphology of ferrite affects low-temperature toughness[4,5] and corrosion resistance[5,6] of austenitic stainless steels weld metals. However, the formation mechanism of the different ferrite morphologies is still uncertain.

Most of industrially useful alloys, such as steel, solidify in two phases, and such dual-phase solidification is known as a eutectic, a peritectic or a monotectic manner. Many researchers have since long studied the mechanisms of such solidification manners. In the case of austenitic stainless steels solidified in FA mode, however, the phase stability and/or the phase selection were mainly discussed[7-12], but

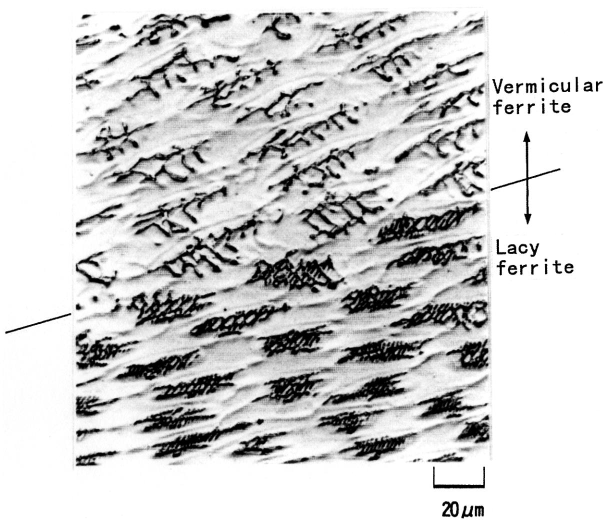

Fig. 1 Typical microstructure as solidified metal of austenitic stainless steel which solidified in FA mode

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solidification morphologies of each phase is still unclear.

In view of the above, the authors investigated the solidification behaviors of austenitic stainless steels solidified in FA mode from the viewpoint of the crystallography of the ferrite and austenite, and proposed a new manner of dual-phase solidification[13,14]. Based on the proposed manner of solidification, the authors elucidated the formation mechanisms of the two different types of ferrite morphology[5,15]. This paper outlines the new solidification manner proposed and the formation mechanisms of the two types of ferrite morphology.

2. Microstructural Change during Solidification in FA Mode

In the present study, the welding process was adopted to examine solidification behaviors, because it is easier to confirm the change in crystallographic orientation relationships between the primary phase and the secondary phase due to changing the solidification growth direction determined by the movement of a heat source. Furthermore, since the solidification of weld metal starts from the base metal (fusion boundary) in a welding process, it is easy to obtain the information at the initial stage of solidification. The material used in the present study was an austenitic stainless steel containing approximately 19wt%Cr and 11wt%Ni. Autogenous welding was performed using a gas tungsten arc (GTA) welding process at a current of 150A and a voltage of 12V with a travel speed of 1.67mm/s. To examine the microstructural change during weld solidification, the liquid tin quenching method[16] was used to quench the solidification front.

Fig. 2 shows the microstructure around solidification front in the weld metal obtained by liquid tin quenching method. Ferrite dendrites can be distinctly observed within a region of around 50 μ m from solidification front. At the ferrite dendrite boundaries, austenite is solidified in succession to retained liquid phase. This result indicates that the solidification mode of the material used in the present study is FA mode, in which ferrite solidifies as the primary phase and then austenite solidifies as the secondary phase.

Fig. 3 shows the front area of austenite, which is solidified as the secondary phase in Fig. 2. At the interdendritic region of the preceding ferrite dendrites, the cellular austenite is solidified and the tip of austenite overhangs forward the solid-liquid interface with curvature. The phase diagram indicates that the formation of the ferrite and austenite of the present steel results from the eutectic reaction. The dendritic growth of ferrite as a primary phase, however, is more favorable than the eutectic formation, because the local composition gets out of a coupled zone at the solidification velocity of a welding process. Thereafter, though a eutectic structure ought to form at the interdendritic region of the primary ferrite dendrites, neither lamellar nor rod-like eutectic of ferrite and austenite is confirmed but the only cellular austenite single phase is observed as seen in Fig. 3. This result suggests that the austenite is formed as divorced eutectic[17], and this behavior results from the suppression of the increase in the interface energy by the formation of an interface between ferrite and austenite.

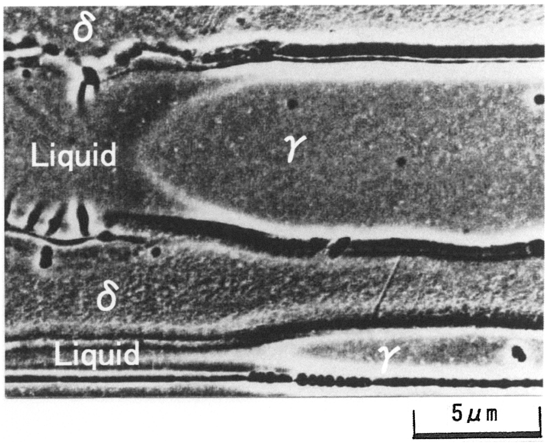


Fig. 3 Growth front of the interdendritic austenite during primary ferrite solidification

