論　文

Effect of Grain Refiners on Aluminum Twin Roll Casting Process*

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The purpose of this study is to investigate the effect of adding the Al-Ti-B grain refiner to the aluminum twin roll casting. The authors analyzed the microstructure of the as-cast strip produced by the twin roll casting based on several casting conditions. The results showed that the amount of the TiB_2 particles and the temperature gradient in the solidification area are the key factors for enhancing the effect of the grain refining. Additionally, this study simulated the behavior of the TiB_2 particles in the aluminum melt. The temperature distribution of the aluminum between the twin rolls was also calculated. The authors clarified the relationship between the grain refiner particles and the temperature gradient for the grain refining effect during the twin roll casting.

Keywords: *twin roll casting, strip casting, grain refining, cooling rate*

1. Introduction

Twin roll casting (TRC) is the one of the casting methods for aluminum sheets. This process can provide thin strips directly from molten metal so that it requires no scalping and hot-rolling which are required for direct chill (DC) casting and has been accepted worldwide as a cost-effective method for the past half-century [1]. In the TRC process, it is well known that grain refinement is less effective than in the DC casting. Two reasons are presumed for this effect. One of the reasons is the high cooling rate, but this effect is poorly understood, although several mechanisms have been suggested [2]. Another one is the low metal flow rate. TRC's production rate is much lower than that of the DC casting so that the metal flow rate is also very low and the TiB_2 particles, which play a role for the heterogeneous nucleation sites, settle in the metal during casting. A fluid flow analysis has been done for optimizing the metal feeding uniformity [3]. However, the study for determining the behavior of particles has not been sufficiently examined.

For the mass production of a thin strip, it is necessary to directly determine the effect of grain refiners on the TRC. The purpose of this study is to clarify the factors for the grain refining during the TRC.

2. Preliminary experiment

2.1 Experimental procedure

This study was conducted on cast strips of the 1050 alloy (Al-Fe-Si) cast at 710℃ before the casting machine. The chemical composition of the metal before adding the grain refiners is listed in **Table 1**. A pilot caster (**Fig. 1**), which is capable of casting 6 mm thick and 300 mm wide strips, was employed to produce 500 mm length strips. The strips were cast at three

Table 1　Chemical compositions of 1050 alloy.

(wt.%)

Al	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	B	V
Rem.	0.05	0.25	0.001	0.001	0.001	0.002	0.001	0.015	<0.001	0.014

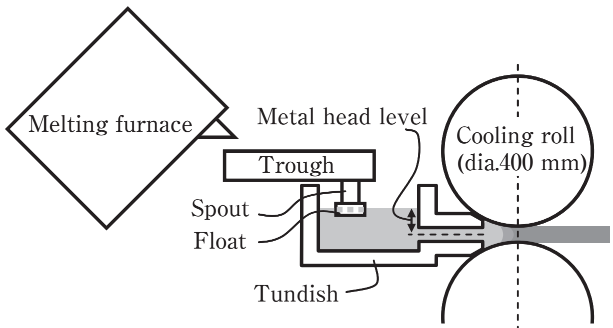

Fig. 1　Pilot caster.

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different grain refining conditions, namely, no-added and Al-5%Ti-1%B (mass%), and two different casting speeds, namely, 0.62 and 0.68 m/min. The grain refining conditions are listed in **Table 2**.

2.2 Results and Discussion

The macrostructures of the longitudinal cross section of the as-cast strips are shown in **Fig. 2**. Without adding a grain refiner A1 and A2, feather crystals were observed at the two different casting speeds and their observed areas were wider in A1 than A2. With the sufficient Al-5%Ti-1%B rod, the whole area was covered with very fine and equiaxed grains regardless of the casting speed. The center of the strips, however, was not refined and feather crystals were slightly observed at the low addition rate. This result indicates that feather crystals grow in the low Ti melt and at a low casting speed.

