NIPPON STEEL TECHNICAL REPORT No. 104 AUGUST 2013

Technical Report

UDC 621 . 746 . 047 : 620 . 192 . 45

Improvement of Continuously Cast Slabs by Decreasing Nonmetallic Inclusions

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Abstract

In order to achieve high quality slab production, to assess the cleanliness of the slab and the cleanliness of the molten steel in the tundish in continuous casting process, made it clear aggravating factor of cleanliness. To ensure the cleanliness of the continuously cast slabs, it is important to prevent the ladle slag outflow, tundish slag entrapment at the teeming point of tundish, and air oxidation. By the application of molten steel flow in mold control technology using electromagnetic force was developed by Nippon Steel Corporation (In-mold electromagnetic stirring and Level Magnetic Field), the slab can be manufactured with excellent internal cleanliness and surface cleanliness of slabs.

1. Introduction

Quality requirements demanded for continuously cast slabs are increasingly becoming stringent in recent years to meet customer demand based on needs of enhancing productivity efficiency through production of flawless products and improvement of processing performance. To realize the production of such high-quality cast slabs to enable customers' production of high-quality and highly functional products, various countermeasures such as thorough purification of molten steel and application of intensified conditioning of cast slabs have been practiced.

Existence of nonmetallic inclusions in molten steel (Hereinafter referred to as "inclusions") is in general one of the major factors that causes steelmaking-caused quality defects, and they are not only directly causing product defects but also clogging nozzles, thereby causing operating abnormalities such as drift of molten steel in a mold and entrapment of powder, thus indirectly causing product defects as well.

"Steel with high cleanliness" cannot be expressed in a simple way as requirements of quality characteristics vary depending on their uses, and therefore, acceptable sizes of inclusions, compositions, and amounts also vary depending on such steel uses. As Uchibori et al.[1] correlated quality characteristics required for highly clean steel to quality control aim in steelmaking process,[1] required material quality and material quality evaluation method vary depending on the use of end products, and as a result, size of inclusions, their amounts and their compositions become varied. Further, strictly speaking, they also vary depending on customers' processing technology and evaluation method. This report introduces firstly a general concept of reducing inclusions, and next, introduces an example of analysis of factors that deteriorate cleanliness in the continuous-casting process for the production of cast slabs with high cleanliness for thin steel sheets, followed by a basic concept of reducing inclusions. Next, how inclusion reduction has been tackled with the application of electromagnetic force is introduced and future subjects are discussed.

2. Concept of Reducing Inclusions

Methods of reducing inclusions and making them harmless are basically classified into two categories: (1) reducing the amount of inclusions and their sizes and (2) making inclusions harmless by controlling their compositions and morphology.

As for (1), aluminum deoxidized steels such as bearing steel,[2, 3] steel sheets for tin coating, automobile outer panels and the like are known, wherein thorough elimination of inclusions of Al_2O_3 system is carried out by keeping strictly required treatment processing time, reforming slag in the secondary refining process, and preventing re-oxidation in a tundish. As for (2), in many cases, silicon and manganese deoxidized steels such as for tire chords[4] and valve springs are known, wherein inclusions are controlled to be reformed to such compositions as to be readily elongated in rolling and lower melting points, but not allowing precipitation of any hard inclusions.

In **Fig. 1**,[1] an example of the concept about the origins of inclusions is shown, which shows that oxide inclusions are classified basically by origin into (1) the deoxidation product formed when a de-

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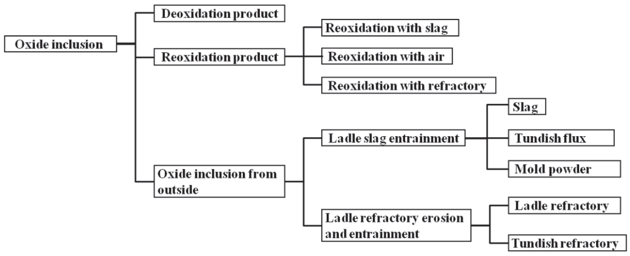