3. Crystallographic Orientation Relationship between Ferrite and Austenite during Solidification

The crystallographic orientation relationships between the primary ferrite and the interdendritic austenite near the solidification front shown in Fig. 2 were analyzed. Both the primary ferrites at dendrite cores and the austenite at dendrite boundaries grow along the <100> directions, their respective preferential growth directions, and the <100> directions of ferrite and austenite are found to be almost parallel along the solidification growth direction. Two or more crystallographic orientation relationships, however, are found between the ferrite and the austenite. This result indicates that no additional specific orientation relationships are identified at the interface between the primary ferrite and the interdendritic austenite near the solidification front, besides the <100> directions of the ferrite and the austenite being parallel to each other. From the viewpoint of the microstructural change during solidification shown in Fig. 3, it was suspected that the austenite at the dendrite boundaries of the preceding ferrite dendrites was formed as divorced eutectic in the case of this FA solidification mode. It was reported that because the secondary phase nucleates on the primary phase as divorced eutectic[17], the

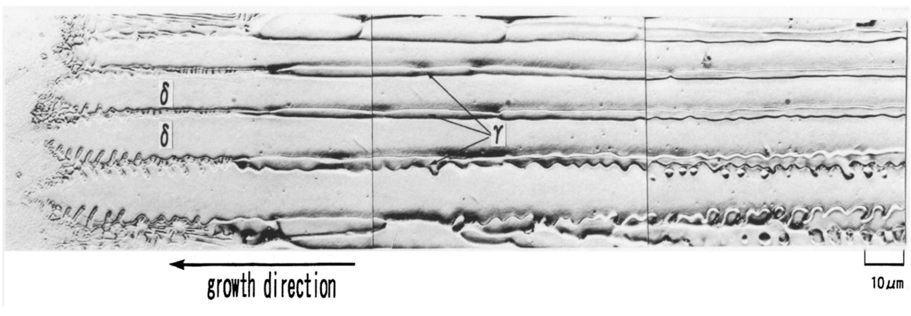


Fig. 2 Microstructural change during solidification in the weld metal obtained by liquid tin quenching method

specific crystallographic orientation relationship needs to be established between the two phases[18]. However, there is no specific crystallographic orientation relationship at the interface between the ferrite and the austenite in the present study.

Weld metal first forms from HAZ (Heat Affected Zone) of base metals. The crystallographic orientation relationships near the fusion boundaries in the weld metal obtained by liquid tin quenching method were analyzed. All of the austenite in both base metal and weld metal has an identical crystallographic orientation, and therefore it is confirmed that the austenite formed at the fusion boundaries in the weld metal results from epitaxial growth with plane-front morphology from the austenite of base metal. Then, ferrite in the weld metal is formed on this planar austenite. Namely, the formation of ferrite is somewhat delayed and occurs away from the fusion boundaries. All of these ferrite, however, has different crystallographic orientation, respectively. Furthermore, the parallel relationship between the <100> direction of ferrite and the <100> direction of austenite is not established, unlike the crystallographic orientation relationship near the solidification front. Nevertheless, between the ferrite and the austenite near the fusion boundaries in the weld metal, the Kurdjumov-Sachs (K-S) orientation relationship[19] is present or close-packed planes[20] are found to be parallel with different variants. These results indicate that the crystallographic orientation relationship between the ferrite and the austenite can not be determined even within one weld metal, and therefore the relationship near the fusion boundaries is different from that near the solidification front. The fact that the K-S relationship or the parallel relationship between close-packed plane is established between the ferrite and the austenite at fusion boundaries indicates that the ferrite is nucleated on the planar austenite with good coherency, and it is necessary for the ferrite to keep the crystallographic correlation with the austenite for its formation. On the other hand, the growth of the austenite at dendrite boundaries as a secondary phase is epitaxial from the base metal austenite. It is suspected that the interdendritic austenite is not crystallographically restricted by the primary ferrite during the growth.

During formation of weld metals, the solidification growth direction is changed in turn by the movement of the weld heat source. The crystallographic orientation relationships at the region where the ferrite changes its growth direction in the weld metal were analyzed. It is confirmed that the ferrite within one austenite grain, which has identical crystallographic orientation, exhibited two or more different crystallographic orientations corresponding to their growth directions. This result indicates that the crystallographic orientation of the austenite does not change even if the crystallographic orientation of the ferrite changes. If the secondary austenite in the interdendritic region is formed as divorced eutectic, the specific orientation relationship is established between the primary ferrite and the secondary austenite, and therefore the crystallographic orientation of austenite must be changed with the formation of the new ferrite. However, the change in the crystallographic orientation of the austenite can not be ascertained. At the other region where the growth direction changes, it is confirmed that the ferrite with identical crystallographic orientation grows across two more austenite grains with different crystallographic orientations. This result indicates that the austenite, whose preferential growth direction is deviated significantly from the heat flow direction, is weeded out by the other austenite, whose preferential growth direction is closer to the heat flow direction, and is displaced regardless of the growth of the primary ferrite.

The crystallographic characteristics in the austenitic stainless steel weld metals solidified as FA solidification mode obtained in the present study are summarized as follows:

a. At the solidification front, the <100> directions of primary ferrite and interdendritic austenite are parallel along the solidification growth direction, but the specific orientation relationships do not exist at the interface between the ferrite and the austenite.
b. At the fusion boundaries, the austenite in the weld metal grows from the base metal austenite in an epitaxial manner.
c. At the fusion boundaries, the parallel relationship between the <100> direction of the ferrite and that of the austenite is rare, but the K-S relationship or the parallel relationship between close-packed planes is established between the ferrite and the austenite.
d. The ferrite with different crystallographic orientation is formed within one austenite grain with identical orientation.
e. The ferrite with identical crystallographic orientation grows across more than one austenite grains with different orientations.

