UDC669.14.018.8-147

Production of Stainless Steel Strip by Twin-Drum Strip Casting Process

Hidemaro Takeuchi*1
Shigenori Tanaka*1
Yasuhiro Yamagami*1
Hiroyuki Nakajima*2
Mamoru Yamada*2
Ryouichi Hidaka*2

Abstract:

The Hikari Works of Nippon Steel developed a twin-drum strip casting process whereby molten stainless steel is charged into a casting unit consisting of a pair of 1,200-mm diameter drums and two side dams, and is directly cast into stainless steel strip. The new process can stably cast 10-ton heats into 800 or 1,300-mm wide strip by closely controlling the liquid steel level and strip thickness. Examination of the cross-sectional solidification structure and columnar zone thickness distribution of the twin-drum cast strip showed that the surface cracking of the strip is caused by nonuniform heat transfer. This finding helped establish technology for directly casting crack-free strip. The strip cast by the twin-drum process has finely dispersed inclusions and a low degree of microsegregation. The cast strip was cold rolled and tested for mechanical properties and corrosion resistance. The twin-drum cast and cold-rolled strip has higher corrosion resistance and smaller crystal orientation anisotropy than the one produced by the conventional process.

1. Introduction

The strip casting process that can produce steel strip directly from molten steel bypassing the hot rolling process has been a dream of steel engineers since Henry Bessemer published his theory in 1856[1]. Since the late 1980s, the development of near net shape casting regained momentum, and this led to the revival of twin-drum (or twin-roll) casting machines of the Bessemer type. At present, twin-drum strip casters of the pilot plant scale are being developed in various parts of the world.

Twin-drum strip casters with a drum width of 800 to 1,330 mm and heat size of 10 to 20 tons are under development[2-15]. Of particular interest are 10-ton pilot plants being developed by Pacific Metals and Hitachi Zosen[3], by Nippon Yakin Kogyo[5], and by Mitsubishi Heavy Industries and Nippon Steel[2] in Japan, and 10-ton test machines by Allegheny and VAI[10] and Usinor-Sacilor[13] abroad. This article outlines the twin-drum strip casting technology, cast strip quality, and product quality.

*1 Technical Development Bureau
*2 Hikari Works

2. Principle and Characteristics of Twin-Drum Strip Casting Process

The twin-drum strip caster is schematically illustrated in **Fig. 1**. Molten steel is poured between two water-cooled drums and rapidly cooled as its heat is removed through the drum surfaces. The two solidifying shells are joined into a single strip at the drum kiss point where the drum gap is the narrowest. **Fig. 2** shows the approximate relationship between the cooling rate and section thickness in the strip casting process as compared with that in the conventional slab casting process. The cooling rate for the strip casting process is 100 K/s or 1,000 times higher than for the conventional slab casting process. The thickness of the cast strip is one-hundredth of that of the cast slab. This dispenses with the hot rolling process to follow. The high cooling rate provides strip-cast products with various characteristics as described later.

3. Outline of Twin-Drum Strip Casting Process

Here are presented the development of a 10-ton, 800 to 1,330 mm-wide twin-drum strip caster installed at the Hikari Works of Nippon Steel. The development work has been jointly conducted by Mitsubishi Heavy Industries and Nippon Steel since 1982.

3.1 Casting machine

The casting machine is schematically illustrated in **Fig. 3**[2]. The machine consists of a pair of drums, two side dams, and a coiler. Molten steel is poured into the pool enclosed by the drums and side dams and is solidified into shells through contact with the drums. The two solidifying shells are joined into a single strip at the kiss point of the drums. Main specifications of the caster are as given in **Table 1**. The drum width is 800 or 1,330 mm, the drum diameter is 1,200 mm. Type 304 stainless steel was cast.

