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Prospects for the control of solidification structures from the viewpoints of weld, hot-workability and near net shape casting

H.TODOROKI et al.

Solidification structures often determine the quality of final products. In this study, three different phenomena related to solidification processing, which are welding, hot-workability and investment casting, have been summarized.

With non-filler welding of SUS836L strips by TIG, segregation of welded material deteriorated corrosion resistance at the bead because of lower Cr and Mo concentrations at the dendrite cores. Employing filler material with higher pitting resistance equivalent (PRE) improved this deterioration. Next, it was confirmed that hot-workability of a stainless steel containing 1.1 mass% boron that has eutectic solidification behavior was more excellent with CC slabs than ingots. This reason is attributed to the fact that the eutectoids consisting of austenite and boride with the CC slab are much finer. Cracks at the stem-like corners of investment casts were often found by the magnetic particle testing. It was considered that the cracks were caused with this position being hot spots. The cracking was improved by changing the size of sprues for molten steel not to hit the corners to prevent hot spots.

As a summary, for high alloys, solidification process still depends on the way of try and error and experience base. Therefore far more investigations are expected to predict how molten steels solidify avoiding any defects and deterioration of every property.

(cf. *ISIJ Int.*, **48** (2008), 256)

Pattern of solidified structure on the inclined observation plane

H.ESAKA et al.

In the chill zone of the alloy casting, many fine grains nucleate on the surface and many dendrites grow their preferred growth direction. Therefore, it is rare that a "typical" dendritic structure can be observed near the chill zone. Usually, the solidified structure exhibits a quite complex pattern. In this study, the observed shape of dendrite will be investigated. Using Al–20mass%Cu alloy, unidirectional solidification with constant temperature gradient and growth velocity was performed. Then the solidified structure was observed on a cross section, which was intentionally inclined from the heat flow direction. The spatial relationship between dendrite and plane for observation has been defined using three angles, θ, ϕ and β. The solidified patterns were analyzed as a function of these angles. 3D-CAD model for solidified pattern has been developed assuming that secondary dendrite arms form plates. Solidified patterns agree quite well with 3D-CAD model.

(cf. *ISIJ Int.*, **48** (2008), 264)

Relation between the traces of nucleation on the surface and grain in the condition of continuous casting of steel

H.MIZUNO et al.

Control of nucleation on the surface of solidified shell is of importance to establish the whole structure of continuously-cast products. In the conventional continuous casting of steel, the nucleation of steel takes place on the molten state of mold flux. Lab-scale dipping tests have been carried out, where the solidification satisfied the above-mentioned condition. Changing the material of chill block and mold flux, the cooling rates of initial solidification have been varied systematically. The detailed observations of the surfaces and cross section of solidified shells have been made.

The grain size was affected by cooling rate and decreased monotonously with increasing cooling rate. Many small protrusions have been found on the surface of the solidified shell. They resembled discs as Biloni *et al.* named. The density of discs was affected by cooling rate and increased with increasing cooling rate. The effective nucleation ratio was defined as the ratio between the number of grains and that of discs. The effective nucleation ratio obtained was a few percent and indicated small dependence on cooling rate in the range of this study.

(cf. *ISIJ Int.*, **48** (2008), 270)

Analysis of the crystallization of mold flux for continuous casting of steel

H.MIZUNO et al.

In continuous casting of steel, mold fluxes are used to prevent surface defects, such as longitudinal cracks. The crystallization of mold flux promotes mild cooling of the steel shell, but crystallization behavior has been still uncertain. Therefore, this study has been carried out to analyze the crystallization processes of mold flux. Mold flux used in this study has high tendency for crystallization. Quenched specimens were heat-treated in various conditions and characterized. Glassy specimen heat-treated in the electric furnace over 550°C for 180 min crystallized. These crystalline were confirmed to be cuspidine by XRD analysis. The number of grains decreased and the average grain size increased with rise of temperature of heat treatment. The growth velocity also increased with rise of temperature.

