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# Progresses and Future Prospects of Steelmaking Technologies†

MIKI Yuji[*1] WATANABE Keiji[*2] OSHIMA Kenji[*3]

***Abstract:***

*The main research and technical development topics in the last decade since the establishment of JFE Steel Corporation are summarized. In the area of refining, priority was placed on reducing slag generation by improving reaction efficiency in the hot metal pretreatment process, improving the level of purification in the BOF and secondary refining processes, and expanding iron source utilization by increasing the heating margin. In slag and refractories, slag reuse techniques, recovery of sensible heat from hot slag, and iron and phosphorous recovery techniques were developed and put to practical use. In casting, stable high-speed casting and defect-free slab production techniques to prevent surface defects and cracks and to reduce centerline segregation were developed. This paper also introduces the future prospects for steelmaking technologies.*

## 1. Introduction

In response to heightened requirements for higher purification levels in steel products, reduction of the impurities such as phosphorus (P) and sulfur (S) in the refining process is increasing. At JFE Steel, generation of steel slag is reduced and the quality of steel products is improved by reducing P and S in the hot metal pretreatment process before converter refining. In addition to reduction of steel slag generation by improving the reaction efficiency of the fluxes used to remove impurities, rational recycling technologies responding to environmental needs are also necessary. In converter and secondary refining processes, high purification technologies under high productivity conditions are required. Moreover, reduction of $CO_2$ emissions in the steel producing process by technologies that expand iron source utilization by reducing heat loss and increasing the heating margin in the steelmaking process, and technologies for improving iron yield are also demanded. The refining techniques introduced in this report are shown in **Table 1**. In this table, BOF means Basic Oxygen Furnace, and parentheses indicate the composition of slag.

In continuous casting, it is necessary to satisfy both high productivity and high quality in order to respond to increasingly intense competition due to globalization. The continuous casting techniques introduced in this paper are shown in **Table 2**. To achieve high productiv-

Table 1 Developed techniques in steelmaking process

| | | |
|---|---|---|
| Hot metal pre-treatment | Reduce and Reuse of steelmaking slag | Increase of Hot metal pretreatment efficiency in torpedo car and BOF |
| | | ($Fe_tO$) control in hot metal dephosphorizatin in BOF |
| | | Blasting and slag hot recycling in hot metal desulfurization |
| BOF | Increase productivity | Tuyer layout in bottom-blowing |
| Secondary refining | | Gas jet control in vacuum condition |
| Increase of heat capasity | | Oxy-fuel burner with chromium ore in smelting reduction converter |
| | | Application of insulated refractories |
| Utilization of cheaper iron scrap | | Cu removal in hot metal |
| Utilization of steelmaking slag | | Fe and P collection from steelmaking slag |

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*1 Dr. Eng.,
Principal Researcher,
Executive Assistant,
Steel Res. Lab.,
JFE Steel

*2 Dr. Eng.,
General Manager,
Slag & Refractories Research Dept.,
Steel Res. Lab.,
JFE Steel

*3 General Manager,
Executive Assistant,
Steelmaking Technology Dept.,
JFE Steel

Table 2 Developed techniques in continuous casting process

| Target | Technological development |
|---|---|
| Clean steel | · Pressurization and depressurization refining<br>· Centrifugal flow tundish |
| High speed casting | · Breakout detection<br>· Intensive secondary cooling<br>· High-pressure water spray<br>· Prevention of submerged entry nozzle clogging (containing MgO and Al) |
| Prevention of surface defect caused by inclusions and mold flux | · Flow control in mold by magnetic force (Flow Control Mold)<br>· Addition of liquid mold flux<br>· Non-Newtonian flux |
| Prevention of surface cracking | · Uniform cooling<br>· Predeformation treatment |
| Prevention of centerline segregation | · Direct measurement of unsteady bulging |
| Control of solidifcation structure | · Prediction of equiaxed crystal ratio |

ity, techniques for stable casting under high throughput, high casting speed conditions are necessary, requiring more advanced breakout (BO) detection technology, development of mold powders for high speed casting, and development of a secondary cooling technology which makes it possible to increase the cooling capacity. For high quality, from the viewpoint of accelerated development of new products, development of technology for production of clean steel, technology for prevention of surface defects responding to strict surface quality requirements such as automotive steel sheets, technology for prevention of surface cracks for high strength, high tensile steel sheets, and technology for reduction of centerline segregation for sour service are strongly demanded.