Fig. 1 Origin of inclusions [1]

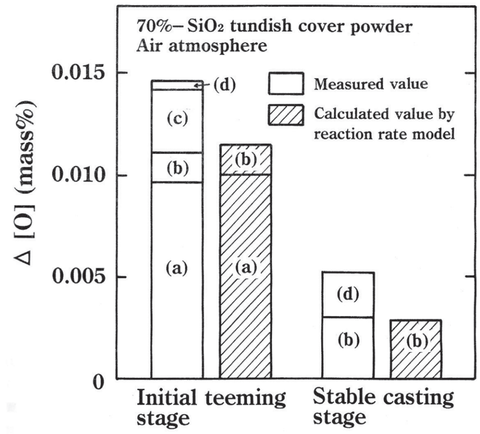


Fig. 2 Amount of oxidation of molten steel in the tundish by the factor responsible for reoxidation [5]

oxidizing agent is cast, (2) the reoxidation product formed by reaction with slag and air, (3) oxide inclusions brought in from outside caused by the entrapment of slag in a ladle and a tundish, and mold powder. As the ultimate form of steel with utmost cleanliness, bearing steel [2, 3] is quoted, and as the example of the case where inclusions are made harmless by reforming inclusion composition, steels for tier chords[4] and valve springs are quoted. However, in this report, for understanding the concept of inclusion elimination and its relation to process conditions, the case of aluminum deoxidized steel sheets is discussed. Inclusions are basically classified with regard to surface cleanliness and internal cleanliness of a continuously cast slab under a stable casting condition and under a transitional nonstable casting condition. They are assessed in the thickness and longitudinal directions. Presently, a kind of compromise is reached between securing required quality and productivity based on the result of the above inclusion evaluation.

3. Technologies of Eliminating Inclusions in the Continuous Casting Process

3.1 Behavior of reoxidation

Based on change in chemical composition in the actual machine tundish right after the start of first casting and on a reoxidation model of molten steel by air, Sasai et al.,[5] by dividing the stage into an initial teeming stage and a stable casting stage, quantified molten steel reoxidation amounts by certain factors: (a) with air at the tundish teeming point, (b) with air at the surface, (c) by the ladle teeming hole filler, and (d) by the tundish flux.

The result is shown in **Fig. 2**.[5] It has been found that in the initial teeming stage, reoxidation with air at the tundish teeming point occupies most of the oxidation, and in a stable casting stage, the amount of reoxidation of molten steel with air is almost equal to the oxidation amount caused by the tundish flux.[5] Similar attempts were made by Higuchi et al.[6] and Tanaka et al.[7] and Sasai summarized their research results as in **Table 1**.[8] Although differences exist among researchers as to the locations of sampling and evaluation methods, it is considered that air at the molten steel surface in the initial teeming stage, ladle slag in the ladle exchange stage, and ladle slag, tundish flux, and air in the stable casting stage are considered to be the major reoxidizing factors of molten steel.[8]

3.2 Origin of inclusions in the cast slab at the transition area in the unsteady stage

As stated in 3.1, adverse effects of factors that deteriorate molten steel cleanliness in a tundish have come to be clarified considerably owing to the research and analysis made thereon.[5-8] However, in actual production, steel is cast via an immersion nozzle and a mold after teeming from a tundish; therefore, possibilities are conceivable of inclusions sticking to the immersion nozzle [9, 10] and fallout, and possibilities are also conceivable of cohesion, coalescence,[11] and floatation of inclusions in a mold and in continuously casting strands. Therefore, it is important to confirm how inclusions behave in a tundish and affect cleanliness of a cast slab. However, since evaluation of cleanliness of a cast slab consumes lot of time and labor, and particularly a long time is needed when cleanliness evaluation is made in regions where cleanliness is worse, difference in cleanliness, evaluated in terms of inclusion behavior, of an actual cast slab in a ladle exchange state has not necessarily been clarified yet.