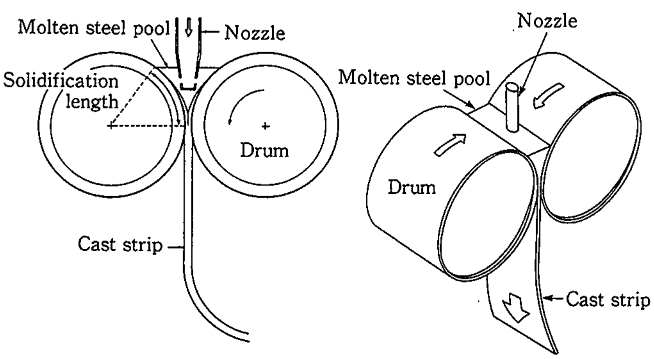

Fig. 1 Principle of twin-drum strip caster

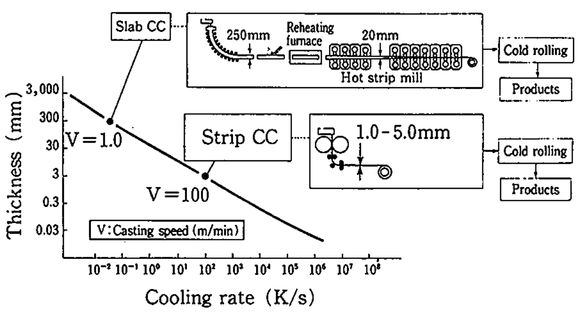

Fig. 2 Comparison of twin-drum strip casting process with conventional slab casting process

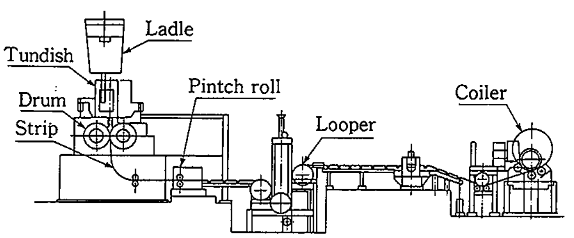

Fig. 3 Schematic diagram of 10-ton twin-drum strip caster

Table 1 Main specifications of twin-drum strip caster

Items	Specifications
Type	Twin drums
Ladle capacity	10 ton
Tundish capacity	1.6 ton
Casting speed	20-130m/min
Strip thickness	1.6-5.0mm
Drum width	800/1,330mm
Drum diameter	1,200mm
Drum seleeve	Cu+Ni plating
Coiler type	Up-coiler

3.2 Casting operation stabilization

Actions to be taken to stabilize the casting operation were: 1) prevention of molten steel leakage by preventing the thermal distortion of side dams[16], and 2) stabilization of the control system.

3.2.1 Liquid level control[17]

The control system consists of a meniscus position detector and a tundish stopper actuator. The tundish stopper moves in response to the detected meniscus level and controls the level of the molten steel pool accordingly. **Fig. 4** shows the liquid level measured when the liquid level is under control. The liquid level can be controlled to a tolerance of ± 1.6 mm ($\pm 0.2°$ in terms of contact are angle).

3.2.2 Strip thickness control[18]

The center solid fraction of the cast strip passing the drum kiss point is considered to depend on the drum-molten steel contact time, casting speed, strip thickness, and drum push force[19]. When the drum push force is constant, the strip thickness is given by

$$d = 2K_R t^n = 2K_R(r\theta/V)^n \quad \cdots\cdots (1)$$

where d is strip thickness (mm); K_R is solidification coefficient (mm/min^{-n}); t is contact time (min); r is drum radius (m); θ is contact arc angle (rad); and V is casting speed (m/min).

As evident from Eq. (1), the strip thickness is proportional to the time during which the molten steel remains in contact with the drums. **Fig. 5** shows the relationship of the contact time with the strip thickness. When K_R is 28.2 mm/min^{-n} and n is 0.6, the measured values agree with the values calculated by Eq. (1). Equa-

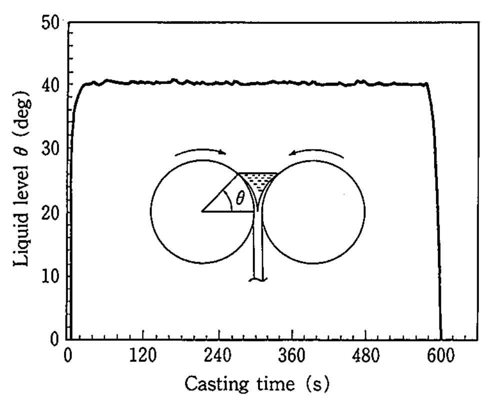

Fig. 4 Results of liquid level control

tion (1) allows the liquid level and casting speed to be preset to suit the desired strip thickness. During casting, the strip thickness and drum reaction force are measured and fed back to the control system. The casting speed and drum gap can thus be adjusted to achieve the target strip thickness.