It is presumed that giant grains, for example feather crystals, tend to be formed when aluminum solidifies at a high cooling rate, high temperature gradient and no disturbance of the metal flow [4]. The cooling rate is equal to the product of the temperature gradient and solidification-interface speed. Their relation is described as:

$$Cv[°C/\mathrm{sec}] = G[°C/mm] \times V[mm/\mathrm{sec}] \tag{1}$$

$$G[°C/mm] = \frac{T_L - T_S[°C]}{l[mm]} \tag{2}$$

where Cv is the cooling rate, G is the temperature gradient, V is the solidification-interface speed, T_L is the liquidus temperature, T_S is the solidus temperature, and l is the mushy zone length.

Compared to the DC casting, the temperature gradient is bigger in the TRC because the mushy zone length in the TRC is shorter than that in the DC casting. The solidification-interface speed, which is equal to casting speed in the center of the strip thickness in the TRC, is then faster than it in the DC casting. Moreover, the melt is more stable than in the DC casting because the mushy zone length in the TRC is shorter and the metal flow rate is lower than in the DC casting. For these reasons, the TRC is the casting method in which giant crystals easily occur.

The reason why the grains of B1, B2, C1 and C2 were finer than those of A1 and A2 is that TiB_2 particles in the grain refiner rods played a sufficient role as heterogeneous nuclei added to the melt of B1, B2, C1 and C2. Nonhomogeneous nucleation in the molten metal occurs by heterogeneous nuclei as the trigger. The number of TiB_2 particles in C1 and C2 is about 4.3 times greater than in B1 and B2 such that the C1 and C2's grains are finer than the B1 and B2's.

The solidification between the twin rolls is shown in **Fig. 3**. We define the "solidification-interface" as the solidus temperature line in this paper. When the

Table 2 Experimental condition.

	Grain refining condition		Casting speed (m/min)
	Grain refiner	Addition rate (ppmTi)	
A1	-	-	0.62
A2			0.68
B1	Al-5%Ti-1%B rod	30	0.62
B2			0.68
C1		130	0.62
C2			0.68

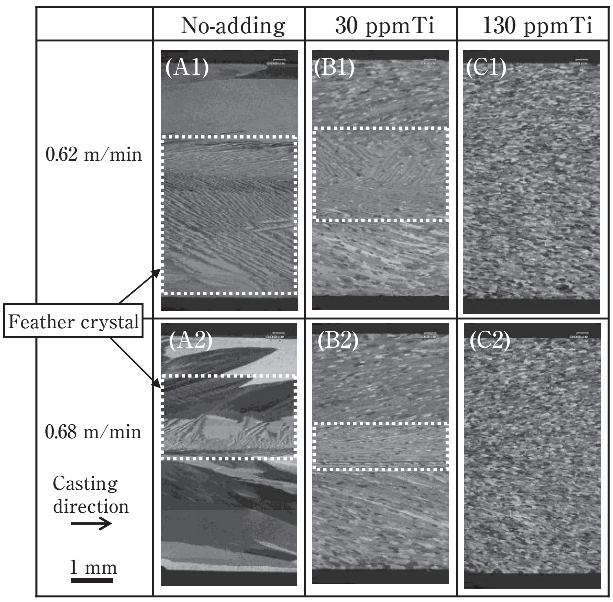

Fig. 2 Macrostructure of longitudinal cross section of the as-cast strips cast at six different conditions.

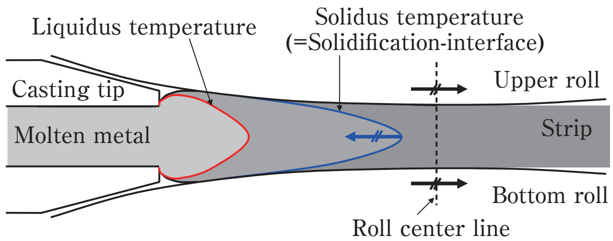

Fig. 3 Solidification between twin rolls.

casting speed increased, the solidification-interface moves toward the roll center line and the liquidus temperature line does not move very much as the solidification-interface. The mushy zone length then becomes longer than in the case of the low casting speed. It seems that the solidification-interface speed becomes faster, but the temperature gradient becomes smaller. Therefore, the solidification structure changes from anisotropy to equiaxed grains [5].