The authors evaluated [12] with the slime method the cleanliness of a slab cast in a ladle exchange state by a vertical bending type continuous casting machine equipped with a conventional (boat-type) tundish. Samples were taken in the longitudinal direction from

Table 1 Influence of oxidation of molten steel by reoxidation factors during casting [8]

Reoxidation factors		Author et al.		Higuchi et al.		Tanaka et al.	
		Stable casting stage	Initial teeming stage (transiotion stage)	Stable casting stage	Ladle exchange stage (transiotion stage)	Stable casting stage (1st. ladle)	Stable casting stage (3rd. ladle)
Air	Reoxidation at teeming point		66			80	60
	Reoxidation at molten steel surface	57	10		24		
Reoxidation with TD flux		43	3	27			
Slag	Reoxidation with ladle slag			73	76		
	Ladle slag entrainment into TD					20	40
Reoxidation with silica sand			21				
Reoxidation with refractory							

a slab continuously cast under the condition as shown in **Table 2**,[12] and catered for investigation. As shown in **Fig. 3**,[12] in a slab cast in the ladle exchange state, greater number of large spherical inclusions are found, and by cast slab inclusion composition analysis and thermodynamic calculation (**Fig. 4** [12]), it was found that alumina cluster grew coarse owing to reoxidation caused by ladle slag inflow and entrapment of tundish slag (**Fig. 5** [12]). Although qualitatively, this agrees with the investigation result stated in section 3.1 about molten steel in tundish.

From the above-mentioned result and also from the result of the evaluation of an actual cast slab, it has been confirmed that prevention of the inflow of ladle slag into a tundish, entrapment of slag at the tundish teeming point, and oxidation with air in a tundish is important to enhance cleanliness of slabs cast in the unsteady state, typically like the transition area slab in continuous casting of an identical steel type (sequential casting).

Table 2 Casting conditions [12]

Casiting velocity	1.2 m/min
Strand width	1.12 - 1.16 m
Strand thickness	0.24 m
Tundish capacity	40 × 10^3 kg

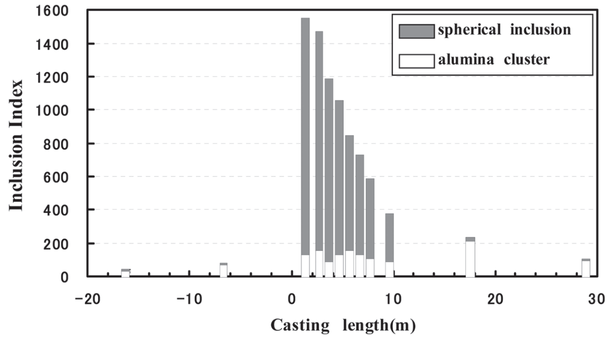


Fig. 3 Distribution of inclusion index [12]

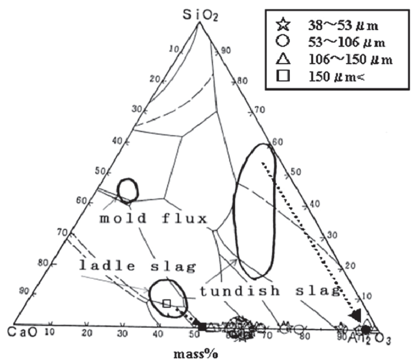


Fig. 4 Thermodynamic calculation results (+3.8m) [12]

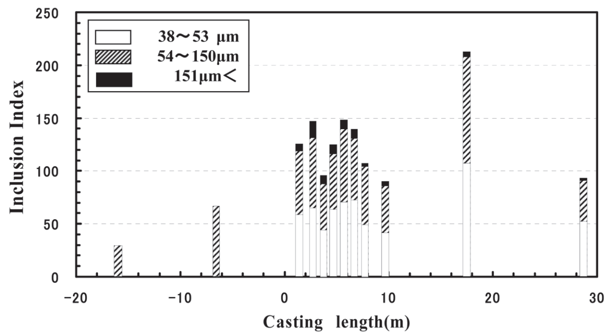


Fig. 5 Distribution of inclusion index (alumina cluster) [12]