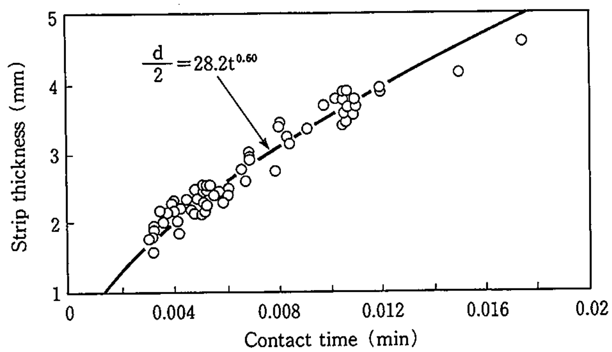

Fig. 5 Effect of strip-drum contact time on twin-drum cast strip thickness

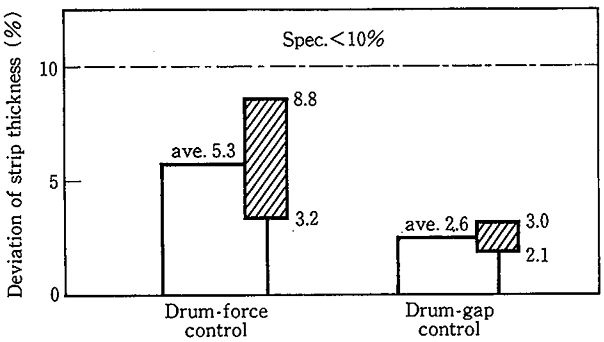

Fig. 6 Results of twin-drum cast strip thickness control by drum push force control and drum gap control

Fig. 6 shows the strip thickness variation obtained as a result of strip thickness control. The strip thickness accuracy is 8.8% or less when the casting speed is controlled while keeping the drum push force constant and is 3% or less when the casting speed is controlled while keeping the drum gap and drum push force constant.

All these techniques combined to realized the stable strip casting of 10-ton heats. **Photo 1** shows a 1,330-mm-wide coil thereby obtained.

4. Quality of Strip Cast by Twin-Drum Strip Casting Process

Photo 2 shows the surface of 1,330-mm wide twin-drum cast strip after pickling. The strip has no surface cracks. **Photo 3** shows the cross-sectional solidification structure of the strip. Columnar crystals grow from both surfaces, and equiaxial crystals are observed at the midthickness of the strip[20].

Taking the columnar zone thickness distribution as a measure of the uniformity of solidification, **Fig. 7** shows the columnar zone thickness measurements taken across the strip width, respectively for 800-mm and 1,330-mm wide twin-drum cast strips. The standard deviation of columnar zone thickness distribution divided by the average columnar zone thickness is defined as the nonuniformity of solidification. This value is about 4% for both strips, which indicates their uniform solidification irrespective of their width[21].