As stated in Section 1 (Introduction) above, a eutectic reaction, a peritectic reaction etc. are known as a dual-phase solidification manner of most alloying metals. These reactions are provided with specific crystallographic orientation relationships between two phases[21,22]. In other words, it is understood that two phases grow dependently of each other not only as to composition but as to crystallographic orientation during solidification. It was considered that the austenite as a secondary phase in the weld metal of the stainless steel used in the present study was formed as outwardly divorced eutectic. However, the crystallographic characteristics described in items a to e above can not be explained by the conventional solidification manner, which two phases grow dependently while keeping a specific crystallographic orientation relationship. Consequently, it is suggested that the possibility of another solidification manner should exist.

4. Solidification Manner in the Austenitic Stainless Steel Solidified in FA Mode

The solidification manner of the ferrite and the austenite in the austenitic stainless steel solidified in FA mode can be summarized in a schematic illustration shown in **Fig. 4**.

When the base metal is fully austenite, the growth of austenite is more favorable than the nucleation of ferrite because of no nucleation barrier of austenite at the fusion boundaries, and therefore austenite first grows epitaxially from the base metal austenite with plane-front morphology. During this planar austenite solidification, because Cr is rejected into the liquid, the stability of ferrite increases in the liquid in front of the solid/liquid interface and causes the nucleation of ferrite on the growing planar austenite by keeping the favorably coherent crystallographic orientation relationship with the austenite. Once the ferrite forms, it grows more rapidly as the primary phase with dendritic morphology to dominate over the planar austenite growth. Furthermore, the only ferrite whose crystallographic preferential growth direction is aligned with the heat flow direction continues to grow. When the preferential growth direction of ferrite deviates significantly from the heat flow direction, its growth stops, whereas new ferrites nucleate successively and the ferrite with the preferential growth direction nearly along the heat flow direction among them can grow.

On the other hand, in the interdendritic region of the primary ferrite at the final stage of solidification, because Ni is rejected into the liquid, the stability of austenite increases and causes the formation of austenite. Austenite, however, grows more easily from the austenite

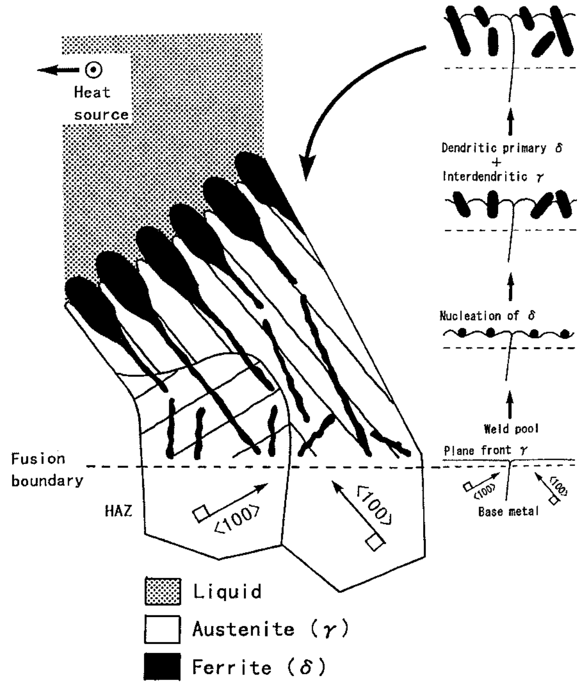


Fig. 4 Schematic illustration on the formation and the growth of ferrite and austenite near the fusion boundary of weld metal solidified in FA mode

that has already solidified than the nucleation of austenite on the preceding ferrite or in the liquid, and therefore the formation of the austenite at the dendrite boundaries is invariably epitaxial growth and fills the interdendritic region of the primary ferrite. There is no inevitability of keeping the favorably coherent crystallographic orientation relationship between the austenite and the ferrite, and the interdendritic austenite is not crystallographically restricted by the preceding ferrite during the growth. Consequently, the austenite grows independently, growing along the preferential growth direction, even when the primary ferrite changes its growth direction. The austenite whose preferential growth direction is nearly aligned with the heat flow direction can grow as forming columnar grain. When the preferential growth direction of austenite deviates significantly from the heat flow direction, the austenite is displaced by another adjacent austenite, whose preferential growth direction is closer to the heat flow direction. As the ferrite and the austenite independently repeat the competitive growth respectively, the parallel relationship between the <100> direction of ferrite and the <100> direction of austenite along the heat flow direction is finally established at the solidification front, but no specific orientation relationship exists at the interface between ferrite and austenite during solidification.

The crystallographic characteristics obtained in the austenitic stainless steel weld metals solidified in FA mode can be explained by the following manner. At only the nucleation stage of new ferrite, the specific crystallographic orientation relationship is established between ferrite and austenite. However, the following growth of austenite at the dendrite boundaries of the primary ferrite is invariably epitaxial and is not crystallographically restricted by the preceding ferrite during the growth. This means that ferrite and austenite grow independently, and the authors named this new growth manner "Independent Two-phase Growth"[13].

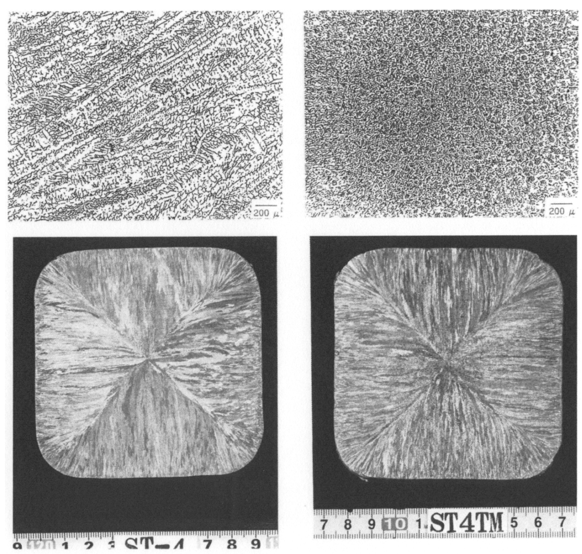
5. Verification of New Solidification Manner

To verify the "Independent Two-phase Growth" manner newly proposed, the following experiment was performed[14].