3.3 Countermeasures to prevent reoxidation of molten steel

In **Fig. 6**, the concept of reoxidation of molten steel in the process from molten steel ~ tundish ~ continuous casting mold is shown in a schematic drawing.[13] The contributory ratio of the respective reoxidizing factor varies greatly in each casting stage. The concept of countermeasures for the prevention of reoxidation corresponding to the respective oxidation factor is outlined as below:

(1) Prevention of molten steel reoxidation with air:
covering of a tundish and sealing with Ar gas, covering of molten steel in a tundish with molten flux

(2) Prevention of molten steel reoxidation by ladle slag:
prevention of flow of ladle slag into a tundish (with an electromagnetic method) and control of slag composition (low (FeO + MnO) + higher CaO/SiO_2)

(3) Prevention of molten steel reoxidation by tundish flux:
high CaO/SiO_2 and low SiO_2

(4) Opening of ladle nozzle in immersed state during sequential casting:
securing of sufficient amount of molten steel in a tundish at a ladle change

(5) Ladle sand:
low SiO_2 and two-layered structure

Based on the above-mentioned concept, reviewing of operating conditions of sequential casting [14-18] and tundish design [18-21] were conducted, and cast slab quality in a steady state has been drastically improved. However, variation of cleanliness of slabs cast in an unsteady state was far greater than that of slabs cast in a steady state. Since demand for stringent slab quality is increasing year by year, it was thought that development of technologies for improving the quality of entire slabs including those cast in an unsteady state is needed.

3.4 Control of inclusion behavior by electromagnetic force

3.4.1 Utilization technology of the electromagnetic field

In the iron and steel industry, electrical energy is utilized in many processes represented by such heating as by electromagnetic induction or by arc. In the continuous casting process in particular, since various remote control systems are needed under a high tem-

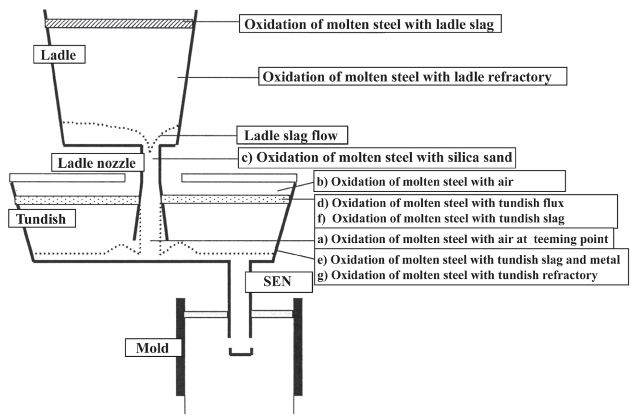


Fig. 6 Schematic diagram of molten steel reoxidation [13]

perature circumstance, various functions that electromagneticity provides are utilized.

The reasons for the application of electromagnetic force in a wide range are ① A clean remote control system is needed to maintain clean operating circumstances to build up quality, ② design of equipment such as induction coils and electric power supply sources is possible in terms of space as the continuous casting mold dimension is about one meter or longer, ③ its circumstance is not threatened by high temperature as there is an originally equipped water-cooled mold installed adjacently, and ④ when compared, cost effectiveness is superior to that of other technologies even though it provides the same level of performance. In Nippon Steel Corporation's continuous casting process, the following technologies have been already put into practical operation: ① Sensing technology like an eddy current level sensor and a slag outflow detector, ② tundish preheating technology, and ③ in-mold flow control technology. In addition to these technologies, various functions of the electromagnetic field are positively studied in the research and development for more sophisticated technologies such as soft shell-mold contacting technology and plasma surface treatment. In this report, the details of control technology for in-mold molten steel flow that ultimately determine inclusion-related cast slab quality are described.