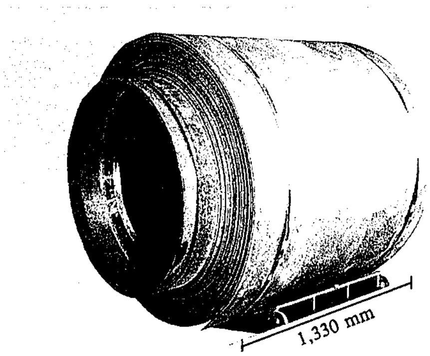

Photo 1 Appearance of 10-ton coil of 1,330-mm wide twin-drum cast strip

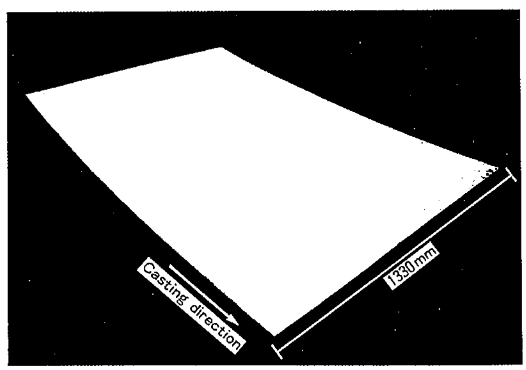

Photo 2 Surface of twin-drum cast strip after pickling

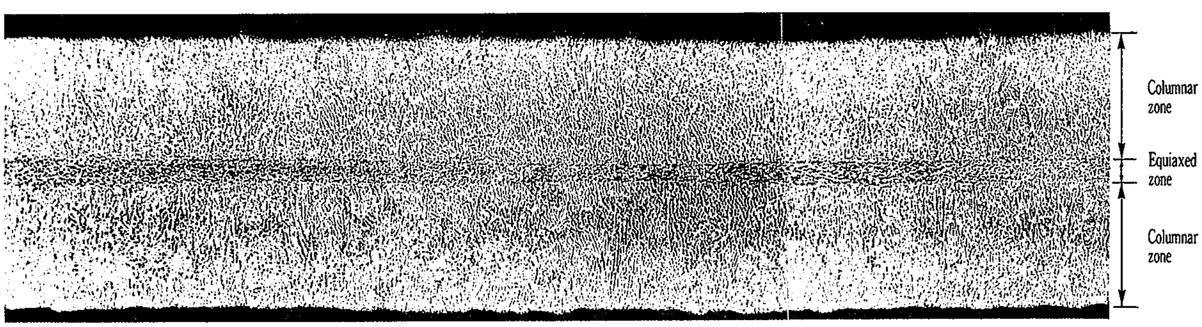

Photo 3 Cross-sectional microstructure of twin-drum cast strip

500µm

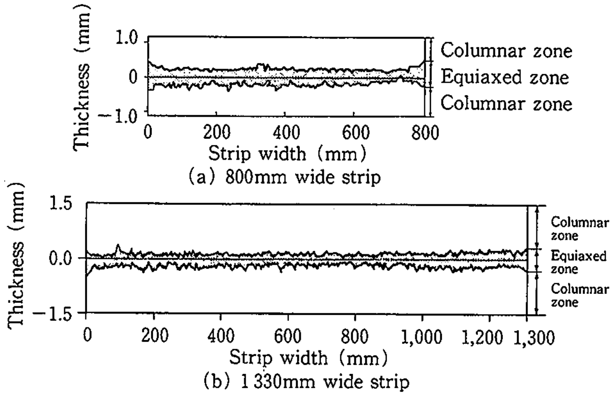

Fig. 7 Variations in transverse columnar zone thickness of 800-mm and 1,330-mm-wide twin-drum cast strips

5. Estimation of Surface Cracking Mechanism and Preventive measures

Photo 4 shows the solidification structure around a longitudinal surface crack. The columnar zone thickness thins down around the crack, which means a smaller amount of heat extraction to the drum surface. The crack is considered to have occurred in the following stages[22]:

First stage: Uneven heat transfer

Second stage: Uneven cooling rate (cooling rate lower by 10 to 20% in cracked area than in sound area)

Third stage: Uneven solidification shrinkage strain

Fourth stage: Crack formation triggered by resultant tensile strain

Fig. 8 shows the through-thickness temperature and strain distributions of twin-drum cast strip solidifying with nonuniform heat transfer as revealed by calculating heat transfer and strain in combination. The heat removed from the area h_2 is calculated to be 70% of that removed from the area h_1. The area h_2 was found to solidify at a lower rate (higher in temperature) and to be subject to a greater tensile strain than the area h_1[23,24].