From the viewpoint of the lattice coherency proposed by Bramfitt[23], it is well known that titanium nitride (TiN) is effective in the ferrite nucleus and makes equiaxed solidification of ferrite promote in ferritic stainless steel[24-26]. Though the material used in the present study is an austenitic stainless steel, the primary solidification phase is the ferrite because of FA solidification mode. Consequently, even in the austenitic stainless steel solidified as FA mode, it is expected that the primary ferrite solidifies as an equiaxed morphology by TiN. The austenitic stainless steel ingots with the same compositions of the present study's steel were cast adding titanium and nitrogen in a suitable content balance[24] for forming equiaxed structures.

Fig. 5 shows the microstructures and macrostructures of the austenitic stainless steel cast ingots with and without titanium and nitrogen added. The vermicular or lacy networks of ferrite are formed in the case of no addition, while the fine ferrite is dispersed and TiN is observed at the center of the fine ferrite in the case of addition. The equiaxed solidification of the primary ferrite caused by TiN is confirmed. In the macrostructure of the same cast ingots, however, coarse grains; namely, the columnar grains of austenite are observed regardless of the addition or no addition of titanium and nitrogen. It is found that the only primary ferrite is solidified as equiaxed morphology but the secondary austenite is solidified as an intact columnar morphology even if titanium and nitrogen are added. The similar phenomenon was suggested in the weld metal of type 321 stainless steel[27].

After the equiaxed solidification of the primary ferrite, each equiaxed ferrite should be surrounded by the respective austenite, if the secondary austenite forms in relation to the crystallographic orientation of the primary ferrite. However, it is confirmed that the equiaxed solidification of ferrite and the columnar solidification of austenite occur simultaneously shown in Fig. 5(b). This fact indicates



(a) No addition (b) Ti and N addition

Fig. 5 Microstructures and macrostructures of austenitic stainless steel ingots, (a) no addition, (b) Ti and N addition

that the growth of ferrite and austenite is crystallographically independent, and can be explained only by the "Independent Two-phase Growth" manner proposed in the present study. Consequently, it is considered that the validity of the newly proposed dual-phase solidification manner can be verified.

6. Range Where "Independent Two-phase Growth" Takes Place

In the austenitic stainless steels with similar compositions to the present study's steel, Fukumoto et al. and Okane et al.[11,12,28] confirmed eutectic structures at the lower solidification velocity (10^{-6}m/s) by directionally solidification method and the K-S orientation relationship between the eutectic two phases was confirmed. In the case where two phases grow simultaneously such as a eutectic solidification, it is necessary that the two phases keep good coherency with each other, and thus, the specific crystallographic orientation relationships are expected to exist between the two. On the other hand, the solidification velocity in the present study is estimated approximately from 10^{-4}m/s to 10^{-3}m/s. As the solidification velocity increase, the solidification morphologies of ferrite are shifted from eutectic growth to cellular or dendritic growth as the primary phase, even if the chemical compositions are identical. This agrees with the test results of Fukumoto et al.[11] and Okane et al.[12]. At the early stage of solidification in such a case, after the single-phase growth with plane-front morphology, it is necessary for the other phase to nucleate, and consequently, the specific crystallographic orientation relationship is expected to exist between the two phases. At the steady state of the succeeding growth stage, the phase that has the higher tip temperature grows as the primary phase. However, because a nucleation is not required for the following growth of the secondary phase at the dendrite boundaries of the primary phase and it has its own preferential growth direction, the formation and growth of the secondary phase depend on its own thermal condition and solute distribution, and therefore, it is presumed to grow without being crystallographically restricted by the preceding primary phase during the growth.

This means that, it is considered that the "Independent Two-phase Growth" manner proposed in this study becomes more feasible at the solidification conditions (solidification velocity and temperature gradient) of industrially practical solidification processes, such as welding, continuous casting or strip casting etc., in which the primary phase grows as cellular or dendritic morphology[29], even if the chemical composition may undergo eutectic reactions.

Most previous investigations for fundamental solidification behaviors were mainly performed by directionally solidification method. Since there are no changes in the heat flow direction by the directionally solidification method, crystals continue to grow keeping the crystallographic orientation relationship established at the stage of nucleation, and for this reason, it looks as though there is the specific crystallographic orientation relationship between two phases. In other words, the crystallographic orientation relationship obtained by a directionally solidification method or at fusion boundaries of welds is the orientation relationship established at the nucleation stage, but does not always indicate the orientation relationship formed at the growth stage. On the other hand, the results obtained in the present study can indicate the actual crystallographic orientation relationship that formed between two phases during growth. This relationship could be clarified for the first time by the examinations using the solidification process, which the crystal growth direction (the heat flow direction) changes. Furthermore, the finding obtained in the present study is of significant importance for materials engineering because the crystal growth direction (the heat flow direction) changes in most of the practical solidification processes.