This report describes recent progress in steelmaking technologies at JFE Steel Corporation as well as the future prospects.

## 2. Development of Refining Techniques

### 2.1 Hot Metal Pretreatment Process

JFE Steel reconstructed the hot metal pretreatment process and introduced new technologies to improve the quality of steel products and reduce generation of steel slag based on production of low-P, low-S steel by hot metal pretreatment process[1,2].

**Figure 1** shows the hot metal pretreatment process and the developed techniques. At East Japan Works (Chiba District) and West Japan Works (Kurashiki District), hot metal desphosphorization (de-P) capacity in torpedo car was increased, and hot metal desulfurization

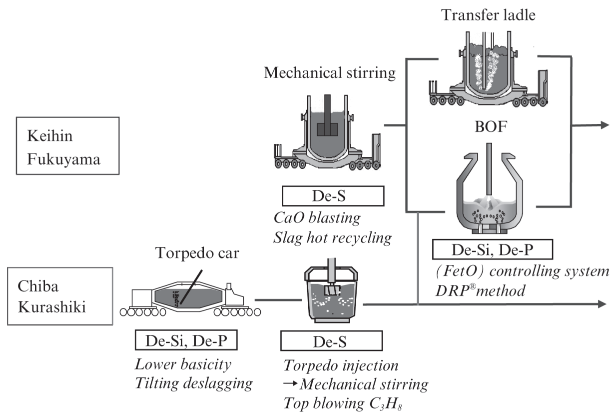


Fig. 1 Developed techniques in hot metal pretreatment process

by mechanical stirring using hot metal charging ladle was introduced, replacing the conventional method of desulfurization by flux injection in the torpedo car[2,4].

For hot metal dephosphorization, a technique which does not use fluorspar and soda ash as refining agents (flux) was developed. In torpedo car de-P, slag melting was enhanced by lowering the slag basicity setting from 2.0 to 1.6, and the feed rate of de-P flux, which consists mainly of iron oxide, was increased to 1.25 times. The problem of slag slopping, which occurs under these conditions, was solved by adopting a deslagging technique in which the torpedo car is tilted 5° and the slag is discharged into a dedicated slag pit. It was possible to increase the de-P capacity by securing actual basicity of 1.5 in the slag after treatment.

East Japan Works (Keihin District) and West Japan Works (Fukuyama District) use hot metal dephosphorization in the converter. At these two steel works, acceleration and control of formation of $Fe_tO$ in the slag during blowing is applied as a fluorspar-free technique[5]. The influence of $Fe_tO$ in slag on the reaction rate in hot metal dephosphorization in the converter was quantified by a reaction model, and a system for estimating $Fe_tO$ formation during hot metal dephosphorization was introduced in the actual process. As the result, dynamic control $Fe_tO$ formation in slag was achieved, and a stable low-P hot metal technique was established[6]. A new converter-type hot metal de-P process called DRP™ (Double-slag Refining Process) was also developed as shown schematically in **Fig. 2**. In this process, the hot metal is charged directly into the converter without performing desiliconization (de-Si) in advance, and de-Si blowing is performed in the converter. After de-Si blowing, blowing is interrupted and intermediate deslagging is performed. After the high $SiO_2$ slag in the converter is discharged, then de-P blowing begins.

As a disadvantage of the torpedo car method used at Chiba and Kurashiki, the hot metal temperature was low in the hot metal desulfurization process, because desul-

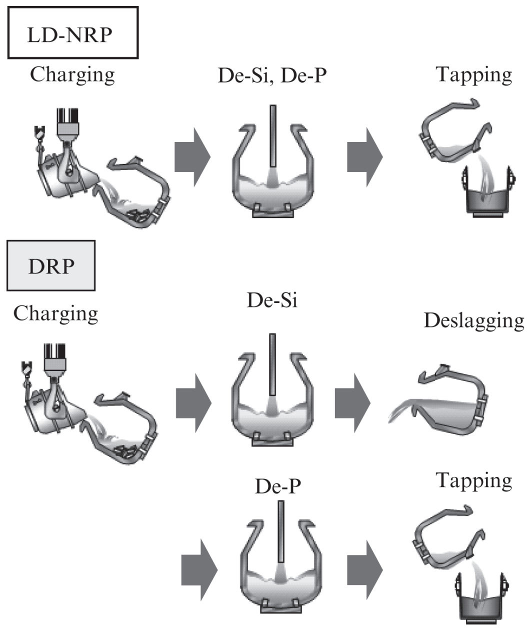


Fig. 2 Schematic image of new hot metal dephosphorization process using converter (DRP®)