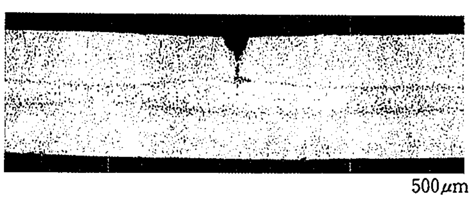

Photo 4 Cross-sectional microstructure of twin-drum cast strip around longitudinal crack

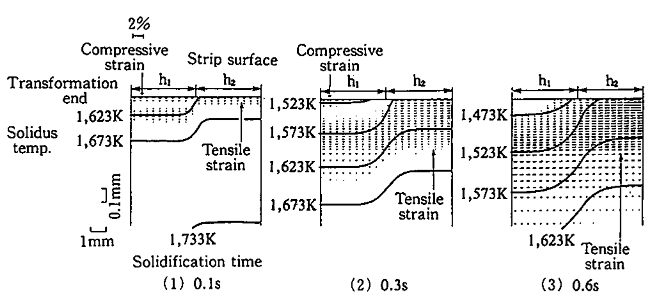

Fig. 8 Temperature and strain distributions of nonuniformly solidified twin-drum cast strip

These findings strongly suggest that uneven solidification causes uneven strain, which in turn triggers the longitudinal surface cracking of the cast strip.

Accordingly, elimination of uneven heat transfer is essential for preventing the cracking of the cast strip. In the twin-drum strip casting process, strip cracking is prevented by stabilizing the liquid level and eliminating turbulence at the liquid surface[25], and by preventing the infiltration of air into the atmosphere shielding the molten steel between the drums, thereby precluding the formation of oxides[2].

6. Characteristics of Stainless Steel Strip Cold Rolled from Strip Cast by Twin-Drum Strip Casting Process

6.1 Mechanical properties and corrosion resistance

A coil of twin-drum cast strip was test rolled at the cold strip mill of Hikari Works. A hot band coil produced by the conventional slab caster-hot strip mill route was used as control. Each cold-rolled strip was pickled or bright annealed.

Table 2 shows the mechanical and corrosion resistance test results of the two cold-rolled strips[26]. The twin-drum cast and cold-rolled strip is equivalent to the conventional strip in elongation and tensile strength, but is lower in anisotropy and higher in pitting potential as a measure of corrosion resistance.

6.2 Characteristics of twin-drum cast strip

The twin-drum cast strip has the following characteristics.

First, it is lower in nonmetallic inclusions than the conventional hot-rolled strip, as shown in **Fig. 9**. For example, the number of 1-μm and larger inclusions is one-fifth of that observed in the conventional hot-rolled strip. This is probably because the growth of inclusions during solidification is suppressed by rapid cooling[27].

Table 2 Property comparison of sheet cold rolled from twin-drum cast strip with sheet cold rolled from conventional hot-rolled strip

Properties / Materials	Mechanical test			Corrosion test
	Elongation (L-direct)	Tensile strength	Anisotropy Δr	Pitting potential V vs SCE
Products from twin-drum cast strip	50.4%	702 (N/mm^2)	−0.24	0.38V
Conventional products	50.8%	702 (N/mm^2)	−0.54	0.26V

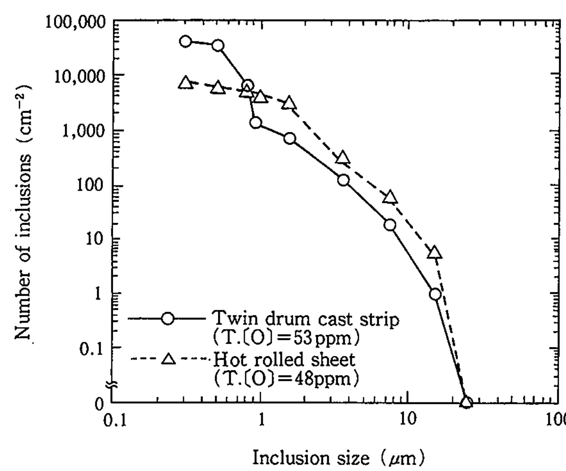

Fig. 9 Comparison of twin-drum cast strip with conventional hot-rolled strip in nonmetallic inclusion size distribution

Next, it is lower also in microsegregation than the conventional hot-rolled strip. **Fig. 10** shows the effect of cooling rate on the concentration of nickel segregation. The twin-drum cast strip has less microsegregation than the conventional cast slab[28]. These characteristics are considered to provide the twin-drum cast strip with corrosion resistance higher than the strip produced by the conventional slab caster-hot strip mill-cold strip mill route.