7. Formation Mechanisms of Different Ferrite Morphologies

7.1 Crystallographic orientation relationship between ferrites with different morphologies and austenite

The microstructure of as-solidified weld metal of austenitic stainless steel solidified in FA mode is dual-phase structure, which consist of ferrites with two types of different morphologies, vermicular ferrite and/or lacy ferrite, engulfed by austenite matrix as shown in Fig. 1. The purpose of the present study is to clarify the mechanisms of the ferrite formation in the FA mode stainless steel welds. Formation sequence of the two different ferrite morphologies has been investigated[15] based on the "Independent Two-phase Growth" above proposed.

The authors have already indicated[30] that between the vermicular ferrite and the austenite in as-solidified weld metals, the <100> direction of the vermicular ferrite is found to be parallel to the <100> direction of the austenite, and they are aligned in the solidification growth direction, but any other specific parallel planes are not identified between the vermicular ferrite and the austenite, on the other hand, between the lacy ferrite and the austenite in as-solidified weld metals, the K-S relationship exists and the <100> directions of the lacy ferrite and the austenite are also almost parallel to the solidification growth direction. These relationships agree with the results reported by Kokawa et al.[31]. In addition, the authors have confirmed the following two[15]: the crystallographic orientation relationship between the vermicular ferrite and the austenite at the solidification front agrees with that between the primary ferrite and the interdendritic austenite at the solidification front among the crystallographic characteristics itemized in Section 3, on the other hand, between the ferrite, that will be cooled to room temperature and turn into lacy ferrite, and the austenite at the solidification front, the K-S relationship establishes and the <100> directions of the two phases are almost parallel to the solidification growth direction in the same manner as in as-solidified structure. Since the ferrite to austenite transformation during cooling after solidification proceeds in an epitaxial manner of the austenite, that has solidified at dendrite boundaries of ferrite, to the primary ferrite at dendrite cores, the crystallographic orientation relationship between the ferrite and austenite established during the solidification is retained down to room temperature[15,30]. The authors have shown that such difference in the crystallographic orientation relationship during the solidification determines the final morphology of the ferrite in the FA mode[30].

Incidentally, according to the "Independent Two-phase Growth", the following growth of the austenite at the dendrite boundaries of the primary ferrite is invariably epitaxial and is not crystallographically restricted by the preceding ferrite during the growth, and therefore the specific crystallographic orientation relationship between ferrite and austenite is established only at the nucleation stage of new ferrite. Because the interface between ferrite and austenite first forms at fusion boundaries in a weld metal, it is considered that the crystallographic orientation relationship between ferrite and austenite is determined at the stage when ferrite crystallizes at the fusion boundaries for the first time.

The crystallographic orientations of the vermicular ferrite and the lacy ferrite formed within one austenite grain, which had grown epitaxially from an austenite grain of base metal and had identical crystallographic orientation, near fusion boundaries in the weld metal were analyzed. Between the vermicular ferrite and the austenite, close-packed planes are found to be parallel, but any other specific parallel directions are not identified. In addition, all the <100> directions of vermicular ferrite deviate substantially from the <100> direction of austenite. This relationship agrees with the crystallographic orientation relationship at the fusion boundaries of the weld metal obtained by liquid tin quenching method mentioned in Section 3, but does not agree with the crystallographic orientation relationship between the vermicular ferrite and the austenite as shown in as-solidified weld metal and at the solidification front. Between the lacy ferrite and the austenite, however, the K-S relationship is present and the <100> direction of the lacy ferrite is almost parallel to the <100> direction of austenite, both of which correspond to the heat flow direction. This relationship agrees with the crystallographic orientation relationship between lacy ferrite and austenite as shown in as-solidified weld metal and at the solidification front explained earlier, and it is clear that the crystallographic orientation relationship between the lacy ferrite and the austenite does not change regardless of at the fusion boundary or at the solidification front.

7.2 Formation mechanisms for vermicular ferrite

From the above results and the "Independent Two-phase Growth", it is considered that the formation mechanisms of the different ferrite morphologies in the weld metal of austenitic stainless steels solidified as the FA mode are as described below. **Figs 6** and **7** show the formation processes of the different ferrite morphologies[15]; note that A to H in Fig. 7 correspond to Cases A to H in Fig. 6, respectively.

At the fusion boundaries, planar austenite first grows epitaxially

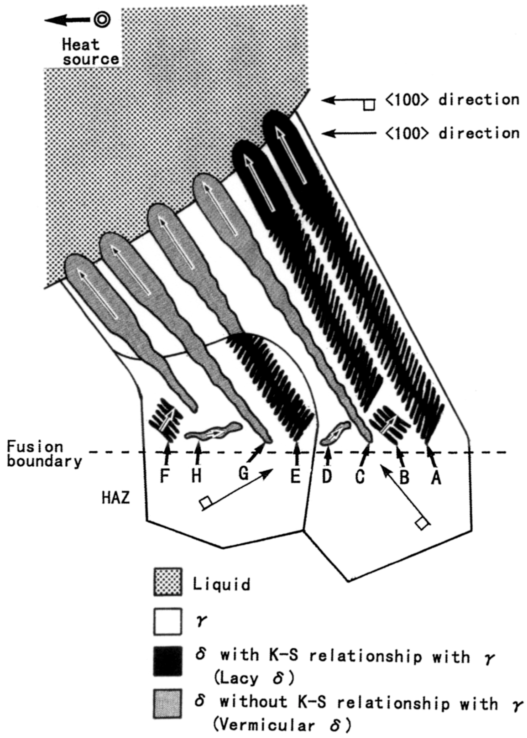
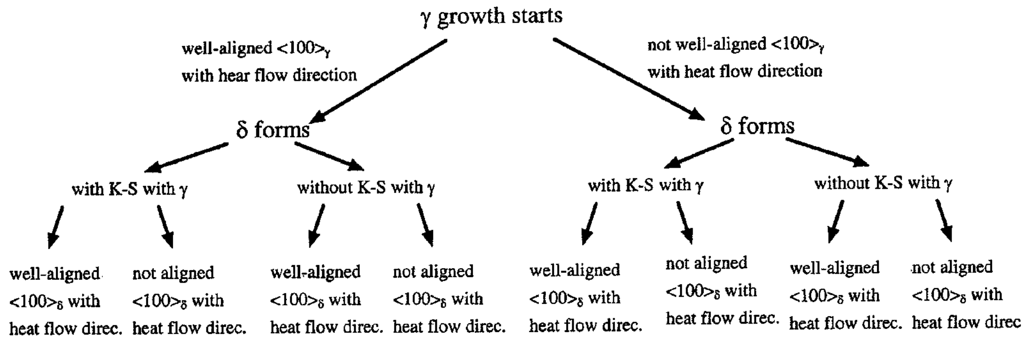