3.4.2 In-mold electromagnetic stirrer

Regarding slab casting, initially, Nippon Steel Corporation introduced a linear motor type electromagnetic stirrer (EMS), aiming at production of rimmed steel by continuous casting. The purpose of the EMS was to suppress the formation of tubular type CO gas blow holes in undeoxidized steel by providing flow to the steel.[22] Since then, installation of the equipment has been promoted in other steel works as well as following effects realized by leveling solidification layer were obtained: 1) suppression of longitudinal cracks and 2) improvement of surface quality of thin sheet products by arresting and suppressing blow holes and inclusions at the subsurface of a cast slab (**Fig. 7**).[23]

In the operation of an in-mold electromagnetic stirrer, as it is important to provide a uniform flow sufficient enough to exceed the critical flow rate in the peripheral direction at the surface of a slab being cast, since the earliest stage of introduction of the equipment, research and development have continued to be oriented to the enhancement of uniformly stirring performance. In continuous slab casting operation, molten steel is fed to a flat rectangular casting space through a single immersion type nozzle having two discharging holes, where the interference of electromagnetically developed flow with teeming flow hampers uniform stirring. A horizontally turning electromagnetic force is provided around the mold meniscus in such a manner as to minimize to the extent possible the interference with teeming flow.

As for the electromagnetic field, since a three-phase linear motor is used to provide an alternately changing and moving magnetic field, there are a number of controlling parameters such as dimensions, number of frequency, number of poles, and phase and waveform. Nippon Steel Corporation has developed electromagnetic field analysis technology using the finite element method with edge elements, and with this, Nippon Steel Corporation is conducting the equipment design that realizes the maximum stirring force with maximum possible uniformity in flow.[24, 25]

To obtain a uniform flow in the peripheral direction of a slab being cast and just below the solidified shell at the surface of the slab, design of the equipment is conducted on the basis of the condition provided by the electromagnetic field analysis. In the case of an alternately changing and moving magnetic field, since the magnetic Reynolds number is relatively small, influence of the magnetic field induced by the interference of flow with magnetic field is ignored and flow analysis is performed by inserting Lorentz force obtained from the electromagnetic field analysis to the external force paragraph of Navier-Stokes equation. Furthermore, when the evaluation of the uniformity of solidification and/or free boundary face behavior become necessary, multi-physics analysis coupled with heat, phase change, and free boundary face is conducted.

It is clear from **Fig. 8**[26] that entrapment in the shell of inclusions and blow holes is remarkable in a region where flow rate becomes lower, and interference of the mutual flow also can be a cause of uneven temperature distribution. An example of electromagnetic fluid flow analysis coupled with heat and free boundary face with powder taken into consideration is given.[26] **Fig. 9**[26] shows the comparisons

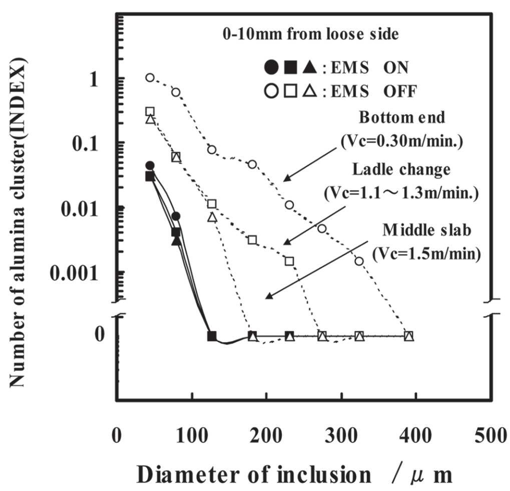
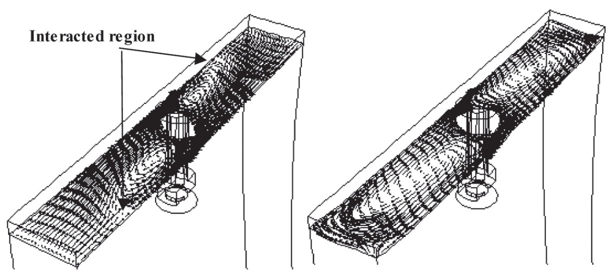
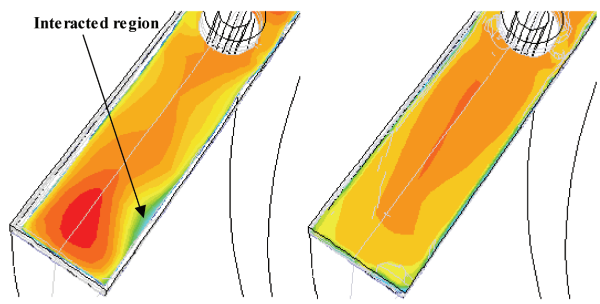