Fig. 11 shows the crystal orientation of the twin-drum cast strip as compared with the conventional strip. The (112) orientation is strong in the conventional strip, whereas the (110) and (210) orientations in the as-cast condition are predominant in the twin-drum cast strip. These orientations are considered responsible for the low anisotropy of the twin-drum cast strip[26].

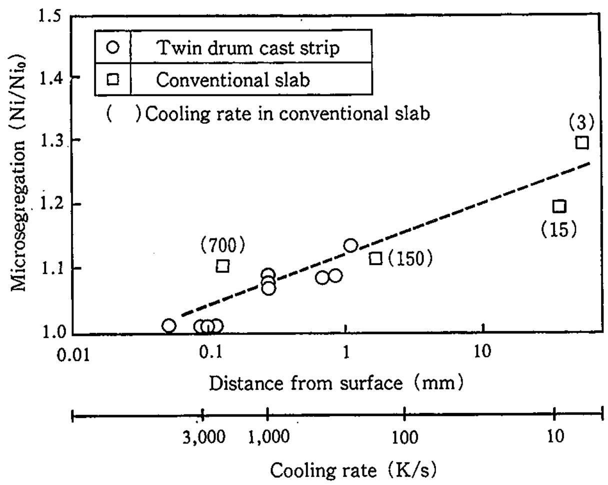

Fig. 10 Comparison of twin-drum cast strip with conventional cast slab in nickel segregation ratio of microsegregation

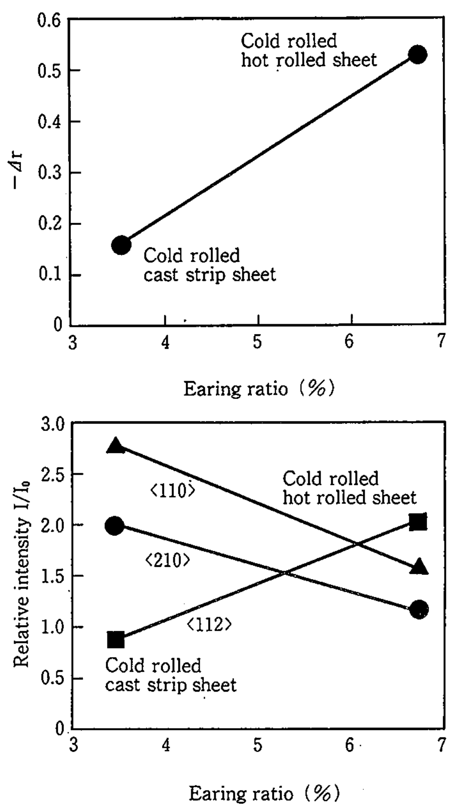

Fig. 11 Effects of anisotropy and crystal orientation on earing ratio of sheet cold rolled from twin-drum cast strip as compared with sheet cold rolled from hot-rolled strip

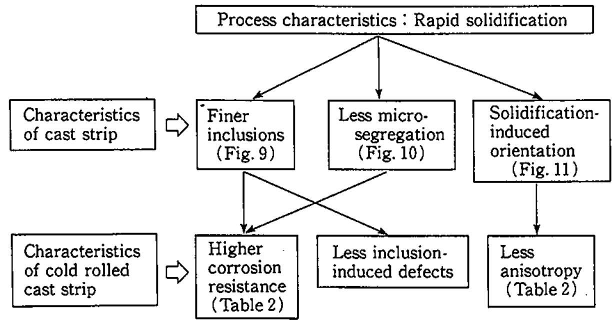

Fig. 12 Characteristics of twin-drum cast strip and corresponding properties of cold rolled strip

Fig. 12 summarizes the characteristics of the twin-drum cast strip. As shown, rapid solidification reduces inclusions and microsegregation. Direct cold rolling makes as-solidified crystal orientations predominant, which results in characteristic corrosion resistance and anisotropy in the twin-drum cast and cold rolled strip. To best exploit these characteristics, the product is applied to building wall panels, sinks, and decorative tubes, and its service performance is now under evaluation.