Fig. 7 Schematic illustration of formation process and mechanism for different ferrite morphologies in weld metals solidified in FA mode. (A-H correspond to cases in Fig. 6)



Case	A	B	C	D	E	F	G	H
Initial morph.	Lacy	Lacy	Vermicular	Vermicular	Lacy	Lacy	Vermicular	Vermicular
δ status	continues	dies off, replaced by new δ	continues	dies off, replaced by new δ	continues	dies off, replaced by new δ	continues	dies off, replaced by new δ
γ status	continues	continues	continues	continues	dies off, replaced by aligned γ	dies off, replaced by aligned γ	dies off, replaced by aligned γ	dies off, replaced by aligned γ
Final morph	Lacy	Vermicular (Case C) or Lacy (Case A)	Vermicular	Vermicular (Case C) or Lacy (Case A)	Vermicular	Vermicular (Case E or G)	Vermicular	Vermicular (Case E or G)

Fig. 6 Proposed mechanisms for formation of different ferrite morphologies in weld metals solidified in FA mode

from the base metal austenite, and then the ferrite nucleates and starts to crystallize on the growing planar austenite. At the nucleation of the ferrite, either the K-S relationship or the parallel relationship between close-packed planes is established between the ferrite and the planar austenite. When the ferrite nucleates with the parallel relationship between close-packed planes (Case C, D, G and H), the coherency between the ferrite and the austenite is not so good. The austenite at dendrite boundaries is likely to grow into ferrite at dendrite cores on ferrite-austenite transformation, with planar austenite/ferrite interface, since the planar growth of austenite is a reasonable consequence that minimizes the interfacial energy and avoids the formation of any additional ferrite/austenite interface. Therefore the morphology of the retained ferrite becomes vermicular.

When the <100> direction as the preferential growth direction of the vermicular ferrite nucleated is aligned with the heat flow direction, then the vermicular ferrite continues to grow (Cases C and G). When the <100> direction of vermicular ferrite is poorly aligned with the heat flow direction, the growth of this vermicular ferrite is halted (Cases D and H), and a new ferrite nucleates. When the preferential growth direction of the newly nucleated ferrite is aligned with the heat flow direction, the ferrite continues to grow as in Cases C and G, but when its preferential growth direction is deviated from the heat flow direction, the growth of the ferrite is halted. On the other hand, the interdendritic austenite, whose <100> direction as its preferential growth direction is aligned with the heat flow direction, independently continues to grow (Cases C) forming columnar grain. When the <100> direction of the austenite is not aligned with the heat flow direction as in Case G, then the austenite is eventually replaced by the adjacent austenite, which is well aligned with the heat flow direction. Accordingly, it is considered that as the ferrite and the austenite independently repeat the competitive growth respectively, the parallel relationship between the <100> direction of the vermicular ferrite and the <100> direction of the austenite along the heat flow direction is finally established, but any other specific parallel planes are not identified between the two phases. Furthermore, this crystallographic orientation relationship agrees with that obtained at the steady solidification stage. Naturally, the ferrite/austenite interface without any specific crystallographic orientation relationships may establish during the course of the competitive growth, but in such a case, the coherency between the ferrite and the austenite is not so good. Therefore, the final morphology of the ferrite is likely to become vermicular.

7.3 Formation mechanisms for lacy ferrite

At the fusion boundaries, when the ferrite nucleates on the epitaxially growing planar austenite from the base metal austenite with the K-S relationship between the ferrite and the planar austenite (Cases A, B, E and F), plate-like austenite readily grows from the interdendritic region into the ferrite of dendrite core epitaxially along the habit plane[20,32,33] on ferrite-austenite transformation because of the good coherency between the ferrite and the austenite, and therefore the morphology of the retained ferrite becomes lacy. It is presumed that the growth of plate-like austenite into the ferrite with keeping the coherent ferrite/austenite interface is more favorable than the planar growth of austenite into the ferrite with keeping the incoherent ferrite/austenite interface because the increase in the total interfacial energy of a whole system can be suppressed, regardless of the increase in the ferrite/austenite interface.