In-situ observation by the laser microscope revealed that the glassy specimen crystallized in a moment over 600°C and the surface of the specimen turned to be rough. This may lead to mild cooling in the mold.

(cf. *ISIJ Int.*, **48** (2008), 277)

Effect of oxide particles on δ/γ transformation and austenite grain growth in Fe–0.05～0.30%C–1.0%Mn–1.0%Ni alloy

S.MORIOKA et al.

The microstructure control through the refinement of solidification structure has been studied in an Fe–0.05～0.30%C–1.0%Mn–1.0%Ni alloy as functions of particle characteristics of TiO_X, Al_2O_3, ZrO_2, Ce_2O_3 and MgO and solidification mode. The numbers of δ and γ grains per unit area have been measured in the samples quenched at the start temperatures of γ single phase (1 673 K at 0.05% C, 1 743 K at 0.15% C and 1 733 K at 0.30% C). The nucleation event of γ phase per one δ grain per unit area increases with decreasing the lattice misfit parameter between oxide and γ-Fe at 0.15 and 0.30% C, not 0.05% C. The results for γ grain density whose inverse value corresponds to the γ grain size can be explained by the grain-growth-inhibition effect. The γ grain size decreases with increasing the Zener pinning force at 0.15 and 0.30% C, not 0.05% C. The γ grain size obtained by quenching at the start temperatures of γ single phase for 0.05% C is considerably higher than that for 0.15 and 0.30% C.

(cf. *ISIJ Int.*, **48** (2008), 286)

Effect of TiN precipitates on austenite grain size in Fe–1.5%Mn–0.12%Ti–Si(<1.1%)–C(0.05 and 0.15%) alloy

H.OHTA et al.

In order to clarify the effect of non-uniformly dispersed TiN particles on the inhibition of austenite grain growth at non-steady state, an Fe–1.5%Mn–0.12%Ti–Si(<1.1%)–N(20～130 ppm)–C(0.05 and 0.15%) alloy with and without Mg deoxidation has been cooled from 1 873 to 1 473 K at 50 or 5 K·min^{-1}, followed by quenching. The austenite grain size distributions have been measured as functions of C, N and Si contents, Mg deoxidation and cooling rate. It was found that the γ grain growth is inhibited by the uniformly dispersed TiN particles which are found at 0.05% C. The effect of Si (0–1.1%) content on the γ grain size at given C, N and Ti contents has not been observed. In Mg deoxidation the number of TiN+MgO and TiN particles is about two times larger than that without Mg deoxidation, thus leading to smaller γ grain size. The mean γ grain size, $\bar{D}_A$, decreases with increasing the Zener pinning force at 0.05% C, but is independent of it at 0.15% C. The $\bar{D}_A$ value at 50 K·min^{-1} is lower than that at 5 K·min^{-1} at 0.05% C, but the $\bar{D}_A$ value is independent of the cooing rate at 0.15% C. This is explained by the fact that with decreasing cooling rate the number of uniformly dispersed TiN particles decrease considerably at 0.05% C, but only TiN particles at interdendritic region decrease at 0.15% C.

(cf. *ISIJ Int.*, **48** (2008), 294)

Grain-growth-inhibiting effects of TiC and ZrC precipitates in Fe–0.15～0.30mass%C alloy

A.O.TITOV et al.

The crystallization and precipitation of TiC and ZrC in an Fe–0.05～0.30%C alloy have been studied from the measurement of particles located at interdendritic region and austenite grain boundaries. The particles and γ grains were observed with the samples quenched at 1 673–1 743 K and those for holding at 1 673 K for 0–180 min. In an Fe–0.05～0.30%C–0.03%Ti alloy with soluble oxygen, the precipitation of $Ti(O,C)_X$ occurs at 0.15 and 0.30% C, while it does not at 0.05% C. The cross section area of particles increases with increasing carbon contents. In the case of TiC precipitation in an Fe–0.20%C–0.06～0.22%Ti alloy the particles at interdendritic region dissolve and re-precipitate at γ grain boundaries during holding at 1 673 K for 0–120 min. The TiC particles at γ boundaries dissolve after 60 min, whereby resulting in the abnor-

mal grain growth. In the case of ZrC precipitation in an Fe–0.20%C–0.02~0.27%Zr alloy, however, the ZrC particles at interdendritic region dissolve and continuously re-precipitate at γ grain boundaries up to 180 min, whereby resulting in the normal grain growth.