furization was performed after de-P in the torpedo car. Conventionally, hot metal de-S had been performed by injecting a desulfurization flux into hot metal in the torpedo car. To solve the problem of temperature drop in the torpedo, $C_3H_8$ gas blowing was applied as a technique for accelerating the desulfurization reaction at lower hot metal temperature[4]. As a result, an effect in which the oxygen partial pressure was reduced and desulfurization reaction efficiency was increased was confirmed. Subsequently, hot metal desulfurization by mechanical stirring was adopted in place of the torpedo injection method. The sulfur partition ratio was increased by adoption of the mechanical stirring method, which can realize the higher stirring energy. In addition, the $C_3H_8$ gas top blowing method was also applied to the mechanical stirring method, and a similar effect by reduction of the oxygen partial pressure was confirmed. Other techniques which have been applied to increase the reaction efficiency of desulfurization flux are the desulfurization flux blasting technique[7], inclined vessel bottom technique[8] and hot slag recycling technique[9]. **Figure 3** shows an outline of the desulfurization flux blasting technique. Conventionally, desulfurization flux consisting mainly of lime was added from the top. This lime was agglomerated and entrained in hot metal during treatment, but a large amount of unreacted lime could be observed inside larger agglomerates. Therefore, a new technique was developed, in which the desulfurization flux is blasted into the hot metal with a carrier gas, accelerating penetration of the flux into hot metal. This suppresses agglomeration of the desulfurization flux, and as the result, unreacted flux is reduced, which means the efficiency of flux utilization in the desulfurization reaction is improved. Other techniques which have been applied at JFE Steel are the inclined bottom of the reaction vessel, which causes an eccentric vortex to form during stirring, and thus accelerates entrainment of the desulfurization flux and the recycled hot slag. As a result, the reaction efficiency of the desulfurization flux increased by approximately 1.5 times, and the amount of desulfurization slag decreased by 30%.

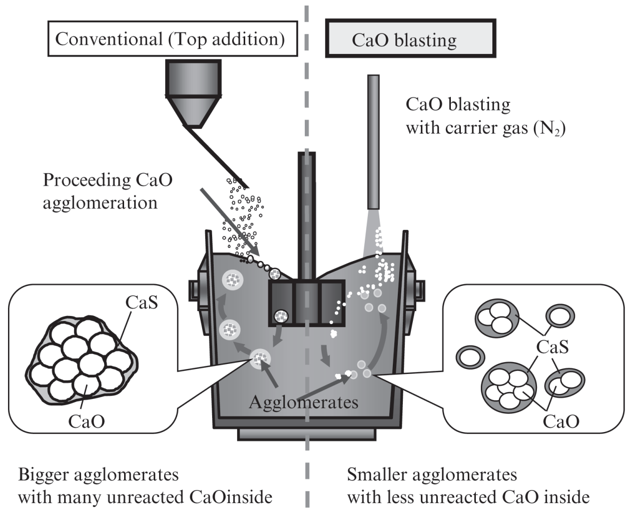


Fig. 3 Comparison of conventional and developed method in hot metal desulfurization with mechanical stirring

### 2.2 Converter and Secondary Refining

In the pure oxygen bottom-blowing converters at East Japan Works (Chiba), the array distance of the bottom-blowing tuyeres was optimized. The effect of the tuyere array distance on the bath flow pattern was investigated in a 1/15 size water model experiments, and a new array design was proposed based on the flow pattern analysis. **Figure 4** shows the results of observation of the bath flow patterns with different tuyere array distances ($L_2/L_1$). The array with $L_2/L_1$=0.227 displayed lower generation of splash. When this design was applied to an actual Q-BOP, molten steel yield improved by 0.2% through preventing hot metal splashing during blowing[10].