Incidentally, it is not easy to specify the factors that decide whether the K-S relationship or the parallel relationship between close-packed planes is established between the ferrite and the planar austenite at the fusion boundaries. Nevertheless, it is presumed that the relationship between the preferential growth direction of the austenite and the heat flow direction is one of the possible factors. When the preferential growth direction of the austenite is not aligned with the heat flow direction (Cases E, F, G and H), the solidification of the planar austenite is delayed[34]. In such a case, only the small delay of solidification causes a large fall in the liquid temperature at the solidification front where the ferrite nucleates, because the temperature gradient near the fusion boundary is large. As a result, the ferrite that requires a large critical under-cooling for nucleation can easily nucleate, and for this reason, the nucleation frequency of the ferrite with the parallel relationship between close-packed planes is expected to become large. (The critical under-cooling for nucleation of the ferrite with the parallel relationship between close-packed planes is larger than that with the K-S relationship between ferrite and austenite.)

When the <100> direction of the planar austenite is aligned with the heat flow direction (Cases A, B, C and D) at the fusion boundaries, the ferrite that requires a large critical under-cooling for nucleation is difficult to nucleate, because the fall in the liquid temperature at the solidification front of the planar austenite is small. Consequently, the nucleation frequency of the ferrite with the K-S relationship between the planar austenite is expected to increase.

Nevertheless, if the <100> direction of the ferrite nucleated with the K-S relationship between the planar austenite is not aligned with the heat flow direction (Cases B and F), the growth of the lacy ferrite is halted at an early stage and a new ferrite nucleates. Furthermore, when a ferrite nucleates satisfying the K-S relationship with the planar austenite and its <100> direction is aligned with the heat flow direction, the ferrite can continue to grow as in Cases A and E. However, when the <100> direction of the planar austenite, which is the ferrite nucleation sites, is not aligned with the heat flow direction (Case E), then the austenite is eventually replaced by the adjacent austenite, which is well aligned with the heat flow direction. Accordingly, the K-S relationship established between the ferrite and the previous austenite is no longer maintained between the ferrite and the replaced austenite, and thus the ferrite morphology changes from initially lacy to vermicular via the replacement of austenite.

Consequently, for the continuous formation of the lacy ferrite as in Case A, it is necessary that the ferrite continues to grow with the K-S relationship with the austenite established at the nucleation stage. In other words, it is necessary (1) that the <100> direction of the austenite, which is the ferrite nucleation sites, is almost aligned with the heat flow direction, (2) that the ferrite nucleates on the austenite with the K-S relationship with the austenite, and (3) that the <100> direction of the ferrite nucleated is parallel to the heat flow direction. Becausethese conditions should be satisfied simultaneously for the lacy ferrite, the probability of the formation of lacy ferrite is relatively low. Between the lacy ferrite forming according to the above and the austenite, the K-S relationship and the parallel relationship between the <100> direction of the lacy ferrite and the <100> direction of the austenite along the heat flow direction is finally established, such a crystallographic orientation relationship is the same as that obtained at the steady solidification stage.

7.4 Verification of formation mechanisms of different types of ferrite

To verify the formation mechanism of different ferrite morphologies proposed, the following experiment was performed. Among the above conditions (1) to (3) for the continuous formation of the lacy ferrite, the only condition that can be manipulated intentionally is condition (1), the crystallographic orientation of the austenite grains of base metal. Therefore, autogeneous GTA welding was performed on the plates made by cutting a type 304 stainless steel cast ingot consisting of columnar austenite grains grown in parallel towards the ingot center. The specimen plates were prepared by changing the cutting direction, as shown in **Fig. 8**, so that the crystallographic orientations of the columnar austenite grains were different. In plate A, which was cut out at parallel to the ingot surface (normal to the growth direction of columnar austenite), the <100> direction as the preferential growth direction of the austenite grains is aligned with the thickness direction (the <100> direction of austenite is normal to the welding plane), and in plate B, which was cut out at normal to the ingot surface (parallel to the growth direction of columnar austenite), the crystallographic orientations of the austenite is random (the <100> direction is in the plane of the plate). Therefore, austenite grains are well oriented with respect to the heat flow direction in plate A and poorly oriented in plate B.

Fig. 9 shows weld microstructures taken near the bottom of the weld. Well aligned austenite in the base metal (Fig. 9(a)) was found to produce a greater amount of lacy ferrite in the weld, the proportion of lacy ferrite to the total ferrite increasing to approximately 30%. Conversely, poorly oriented austenite (Fig. 9(b)) was found to produce less lacy ferrite and the fraction of lacy ferrite is about 5%. Namely, the significant difference in the formation ratio of lacy ferrite can be confirmed only when the cutting direction of the same ingot is changed, while the total amount of ferrite is the same. This suggests that chemical composition does not significantly influence the morphology of ferrite, and that the formation of vermicular ferrite and lacy ferrite is determined primarily by the crystallographic orientation relationship between ferrite and austenite established at the ferrite nucleation stage, and also by the relationship between the heat flow direction and the preferential growth directions of ferrite and austenite respectively.

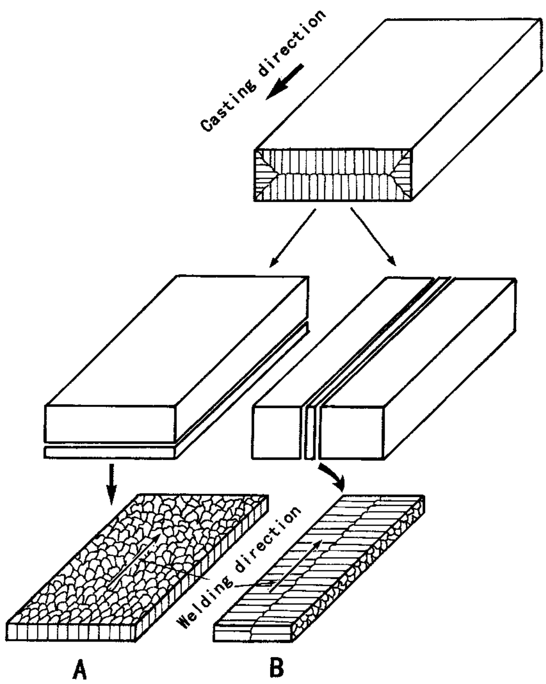


Fig. 8 Schematic illustration of plate preparation from ingot, cutting austenite columnar structure vertically (A) and cutting parallel to austenite columnar structure (B)