(cf. *ISIJ Int.*, **48** (2008), 301)

Size distribution of deoxidation products with Ti, Pr and Ti/Pr in Fe–10mass%Ni alloy

M.WARNE et al.

Deoxidation experiments using Ti, Pr and Ti/Pr have been conducted using a Fe–10 mass% alloy at 1 600°C. The purpose of the experiments was to study the change of particle size distribution as functions of holding time, difference between the different deoxidation procedures, and amount of deoxidant added. The Fe–10%Ni alloy was melted in a induction furnace and Ti, Pr or Ti/Pr were added as deoxidants. Samples were taken at different times after the addition of deoxidants. Thereafter, particles from each sample were extracted using electrolytic extraction. These particles where then examined in a SEM and image analyzer. Results show that the peak height of the size distribution decreases and the modal value increases with an increasing holding time. Furthermore, that the number of particles increases with an increase of deoxidant for a given initial oxygen content and holding time. The size distribution in case of the complex deoxidation using Ti followed by Pr deoxidation was also compared with deoxidation using only Pr.

(cf. *ISIJ Int.*, **48** (2008), 310)

Solidification behavior of AZ31 magnesium alloys using an electromagnetic vibration technique

M.LI et al.

The commercial magnesium-based AZ31 alloy was solidified in a static magnetic field when an alternating electric current, perpendicular to the direction of the magnetic field, passes through the alloy. In this case, the periodical Lorentz force is generated, making the conductor vibrate centering on the initial equilibrium position. In this paper, we investigated the microstructure evolution of the alloy as a function of vibration frequency, magnetic flux density and electric current, respectively. The solidification behavior was discussed and the mechanism for the formation of the microstructure was proposed when considering the electrical properties of solid and liquid at high temperature. Because the electrical resistivity of liquid in the mushy zone is about twice that of the solid, this significant difference drives the solid to move faster than the liquid and thus generating a leading displacement for the solid over the liquid even within one vibration cycle. The uncoupled movement between the solid and liquid also gives rise to melt flow, which may be the reason to segment dendrites into fine particles. Meanwhile, the uncoupled movement makes it difficult to establish a steady state for solute redistribution during solidification and thus favoring equiaxed structures instead of dendrites. Considering these two factors, we examine the solidification behavior of the alloy separately when vibration frequency, magnetic flux density, and electric current are set as independent variables and the microstructure evolution as a function of these processing parameters can be well interpreted.

(cf. *ISIJ Int.*, **48** (2008), 820)

Refinement of solidified structure using DC electromagnetic field

M.USUI et al.

The Sn–10%Pb alloy has been solidified under the imposition of a direct current and a static magnetic field perpendicular each other for the excitation of an electromagnetic force in the local region of the sample to clarify the effect of operating parameters on the solidified structure. The electromagnetic force induced by the simultaneous imposition of the direct current and the static magnetic field does not excite the nucleation in this investigation. And the solidified structures obtained under the different intensities of the direct current and the static magnetic field are compared each other for optimization of the electromagnetic field in this process. Increase in the direct current is preferable for the refined structure formation under the constant magnetic field intensity. Under the constant product of the direct current and the static magnetic field, refining effect of the solidified structure is the same level under the certain value of the magnetic field. Over this critical magnetic field, the refining effect decreases because the melt flow caused by the imposed electromagnetic force is suppressed by the interaction between the magnetic field and the fluid motion.

(cf. *ISIJ Int.*, **48** (2008), 330)

Peritectic transformation in low carbon steels containing high phosphorus concentration

M.KUDOH et al.