A new designed top blowing oxygen lance for decarburization was developed in RH vacuum degasser process. The behavior of the top-blowing jet under a vacuum was preliminarily investigated by a 1/10 model experiment and 3-dimensional numerical analysis[11,12], and based on the results obtained, a new top-blowing oxygen lance was applied to the actual RH degasser. As a result, the decarburization rate in the range of [mass%C] $\geqq$ 0.015 improved by 7.5%, and temperature drop during treatment decreased by approximately 4°C by increasing post-combustion (secondary combustion). In the range of [mass%C] < 0.015 under a high vacuum, molten steel splashing decreased, and skull formation in

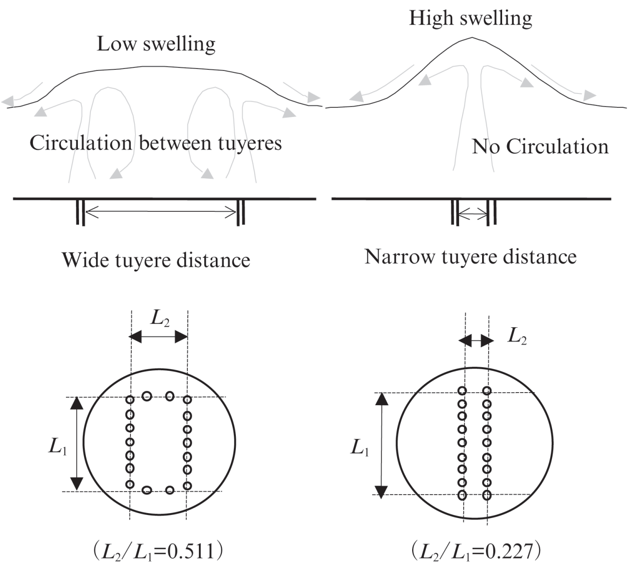


Fig. 4 Observation results of bath flow patterns with different tuyere array distances

the vacuum vessel was reduced by half.

### 2.3 Techniques for Expansion of Heating Margin and Utilization of Inexpensive Iron Sources

Development of refractories for refining process and transportation vessels was carried out with the aim of expanding the heating margin in the steelmaking process[13]. The arrangement of the wear bricks, which are in direct contact with the molten metal, and the microporous heat-insulating material was optimized considering their respective features, making it possible to maximize insulating performance while avoiding adverse effects on durability.

In the torpedo car, when a 3 mm thick layer of microporous insulation was installed between the steel shell and the permanent refractory, a decrease of approximately 50°C in the temperature of the steel shell and a 25% reduction of radiant heat loss were confirmed. In the hot metal ladle (blast furnace ladle), low thermal conductivity wear bricks were adopted, and a 5-mm thick layer of microporous insulation was installed between the steel shell and the permanent refractory, resulting in a 96°C decrease in the temperature of the steel shell and 45% reduction of heat loss. In ladles using monolithic refractories, which are kneaded with water, installation of the microporous insulation between the permanent refractory and the steel shell, which is not in contact with the moisture of the monolithic wear refractory, resulted in a 70°C decrease in the shell temperature and a 36% decrease in heat loss, as shown in **Fig. 5**, while also securing the durability of the monolithic refractory and the insulating material.

East Japan Works (Chiba) produces stainless steel by a distinctive process in which smelting reduction of chromium ore and decarburization refining are performed using a pair of strongly-stirred top-and-bottom blowing converters. Because smelting reduction of Cr ore is an endothermic reaction, a heat compensation technique is critical for maintaining high productivity and enabling reduction of a large quantity of Cr ore, which is an inexpensive chromium source. Conventionally, heat compensation had been performed by primary and secondary decarburization reactions by addition of a carbon source and oxygen blowing, respectively. JFE Steel developed a technology (**Fig. 6**) which realizes high thermal efficiency by converting the dedicated lance used to add Cr ore to a pure oxygen burner device[14]. It was found that high burner combustion heat transfer of 80% can be obtained by increasing the proportion of Cr ore relative to the combustion heat, and utilizing this Cr ore as a heat transfer medium for the burner combustion heat. Introduction of the Cr ore burner resulted in a 17% reduction in unit energy input with the same amount of ore. Moreover, considering the smaller carbon content of the hydrogen-based fuel, the amount of energy derived from carbon combustion was

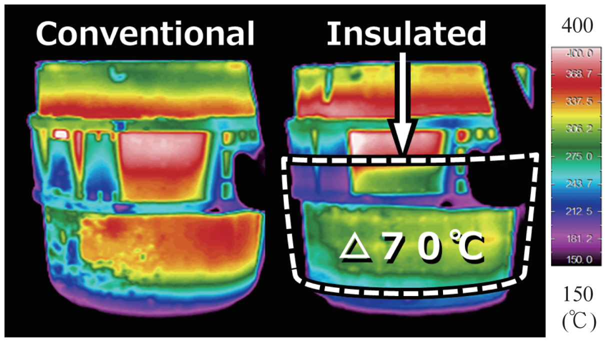


Fig. 5 Comparison of temperature distributions in steel ladles with and without heat insulation