Fig. 7 Effect of EMS on diameter distribution of alumina clusters[23]



(a) insufficient arrangement (b) sufficient arrangement

Fig. 8 Distribution of molten steel velocity in the mold meniscus[26]



(a) insufficient arrangement (b) sufficient arrangement

Fig. 9 Distribution of molten steel temperature in the mold meniscus[26] of the velocity and temperature distributions at the mold meniscus for the case where stirring force is weak and the reverse flow of teeming flow interferes with electromagneticity-caused stirring force and for the case where the stirring force is strong and suppressing interference. At interfering points, uneven temperature distribution also takes place, and therefore, significance of uniform flow is understood.

3.4.3 In-mold electromagnetic brake

An electromagnetic brake was introduced in the 1980s, aiming at controlling the velocity in a continuous casting machine mold. An electromagnetic brake was developed to apply braking force to the discharge flow from an immerged nozzle. Historically, a two-pole local magnetic field, later called as "first generation," was first used, and then developed itself to the second-generation uniform magnetic field for the purpose of improving braking efficiency. Up to now, the uniform magnetic field of second generation has yielded several variations depending on the difference of the controlling concept. Nippon Steel Corporation now applies to practical operation the uniform magnetic field with a pair of yokes (LMF: Level Magnetic Field) installed near the bottom nozzle end level with a maximum magnetic field intensity of about 0.3 T at the mold center. As the effect, reduction of inclusions and blow-hole-caused defects have been realized by suppressing direct flow into a slab, and with this flow suppressing effect, molten-steel-mixed length at a joint in sequential casting of different quality steels is successfully made shorter, and decreasing the discharge flow velocity contributes to high-speed casting.[27]

Although this is a simple process in principle that interference of flow with a magnetic field produces an induced current and the interference of the induced current with the magnetic field produces a braking force, a complicated flow pattern is practically generated in the molten steel pool on account of the following two reasons: discharge flow has a velocity distribution and the direct current magnetic field is not completely uniform but has a distribution. Since molten steel is a good electrical conductor, the circuit of the equipment must be designed such that the induced current generated by discharge flow and direct current magnetic field is preserved. Inside a mold, a boundary condition near the insulated state by flux exists; therefore, current produced inside a shell is mostly enclosed in the molten steel pool surrounded by a solidified shell. Hence, two phenomena crucial to the control of flow emerge.

One is the phenomenon that the braking force decreases near the mold short side edge. This is a phenomenon in that as a current loop is produced for the preservation of the current, a region where flow is accelerated appears near the region where the current flows counter to the direction of the magnetic field, generating a brake force to suppress the flow.[28] Another concerns the flow in reverse direction that appears around the flow from discharge.[29] This also is a phenomenon that appears as the result of the reverse electromagnetic force acting on and around the intense flow of discharge. As flow carries inclusions and blow holes entrapped in molten steel, and further, governs flux entrapment, the former phenomenon adversely influences the enhancement of the internal quality of a continuously cast slab as opposed to the important function of a electromagnetic brake, while the latter phenomenon influences flow near the molten steel surface, which affects the continuously cast slab surface quality, and greatly influences the flow behavior around the center of the mold in particular. As for the accelerated flow generated near the mold short side edge, happily enough, their unfavorable effects can be suppressed because the existence of a shell that does not flow