A boundary of austenite grain formed in the primary arm spacing of dendrites when the niobium concentration was over 1 mass% in Fe–0.1mass%C–*X*mass%Nb ternary alloys. This means that the shape of the group of a delta primary dendritic array might be indicated that of the subsequently formed austenite grain, depending on the addition of a ferrite former such as niobium. In this study, phase transformation from the delta to austenite phases and the effect of phosphorus on the correlation between the morphologies of the group of the delta dendritic array and austenite grains were investigated in carbon steels with various phosphorus concentrations. The results showed the occurrences of the delta, austenite and their coexisting phases might agree with each phase in the pseudo-binary phase diagram of an F–1.0mass%C–*X*mass%P alloy, in which *X*mass% shows the P concentration within 0.01 to 0.40 mass%. Moreover, the shape of the group of the primary delta dendritic array coincided with that of the subsequently formed austenite grains in alloys over 0.26 mass% P. However, the shape of the group of the delta dendrites did not coincide with that of the austenite grains in alloys under 0.18 mass% P. even though dendritic patterns could be seen.

(cf. *ISIJ Int.*, **48** (2008), 334)

Refinement of austenite grain in carbon steel by addition of titanium and boron

M.SASAKI et al.

The effects of the addition of titanium and boron on the austenite grain refinement in as-cast S45C carbon steel have been investigated and the results have been discussed based on an Fe–TiB_2 pseudo-binary phase diagram. The molar ratio of the added titanium and boron was fixed at 1 : 2 and the estimated molar percent of the added TiB_2 was varied from 0 to 0.5. The average austenite grain diameter decreased from 1 900 to 250 μm as the TiB_2 addition increased from 0 to 0.2 mol%, when the cooling rate was 0.02 K/s. The austenite grain diameter, however, did not exhibit further decrease when the TiB_2 addition increased from 0.2 to 0.5 mol%. The lower limit grain diameter of 250 μm was very close to the secondary dendrite arm spacing, which was not affected by the addition of titanium and boron. When the cooling rate of the molten steel increased, the grain size and the dendrite arm spacing decreased. For all cooling rates, the lower limit grain size was very close to the secondary dendrite arm spacing. Metallographic observations revealed that one austenite grain included many dendrite arms when titanium and boron was not added, while with the addition of these elements one dendrite arm included several austenite grains having the dimension of the dendrite arm diameter. It was suggested that TiB_2 particles and other inclusions such as TiC and Fe_2B were formed in the inter-dendritic positions during and after solidification and they controlled the grain boundary migration in the inter-dendritic positions.

(cf. *ISIJ Int.*, **48** (2008), 340)

Evolution of columnar γ grain in low carbon steel and its refinement by additional elements in thin slab casting simulator

Y.KOBAYASHI et al.

The evolution of as-cast γ grain in low carbon steel has been investigated using thin slab cast simulator developed in NIMS (National Institute for Materials Science). Fine columnar γ grain evolved from the surface to the center of the ingot was obtained, and second dendrite arm spacing and γ grain size of the ingot along with the distance from the surface showed a good agreement with those of commercially produced 50 mm thick slab by a thin slab caster. Thus, we succeeded to simulate the macro-structure and micro-structure of the thin slab produced by practical thin slab continuous casting process. The γ grain size for the present cooling rate of approximately 4 K/s showed a relatively good agreement with the estimated value by the previously predicted line of $d_\gamma = 1.52\dot{T}^{-0.5}$ for low carbon steels based on the Classical Grain Growth Model (CGGM).

Phosphorus, one of the typical impurities in steel, well known as the strong b.c.c. stabilizer, was added to low carbon steel aiming at the refinement of γ grain by the suppression of its growth. The γ grain size was drastically reduced to about a half of normally cast one even with a little addition of phosphorus lower than 0.05 mass%. It was probably

caused by the retardation of γ phase birth by the phosphorus segregation in the inter-dendritic region and the retardation of completion of δ/γ transformation which leads to pinning of the γ grain growth.