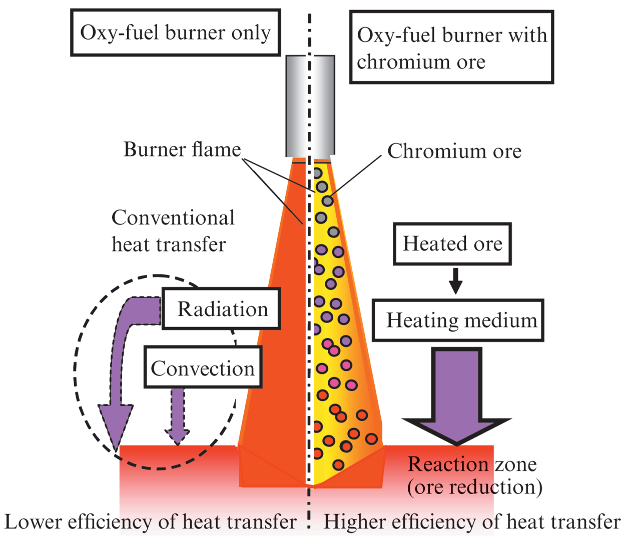


Fig. 6 Comparison of conventional and developed heat transfer

reduced by 26% in comparison with the conventional method.

Melting of iron scrap by expanding the heating margin is an effective technique for reducing the amount of $CO_2$ generated in the steelmaking process. However, the purity of iron scrap is tending to decrease year by year, and iron scrap containing tramp elements is increasing. Therefore, JFE Steel developed techniques for removing the typical tramp elements, Cu[15] and Sn[16], in the hot metal stage. The following describes the technique for removal of copper from hot metal. In anticipation of future increases in waste scrap and mixing of scrap with blast furnace pig iron, copper removal from hot metal from 0.25 [mass%Cu] to 0.15 [mass%Cu] (i.e., copper removal rate of 40%) was targeted. In an experiment using a 10-kg small-scale melting furnace, a flux comprising $NaCO_3$(25 kg/t)+FeS(52 kg/t) was added at 1 250°C, and mechanical stirring was performed. As a result, a copper removal ratio of 57% was obtained. A 3 ton-scale hot metal copper removal experiments were then performed with mechanical stirring. In this case, a flux consisting of $Na_2CO_3$(33 kg/t)+FeS(56 kg/t) was added at 1 250–1 400°C, and mechanical stirring was performed. A copper removal rate of 46% was achieved with stirring in 12 min[17]. Moreover, a slag/metal copper partition ratio of 18 was obtained. This result is close to the previously-reported equilibrium value of 24 for the copper partition ratio with a $NaS_{0.5}$ system flux[18]. As shown by these results, this research demonstrated the possibility of hot metal copper removal with a flux consisting of soda ash and iron sulfide, which is already used industrially.

JFE Steel has also developed various recycling technologies for steel slag, including hydrated steel slag blocks[19–21] and products for marine use[22–24], and has put those products into practical use. The company is also grappling with research and development on a continuous solidification process for recovery of sensible heat from steel slag and use as a recycled material[25–27], and a technology for recovery of Fe and P from steel slag[26]. Japan depends on imports of P as a natural resource, and the P contained in the steelmaking slag generated by the Japanese steel industry is equivalent to Japan's annual imports of P as a natural resource, which total approximately 110 000 tons. Moreover, the Fe component which is lost in slag in the form of iron oxide is equivalent to about 3–4% of Japan's iron and steel production. Accordingly, recovery of Fe and P from steel slag, which is a byproduct of the steelmaking process, will contribute to improvement of iron yield and effective utilization of phosphorous resources. Using a small scale furnace, carbothermic reduction of the Fe and P which exist as oxides in steel slag was performed, and those substances were recovered. As a result, more than 90% of the Fe content was recovered as metallic iron, and the phosphorus content of the slag after treatment was reduced to 0.3% or less. In this process, P in slag was concentrated to approximately 2–3% in the reduced iron. It can be expected that P in the obtained high phosphorus iron is concentrated in the slag by de-P treatment, and use as a phosphatic fertilizer. Scaling-up experiments are currently in progress, aiming at industrialization of this process.