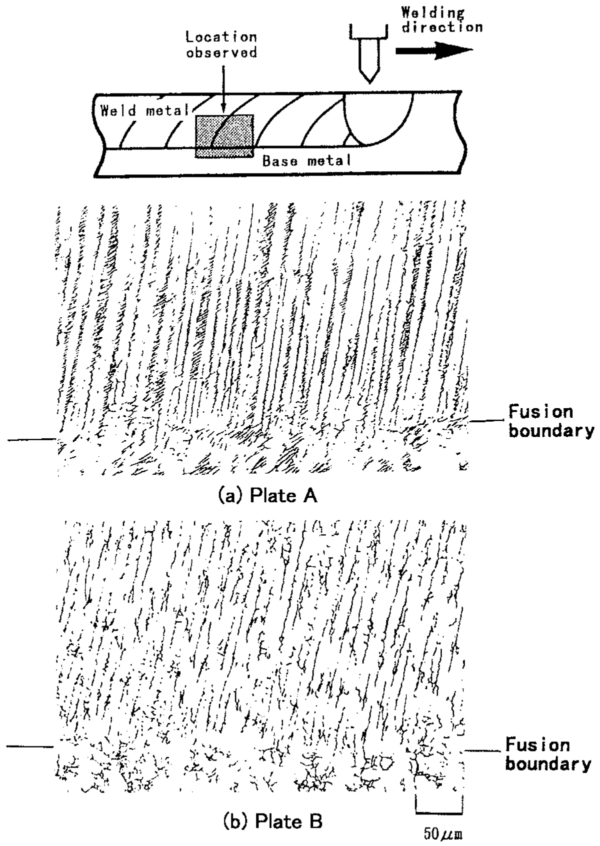


Fig. 9 Microstructures taken near bottom of weld center, parallel to welding direction, in autogenous TIG welds on (a) plate A and (b) plate B in Fig. 8

8. Summary

Solidification behavior of austenitic stainless steel solidified in the FA mode was investigated in terms of crystallography, and the dual-phase solidification manner and the formation mechanisms of two types of ferrite morphology was discussed. The results obtained in the present study are summarized below.

1) The cellular austenite as a secondary phase is formed at the dendrite boundaries of the preceding primary ferrite during solidification.
2) The following crystallographic characteristics (a-e) were observed in the weld metals solidified as FA mode.
   a. At the solidification front, the <100> directions of primary ferrite and interdendritic austenite are parallel along the solidification growth direction, but the specific orientation relationships do not exist at the interface between the ferrite and the austenite.
   b. At the fusion boundaries, the austenite in the weld metal grows from the base metal austenite in an epitaxial manner.
   c. At the fusion boundaries, the parallel relationship between the <100> direction of the ferrite and that of the austenite is rare, but the K-S relationship or the parallel relationship between close packed planes is established between the ferrite and the austenite.

d. The ferrites with different crystallographic orientations are formed within one austenite grain.
e. The ferrite with identical crystallographic orientation grows across more than one austenite grains with different orientations.

3) In austenitic stainless steel weld metals solidified as FA mode, ferrite and austenite do not grow dependently in terms of crystallographic orientation during the solidification. Only at the nucleation stage of new ferrite on austenite, the specific crystallographic orientation relationship is established between the ferrite and the austenite. The following growth of the austenite in the dendrite boundaries is invariably epitaxial and would not be restricted crystallographically by the preceding ferrite during the growth. Thus, the ferrite and the austenite grow independently, and this growth manner is named as "Independent Two-phase Growth".
4) The coexistence of equiaxed solidification of ferrite and the columnar solidification of austenite in TiN dispersed stainless steel can be explained only by the "Independent Two-phase Growth" mechanism mentioned above.
5) The "Independent Two-phase Growth" manner could be clarified for the first time through studies of the solidification process that can change the growth direction of solid (i.e., the heat flow direction).
6) The crystallographic orientation relationship between the primary ferrite and the austenite formed during solidification determines the final ferrite morphology. When the parallel relationship between close packed planes, rather than the K-S orientation relationship, is satisfied between the ferrite and the austenite at the solidification stage, the ferrite/austenite interface is planar during post-solidification cooling, and this leads to vermicular ferrite morphology. When the K-S orientation relationship is established between the ferrite and the austenite at the solidification stage, the plate-like austenite grows into the ferrite epitaxially along the habit plane during the post-solidification cooling, to form the lacy ferrite.
7) When the <100> direction of the ferrite and/or the austenite is not aligned with the heat flow direction, the replacement of the ferrite and/or the austenite occurs and the well aligned ferrite and austenite can eventually continue to grow. For the continuous formation of lacy ferrite, it is necessary that the ferrite and the austenite maintain the K-S relationship and <100> directions of the both phases are aligned with the heat flow direction.
8) The formation of the vermicular ferrite or the lacy ferrite in the FA mode solidified weld metal is primarily determined by the crystallographic orientation relationship between the ferrite and the austenite established at ferrite nucleation, and also by the relationship between the heat flow direction and the preferential growth directions of ferrite and austenite.

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