To clarify if the mushy zone becomes wider by increasing the casting speed, a calculation was carried out using the thermal equation **(Fig. 4)**.

The calculation indicates that the temperature gradient and cooling rate monotonically decrease by increasing the casting speed. On the other hand, the measurement of the dendrite cell size (DCS) has been done. It is known that the dendrite cell size or the second dendrite arm spacing (DAS) is in inverse proportion to the cooling rate [6]. The measurement proved that the cooling rate decreased by increasing the casting speed in the range of the preliminary experiment. The measurement results then agree with the above calculation result.

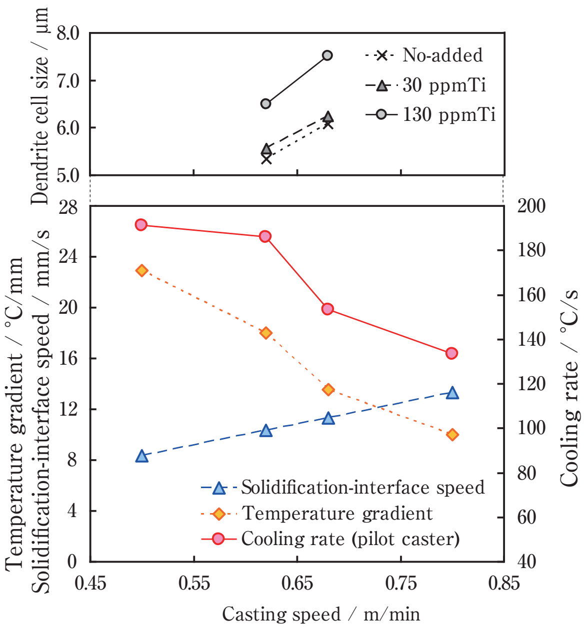

Fig. 4 DCS measurement and the casting parameters calculated by thermal equation of the preliminary experiment

The preliminary experiment leads to the following hypothesis:

"A high speed casting makes grain refiners more effective because the cooling rate decreases".

To confirm this idea, we determined if the high casting speed lowers the cooling rate and decrease the grain size.

3. Verification experiment

3.1 Experimental procedure

The verification experiment was conducted using cast strips of the 1050 alloy (Al-Fe-Si) cast at 700℃ before the casting machine. The chemical composition of the metal before adding the grain refiners is given in **Table 3**. A mass production casting machine **(Fig. 5)**, which is capable of casting 6 mm thick and 1500 mm wide strips, was employed to produce 1000 mm length strips. The experimental conditions are given in **Table 4**. Strips were cast at four different casting

Table 3 Chemical compositions of 1050 alloy. (wt.%)

Al	Si	Fe	Cu	Mn	Mg	Zn	Cr	Ti	B	V
Rem.	0.12	0.27	<0.001	0.002	0.001	0.004	0.001	<0.01	<0.001	0.014

Table 4 Experimental conditions.