## 3. Development of Casting Technologies

### 3.1 Technology for Production of Clean Steel

In the process from vacuum degassing (RH) treatment to the tundish process, JFE Steel carried out technical development for removal of non-metallic inclusions from the molten steel in response to stricter standards for the high cleanliness steels. Although removal of fine inclusions is required in bearing steels, JFE Steel developed the pressurization and depressurization refining method[28], which takes advantage of the fact that depressurization during vacuum degassing (RH) treatment causes soluble gases such as nitrogen gas, etc. to form fine bubbles, and thereby promotes flotation and removal of inclusions. In ferritic stainless steel, the oxygen value can be reduced, contributing to higher product quality, by the centrifugal flow tundish[29], which utilizes the large increase in inclusion separation capacity by rotating magnetic stirring.

### 3.2 High Speed Casting Technology

In order to achieve stable high speed casting, development of technologies which solve various operational and slab quality problems is desirable. These include (1) technology for prevention of breakout (B. O.) due to constraint and rupture of the solidified shell in the continuous casting mold, (2) development of mold powder which enables lubrication between the mold and the strand and prevents entrainment of the mold powder during high speed casting, (3) technology for prevention of surface cracks due to the brittle temperature at the bending and unbending position, and (4) technology for prevention of internal cracks due to increased solidification interface strain and increase of cooling capacity.

As a technology for detection of various types of B. O., JFE Steel constructed a system which calculates the solidified shell thickness from the temperatures measured by multiple thermocouples embedded in the copper plates of the casting mold[30], enabling real-time monitoring of the solidified shell thickness at the lower end of the mold. The effectiveness of this technology in detecting abnormalities during high speed casting has been verified.

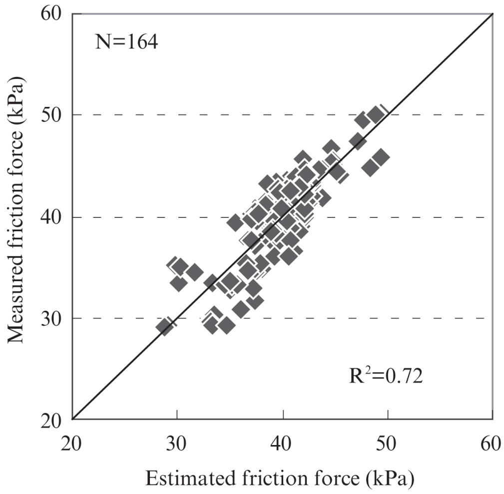


Fig. 7 Estimation of friction force

To reduce powder entrainment during high speed casting, a non-Newtonian powder was developed[31,32], and its effect in reducing powder entrainment was confirmed in laboratory experiments. The non-Newtonian fluid property, whereby the viscosity of the molten powder changes depending on shear stress, was realized by introducing nitrogen into the powder. JFE Steel has also carried out measurements and analysis of the effects of mold oscillation conditions and the physical properties of the mold powder, etc. on the frictional force between the mold and the strand. JFE proposed an equation for estimation of friction force based on the assumption that liquid friction is the controlling factor[33], as shown in **Fig. 7**, and is continuing to use indexing of the effects of mold powders on operation and product quality.

JFE Steel has also actively developed a secondary cooling technology for prevention of surface cracks and internal cracks in high speed casting. The effects of various factors, including water flow rate and pressure, on spray cooling intensity were evaluated[34,35], and a secondary cooling device was developed[35].

### 3.3 Technology for Control of Molten Steel Flow in Casting Mold

In some cases, bubbles and inclusions which are entrapped during continuous casting cause defects during hot rolling or cold rolling. Therefore, based on the requirement of satisfying both high productivity and high quality, technical development which makes it possible to reduce entrapped defects, even during high throughput casting, has been desired. JFE Steel developed a technology which makes it possible to reduce defects, including those which occur under high throughput conditions, by an electromagnetic flow control device called the Flow Control (FC) Mold, which features an upper and lower, two-stage static (DC) magnetic field, as shown in **Fig. 8**[36]. Among other new casting technologies, the company also developed an ultrasonic flaw detection method which enables rapid measurement of the distribution of defects with diameters of 0.6 mm and larger in the region 2–10 mm below the surface in slab samples, and has conducted a wide-ranging investigation of the relationship between the position of defect occurrence and the casting conditions and condition of the molten steel flow in the mold.