Moreover, tin, one of the typical impurities in steel scrap, also known as a b.c.c. stabilizer, was tried for addition. In spite of weaker b.c.c. stabilizing ability than phosphorus judging from the shape of iron binary phase diagram, a compatible γ grain refining effect was observed with addition of 0.1 mass% tin. According to these results, b.c.c. stabilizing elements such as phosphorus and tin are found quite useful to micro-structure control during solidification and cooling process.

(cf. *ISIJ Int.*, **48** (2008), 344)

Austenite grain refining of as-cast bloom surface by reduction of oscillation mark depth

Y.OHBA et al.

Austenite grain refining in the surface layer of as-cast bloom is effective for the reduction of surface cracks in steel production. This study was carried out to clarify the influence of cooling rate on the as-cast austenite grain size and its growth mechanism. Depth and interval of oscillation marks were reduced and the austenite grains at the bloom surface were refined under the oscillation conditions of shorter stroke and higher frequency. The average cooling rates were estimated to be from 6 to 16 K/s in austenite phase temperature and the rates were related to characteristics of oscillation mark. It was found that the austenite grain growth direction did not vary even when characteristics of oscillation mark changed. The austenite grain size below the surface layer was also determined by austenite grain size at the bloom surface.

(cf. *ISIJ Int.*, **48** (2008), 350)

Evaluation of crystal multiplication at mold wall during solidification of casting

T.AKAGIRI et al.

The effect of crystal multiplication at the mold wall during casting process, so-called "Big Bang" phenomenon, on the macrostructure of Al–Si alloy was examined. Conventional casting experiments were carried out and the degree of the crystal multiplication at the mold wall was evaluated by simulating the macrostructures similar to the experimentally observed ones using a cellular automaton method. The degree of the crystal multiplication decreased with increase in superheat of the molten alloy at the pouring. The reason of this can be attributed to the remelting of suspended crystals formed due to the crystal multiplication by superheated melt.

(cf. *ISIJ Int.*, **48** (2008), 355)

Numerical model of solidification structure formation in Fe–C alloy with peritectic transformation

M.YAMAZAKI et al.

A numerical model was developed for the simulation of structure formation during the solidification of an Fe–C alloy with peritectic transformation. In this model, the front tracking method was used to simulate the dendrite growth of primary δ phase and subsequent peritectic transformation. Diffusion in liquid and solid, mass conservation at the solid/liquid interface and local equilibrium at the solid/liquid interface with consideration of curvature undercooling were solved to determine the positions of the solid/liquid and δ/γ interfaces. A simulation was carried out for the growth of many primary δ dendrites to simulate the formation of initial gamma grain structure. The simulated results showed that the number of the initial gamma grain depends on the nucleation mechanism of gamma phase during peritectic reaction.

(cf. *ISIJ Int.*, **48** (2008), 362)

Monte Carlo simulation of grain growth taking into account the influence of temperature

S.OGIBAYASHI

The influence of temperature on the grain growth behavior in Monte Carlo simulation has been studied based on the original Potts model proposed by Anderson *et al.* Grain growth kinetics in Monte Carlo simulation are represented in the non-dimensional form by non-dimensional grain radius and the ratio of Monte Carlo step to total orientation number Q. It has been revealed that the influence of temperature in Monte Carlo simulation could be mainly introduced through the correspondent relationship between Monte Carlo Step and real time, rather than through the transition probability of re-orientation attempts. A new equation for the relationship between Monte Carlo Step and real time has been derived based on the idea of the law of similitude in grain growth. The grain growth during cooling for the actual time–length system has been estimated using newly derived equation and the estimated grain size as a function of temperature showed quantitatively good agreement with the observed results reported in the literature when lattice constant in the calculation system as a characteristic length for conversion was set to be 0.015 cm which was a half of the initial grain diameter in the real system.

(cf. *ISIJ Int.*, **48** (2008), 367)