7. Conclusions

The development of the twin-drum strip casting process provided the following findings:

(1) Stable strip casting was made practicable through liquid level control and strip thickness control. As a result, 10-tons coils of 800-mm and 1,330-mm wide strip were successfully produced.
(2) It was confirmed that crack-free strip of uniform solidification can be produced.
(3) The strip solidification process and strip cracking mechanism were successfully estimated.
(4) The twin-drum cast and directly cold-rolled strip features less nonmetallic inclusions and segregation than strip produced by the conventional slab caster-hot strip mill-cold strip mill process. The low inclusion content and segregation degree assure high corrosion resistance and low anisotropy of crystal orientation.

The twin-drum strip caster is about to be commercialized after years of progress and accumulation in industrial technologies since Henry Bessemer published its concept in 1856.

Acknowledgments

In 1982, Nippon Steel started the joint research and development of the twin-drum strip casting process with Mitsubishi Heavy Industries, particularly Hiroshima Machinery Works and Hiroshima R & D Center. The authors would like to express deep gratitude to the staff concerned at Mitsubishi Heavy Industries for their cooperation in this joint R & D project.

References

1) Bessemer, H.: Annual Meeting of The Iron and Steel Institute. 6 (10), (1891)
2) Yoshimura, Y. et al.: CAMP-ISIJ. 4, 993 (1991)
3) Yamada, K. et al.: CAMP-ISIJ. 5, 1021 (1992)
4) Ohno, K. et al.: Intern. Conf. on New Smelting Reduction and Near Net Shape Casting Technologies for Steel (SRNC-90), Pohang, Korea, 1990, p.682
5) Tekko Shimbun. September 29, 1992
6) Ban, T. et al.: CAMP-ISIJ. 3, 1160 (1990)
7) Yamane, H. et al.: CAMP-ISIJ. 5, 1072 (1992)
8) Inoue, T. et al.: CAMP-ISIJ. 5, 1018 (1992)
9) Niide, T., et al.: CAMP-ISIJ. 5, 1019 (1992)
10) Schwaha, K.L. et al.: ISIJ Technology Meeting in Vienna. May 3 and 4, 1993
11) Tolve, P. et al.: IISI Technology Meeting in Vienna. May 3 and 4, 1993
12) Robson, A.L. et al.: IISI Technology Meeting in Vienna. May 3 and 4, 1993
13) Financial Times. July 15, 1991, p.17
14) McCutcheon, D.B.: IISI Technology Meeting in Vienna, May 3 and 4, 1993
15) Hentrich, R. et al.: Stahl u. Eisen. 2, 111 (1991)
16) Kasama, A. et al.: Intern. Conf. on New Smelting Reduction and Near Net Shape Casting Technologies for Steel (SRNC-90), Pohang, Korea, 1990, p.643
17) Arai, T. et al.: CAMP-ISIJ. 6, 254 (1993)
18) Yamamoto, K. et al.: CAMP-ISIJ. 4, 994 (1991)
19) Ogawa, S. et al.: CAMP-ISIJ. 3, 216 (1990)
20) Fukuda, Y. et al.: CAMP-ISIJ. 6, 225 (1993)
21) Fukuda, Y. et al.: CAMP-ISIJ. 4, 995 (1991)
22) Suichi, I. et al.: CAMP-ISIJ. 5, 1209 (1992)
23) Miyazaki, M. et al.: CAMP-ISIJ. 4, 998 (1991)
24) Suichi, I. et al.: CAMP-ISIJ. 4, 999 (1991)
25) Suichi, I. et al.: CAMP-ISIJ. 3, 215 (1990)
26) Suehiro, T. et al.: CAMP-ISIJ. 3, 214 (1990)
27) Fukumoto, S. et al.: CAMP-ISIJ. 5, 1024 (1992)
28) Fukuda, Y. et al.: CAMP-ISIJ. 5, 1023 (1992)