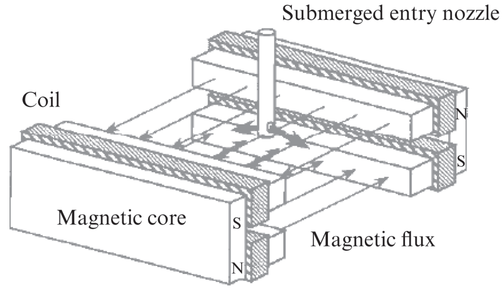


Fig. 8 Schematic drawing of Flow Control Mold

As a magnetic field condition, it was confirmed that the momentum of molten steel can be reduced by 50% or more by applying electromagnetic braking force so as to achieve a Stuart number of 3.5 or higher[37]. The Stuart number expresses the ratio of an external force term and an inertial force term. In order to optimize electromagnetic brake conditions and casting conditions, the correspondence between actual slab evaluation values and values obtained by numerical calculations was investigated. **Figure 9** shows an example of the distribution of entrapped bubbles with the diameter of 0.5 mm at the solidification interface (solid fraction $f_s$=0.2) by numerical calculation[38]. The effect of increasing the electromagnetic brake force in suppressing bubble entrapment can be confirmed. Moreover, good correspondence between these results and the actual measured values of cast slabs obtained by the above-mentioned ultrasonic flaw detection method was also confirmed.

### 3.4 Surface Crack Prevention Technology

In new product development, high tensile strength

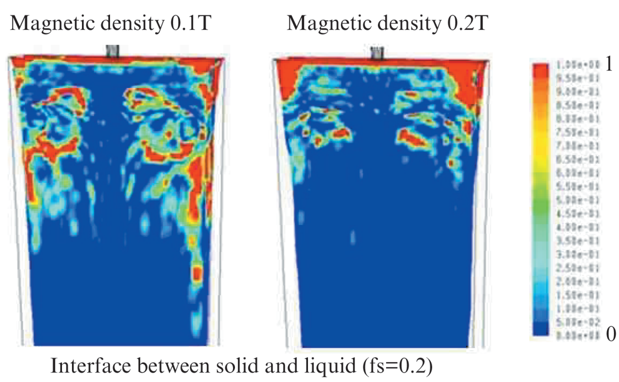


Fig. 9 Calculated results of entrapped bubble concentration

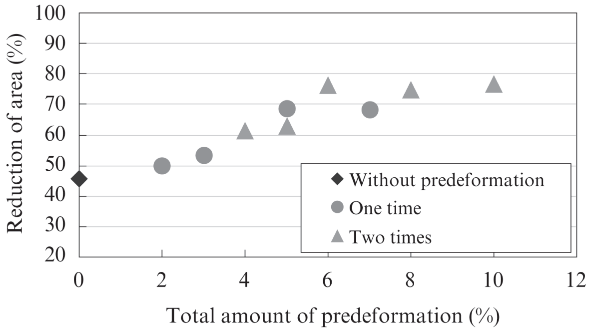


Fig. 10 Improvement of hot ductility by predeformation treatment

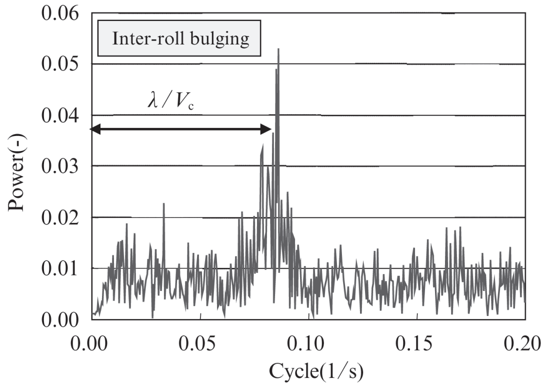


Fig. 11 FFT analysis of inter-roll bulging fluctuation

steel sheets are being developed in response to the requirements of high strength and weight reduction in automotive steel products. However, because hypo-peritectic carbon steel compositions that contain alloying elements such as Nb, V, etc., display high crack sensitivity, occurrence of surface cracks during continuous casting becomes an issue. Although currently in the stage of basic experiments, JFE Steel is developing a new technology that realizes a hot ductility improvement effect by applying pre-strain before the application of the strain corresponding to bending and unbending[39]. As shown in **Fig. 10**, research has shown that this technique has a hot ductility improvement similar to that of accumulated strain when pre-strain of 2–5% is applied twice.