	Grain refining condition		Casting speed (m/min)
	Grain refiner	Rod speed (mm/min)	
a	Al-5%Ti-1%B rod	220	0.85
b			0.95
c			1.00
d			1.10

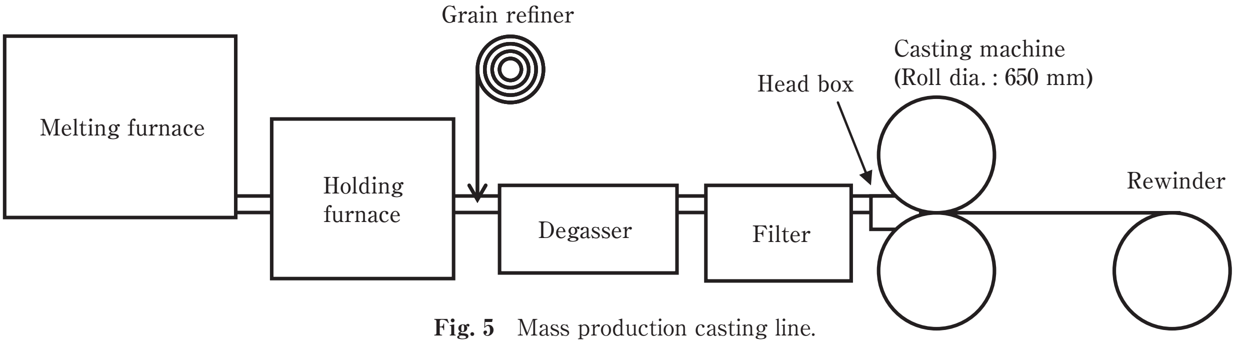

Fig. 5 Mass production casting line.

speeds, namely, 0.85, 0.95, 1.0, and 1.1 m/min. The Ti composition and grain size of each strip were measured by an OES analysis and grain counting method.

3.2 Results and Discussion

The macrostructures of the as-cast strips are shown in **Fig. 6**. When casting at 0.85 m/min, columnar crystals were observed in the center of the strip (a). At the other casting conditions at and above 0.95 m/min, the columnar crystals disappeared and fine equiaxed crystals were observed in the whole area (b), (c) and (d).

The measurements of the grain size and Ti amount are shown in **Fig. 7**. The most refined strip was cast at 0.95 m/min. The grain size becomes smaller in association with the decreasing Ti amount, except at 0.85 m/min. Though columnar crystals exist in the casting at 0.85 m/min, the Ti amount is higher than

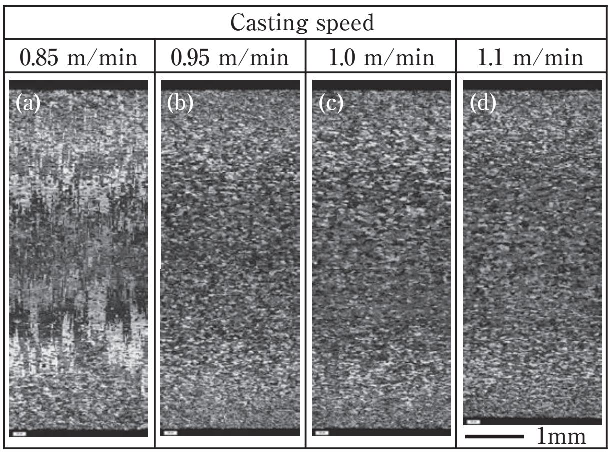

Fig. 6 Macrostructure of lateral cross section of the as-cast strips cast at four casting speeds.

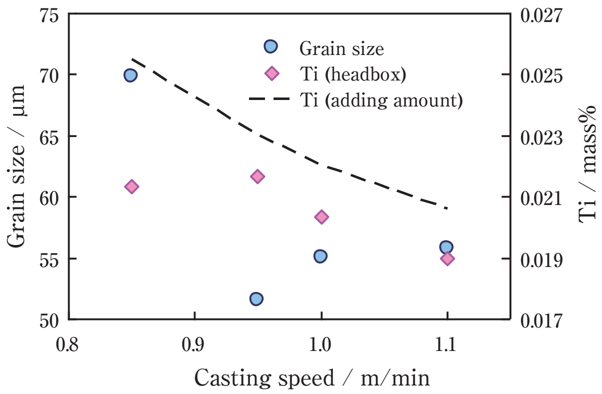

Fig. 7 Grain size and Ti amount versus casting speed.