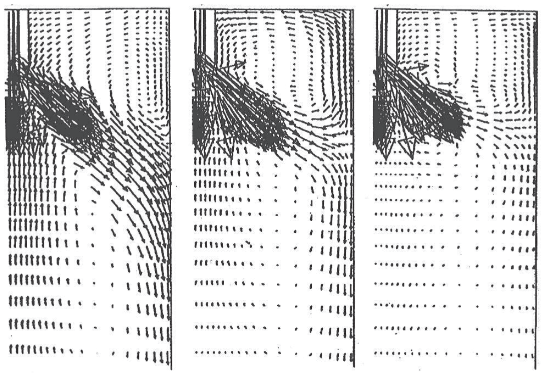


Fig. 10 Change in calculated flow vector distribution with Magnetic flux density: changed views of the meniscius[30]

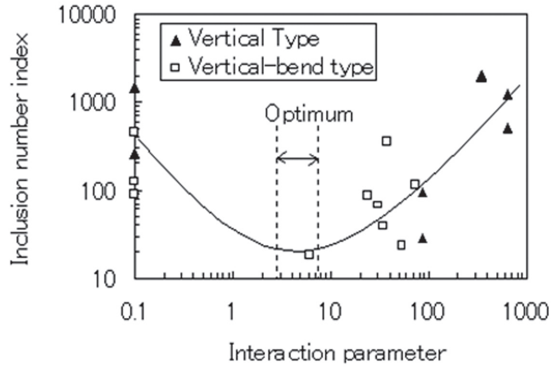


Fig. 11 Relation between interaction parameter and inclusion number[30]

even under the electromagnetic force that acts as an accelerating force relieves this phenomenon. In **Fig. 10**, the result of numerical analysis as to the above is shown.[30]

Although the controlling condition of an electromagnetic brake depends on the targeted flow condition in a mold, therefore becomes complicated, however unitarily, it can be arranged by an interaction parameter (Stuart number), a ratio of electromagnetic force to inertia force, and a dimensionless number as defined later. Electromagnetic force is represented by $\sigma B^2 u/L$, where σ is the electrical conductivity, B is the magnetic flux density, u is the flow rate, and L is the representing length, and inertia force is represented by $\rho (u/L)^2$, where ρ is the density. The ratio, interaction parameter, is $\sigma B^2 L/\rho u$. If the dimension is the same, and the throughput is raised, a macroscopically similar condition is obtained when the magnetic flux density is raised in proportion to the square root value of the throughput.

As shown in **Fig. 11**, examination of the inclusion-related slab quality shows that a tendency is observed that the application of a moderate magnetic field shows the best quality, and it is interesting to know that the fact shows that inclusion-related slab quality can be arranged by all together of various dimensions and velocities, magnetic field condition and that slab quality is governed by the basic parameters of electromagnetic braking in spite of the complexity of flow control and further, the complexity of the phenomenon governing the inclusion-related quality.[30]

4. Conclusion

The actual states of cleanliness of slabs continuously cast in both steady and unsteady states have been clarified from the viewpoint of reoxidation of molten steel, and then basic inclusion-reducing technologies applied at a tundish have been discussed. In addition, as technologies for improving cleanliness of continuously cast slabs, it was proven that application of an electromagnetic stirring technology and an electromagnetic brake technology to in-mold molten steel flow that determines ultimate cast slab quality can secure surface cleanliness and internal cleanliness of cast slabs without being influenced by the change in operating conditions.

There are as many different behaviors of inclusions in continuously cast slabs as the number of steel types, and further, the behavior also varies depending on production process; therefore, it is important to grasp the characteristics of deoxidation of each steel type and clarify the rate-determining step of each process. Generally, in many cases, enhancing cleanliness to a high degree and the stabilization of quality conflict with the improvement of productivity, and the relation apparently becomes incoherent in many cases too. It is important to grasp the actual state under a steady condition to grasp the actual state under an unsteady condition. For this purpose, development of technologies is important not only for casting but also for inclusion evaluation, enabling speedy and exact evaluation of cast slab cleanliness. From now on as well, customers' demands for higher quality including reduction of inclusions will continue to stay high, and thereby the development of technologies for a more simplified process for the production of highly clean steel is demanded.

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