### 3.5 Unsteady Bulging Prevention Technology

The phenomenon of unsteady bulging, which causes periodic mold level fluctuations and segment fluctuations during continuous casting, is an extremely important factor that cannot be ignored. Unsteady bulging not only causes operational problems such as decreased casting speed, but also induces suction of enriched molten steel by inter-roll bulging in continuous casting segments, which is particularly a problem in steels with strict centerline segregation requirements. JFE Steel developed a technology which enables direct measurement of the amount of fluctuation in inter-roll bulging during continuous casting by utilizing a water column-coupled ultrasonic distance sensor. This high accuracy technology realizes resolution of 0.01 mm. As shown in **Fig. 11**, the period of inter-roll bulging fluctuation obtained by direct measurement corresponds to the roll pitch $\lambda$[40] and is in good agreement with the bulging period shown in **Fig. 13**, which was calculated by a numerical simulation (**Fig. 12**) of the amount of displacement of the liquid phase in an elasto-plastic analysis[41].

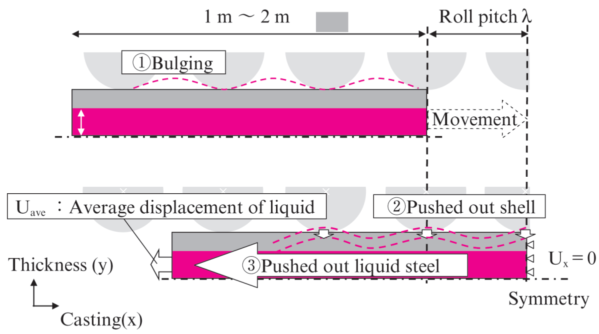


Fig. 12 Schematic drawing of displacement of liquid in elasto-plastic analysis

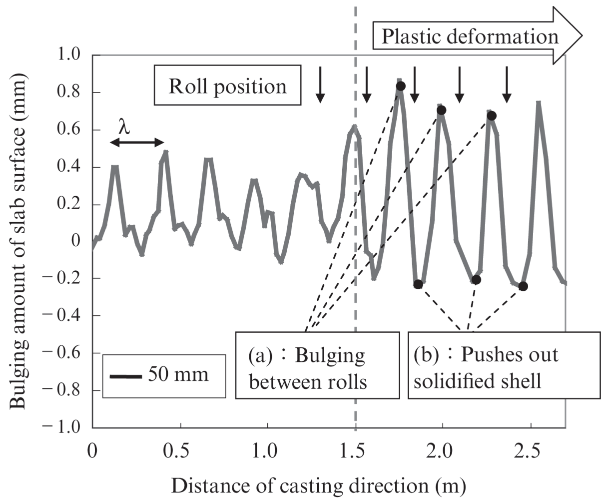


Fig. 13 Bulging amount of slab surface (shell thickness 50 mm)

### 3.6 Other Technologies

The occurrence of powder defects, which are caused by an insufficient supply of heat at the start of casting, was a problem in the quality of stainless steel slabs at East Japan Works. As a countermeasure, JFE Steel developed the melted-powder addition method[42], in which mold powder which has been melted in advance is added to the mold in the initial period of casting, and confirmed that a large reduction in powder defects is possible. As another issue, because the solidification structure of ferritic stainless steels has a large effect on product properties, it is necessary to control the columnar crystal/equiaxed crystal ratio, etc. Therefore, JFE Steel constructed an equiaxed crystal ratio prediction model which considers the effects of casting conditions, strand electromagnetic stirring and other factors on the formation of equiaxed crystals[43], and demonstrated the fact that slab production with a stable equiaxed crystal ratio can be achieved.

## 4. Future Prospects of Steelmaking Technology

In the future, even higher quality requirements for steel products, and a decline in the quality and fluctuations in the price of main raw materials (i.e., iron ore and iron scrap) are foreseen. In the refining area, further improvement in the reaction efficiency of refining fluxes and the development of technologies for achieving high purity, which reduce the concentration of impurities with high efficiency, will become important. Where steel slag is concerned, in addition to reduction of slag generation by improving reaction efficiency, recovery and recycling technologies for thermal energy and components contained in slag and new functional materials utilizing slag will become even more important in the future. Improvement of the energy efficiency of the steelmaking process by reduction of heat loss and technologies for use of waste heat, etc., will also be essential. In the field of casting technology, satisfying both stable high speed casting and defect-free casting by reduction of surface defects and centerline segregation will be an important challenge.

## 5. Conclusion

The technologies introduced in this report have realized higher productivity and reduced generation of steel slag, and at the same time, have also realized high purity and improved product quality in steel products. As a result, these recently-developed technologies will contribute to improvement of customer satisfaction in the form of shorter delivery times, etc., as well as high quality in steel products, namely, prevention of surface defects, surface cracks, reduction of centerline segregation, and protection of the global environment.

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