1.0 m/min. Hence, the reason why the strip cast at 0.85 m/min was not refined is not fewer TiB_2 particles, but an insufficient solidification condition.

The temperature gradient and the cooling rate were calculated by the same thermal calculation used in the preliminary experiment. The dendrite cell sizes were also measured by the same method as in the preliminary experiment. The measurement result is compatible with this calculation result (**Fig. 8**).

In the verification experiment, the temperature gradient monotonically decreases when the casting speed increases the same as in the preliminary experiment. The cooling rate does not monotonically decrease with the increasing casting speed.

Therefore, if the temperature gradient is reduced, it is easy to obtain fine grains for strip casting whether the cooling rate is high or low.

3.3 The points of grain refining in the TRC

As has been noted, we need to take care of the following points to make the grains of the strip fine:

1. An adequate amount of heterogeneous nuclei (for example, TiB_2 particles) which are obtained by adding grain refiners to the molten metal.
2. Low temperature gradient which is achievable by increasing the casting speed.

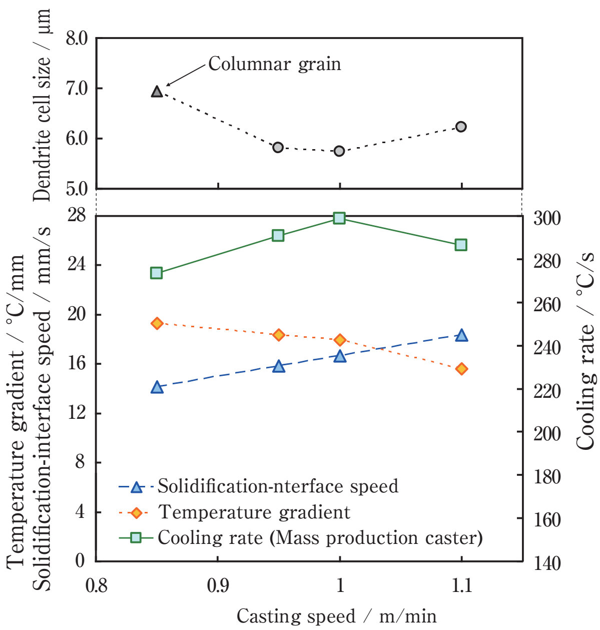

Fig. 8 DCS measurement and the casting parameters calculated by thermal equation of the verification experiment.

3.4　The behavior of the TiB_2 particles

Fig. 7 indicates that the TiB_2 particles settle as sediment during the casting. At each casting speed, the actual Ti values are less than the theoretical values. The added yield at 0.85 m/min is 83.7% and it is the lowest in the four speed conditions. Therefore, it is presumed that if casting at a low speed, the amount of the grain refiners increases because of adding at a uniform rod speed, but the heterogeneous nuclei tend to settle and not reach the casting machine.

To clarify the behavior of the TiB_2 particles, we calculated the number of particles which reach the casting machine on the mass production model.

4. Numerical simulation

4.1　Calculation procedure

The goal of the present study is to analyze the behavior of the TiB_2 particles from the trough to the headbox and the tip. A fluid flow analysis of the molten metal was performed by employing specifically designed 3-dimensional finite element software. The calculation condition is given in **Table 5** and the modeled metal flow path is shown in **Fig. 9**.

4.2　Results and Discussion

It was clarified that TiB_2 particles collect where the metal is stagnant, for instance, the corner in the headbox **(Fig. 10)**. Especially, bigger particles tend to collect.

The TiB_2 particles of each size were then divided into two groups. One is the effective particles which have reached the casting machine and the other one is the non-effective particles which have settled or collected before the tip outlet. The total added yield of the TiB_2 particles, which was calculated by the nucleus number of the two groups, decreased when the casting speed decreased **(Fig. 11)**.

Table 5　Calculation condition.

Fundamental equation	Uncompressed Navier-Stokes equation	
Turbulence model	k-epsilon model	
Calculation method	Metal flow : Steady analysis	
	Particle transport : Transient analysis	
Molten Al	Density (kg/m^3)	2350
	Viscosity (Pa･s)	0.001
TiB_2 particles	Density (kg/m^3)	4510
	Shape	Sphere
	Diameter (μm)	1, 10, 100
	Adding number (parts/sec)	100

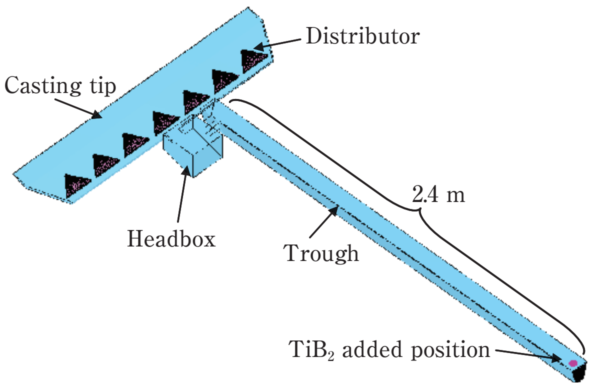

Fig. 9　Calculated model of metal flow path.

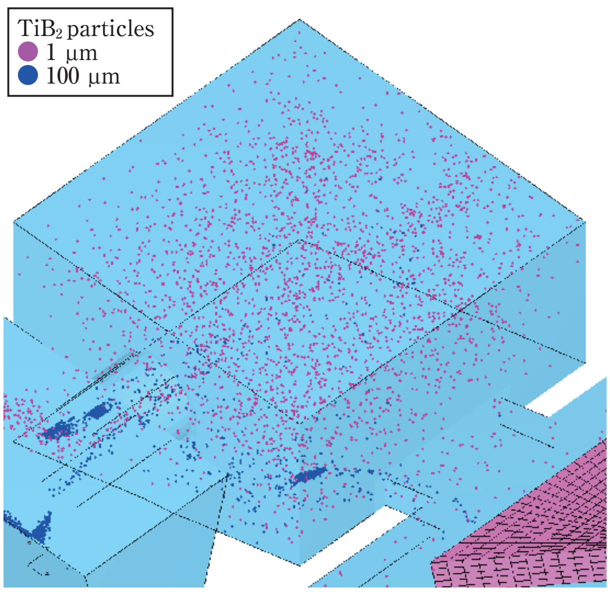

Fig. 10　TiB_2 particles which collect in the headbox.

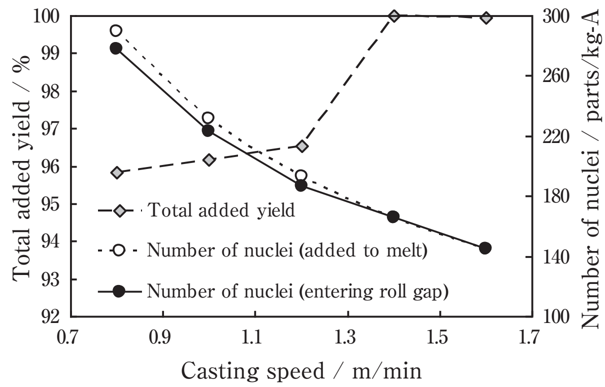

Fig. 11　Total added yield of TiB_2 particles.

5. Conclusion

The following can be concluded from this investigation:

1. The proper amount of heterogeneous nuclei and low temperature gradient are required to decrease the grain size in the TRC.
2. A low temperature gradient is obtained by increasing the casting speed.
3. A low casting speed is likely to make the heterogeneous nuclei settle or collect in the metal flow path.
4. The amount of heterogeneous nuclei, temperature gradient and metal flow path should be optimized to maximize the effect of the grain refiners.

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