Development of Continuous Casting Operation*

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I. Introduction

The recent marked increase in the production capacity of crude steel in the world may be attributed to the establishment of larger plants and mill equipments, wider application of continuous casting process (abridged as C.C.), and the introduction of automation. Particularly, C.C., which is regarded as the second significant technical innovation recently developed after the advent of the oxygen steelmaking process, has made a great progress in recent years.

In the early 1960s, the number of C.C. installations throughout the world was less than 30; most of these were of a single strand, pilot-plant-scale facilities capable of casting steel fed by 10 to 20 t ladles into billets with small cross-sectional dimensions. Today, the number of C.C. installations has increased 10 times as that of a decade ago, and the capacity of ladle has become as large as 300 t.

For the teeming of steel, which is relatively retarded in the modernization, the application of C.C. has received much of attention as a means to solve the problems inherent to the conventional teeming operations such as low efficiency, greater yield loss, and poor working environment caused by high temperature, etc.

Since the C.C. steels have less segregations as compared with the conventional ingots and the use of larger slabs is increased in the modern wide strip mills, the application of C.C. would be most helpful in eliminating various quality and installation problems associated with the teeming of ingots large enough to be reduced to extra-heavy slabs weighing as much as 40 t required for such modern strip mills.

There has been a trend in recent years toward casting billets with larger cross-sectional dimensions because of the quality of billets. In addition to the above trend there are some factors facilitated wider commercial application of C.C. These include the development of multi-strand machine, improvement of casting efficiency, increase in casting speed and broadening of steel grades available; all have been made possible along with the modifications of casting practices ensuring the stable operation of C.C. machine.

In order to achieve such results as mentioned above, it is necessary to establish more precise method of controlling the operating conditions as well as to adjust the C.C. system as a whole in connection with the quality of steel to be cast.

However, there are many problems yet to be solved

for the C.C. process. To develop appropriate methods capable of producing high quality castings, it is necessary to calculate the ideal parameters for casting speeds and cooling rates by taking into account the grade, size and sectional dimensions of cast steel, and to compare the theoretical parameters thus obtained with the actual values gained through the operating methods which are economical and qualitywise in all aspects of C.C. process.

The modification of the machine design from vertical to a curved type in order to reduce the static pressure of molten steel and to prolong the length of the secondary cooling zone, is a drastic change and has contributed greatly to the wide commercial application of the C.C. process.

For attaining the stable casting operation, it is important to have precise end point control at the steel making furnace so as to keep the pouring temperatures within the specified ranges. In this connection, the adjustment of the tapping cycle of steel from the furnace becomes also important, and a careful consideration must be given to the coordination in such an operation as the movement of crane and the delivery of slabs or billets to the next process.

II. Treatment of Molten Steel

When the steel in the ladle is not so clean, increased surface conditioning becomes necessary.¹⁻⁵⁾ This causes not only the reduced yield, but also the breakout during casting caused by the delay in the solidification of steel directly under the slag inclusions.

In the casting of billets having small sectional dimensions aluminum wire is added to the molten steel automatically between tundish and mold because the tundish nozzle becomes to clog due to the aluminum clusters.

There is a new method, in which aluminum wire or bullets is fed at high speed into the molten steel still covered with slags in the ladle while the steel is being stirred by the injection of inert gas. By this method, it is possible to hit a target of sol. Al^{6,7)} in a narrow range.

In the casting of blooms, the number of slag inclusions, the Al₂O₃/SiO₂ ratio of the scums and its melting temperature can be reduced markedly by the deoxidation with Ca-Si instead of aluminum and a part of ferro-silicon.

For the improvement of shelf energy in the horizontal direction of finished products by sulfide shape

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control, the addition of the misch metal of rare-earth metals REM (Ce, La, Nd, Pr, etc.) is considered.

According to Kaki, *et al.*,⁸⁾ only sulfur in the central segregations disappeared and the contents of other elements did not change by the addition of REM in the case of heavy C.C. slabs. The behaviors of these elements except sulfur were nearly the same as that observed in the inverted V-shape segregation of the conventional ingot added REM. Such behaviors seem to be caused by the fact that the content of sulfur dissolved in the steel drastically reduced and the interdendritic density became smaller because of the effect of rare-earth elements.

Asano, *et al.*⁹⁾ mentioned that the amount of free crystals in the cast steel was increased by the addition of REM and that the segregation of C was reduced. Judging from the analytical results of total oxygen, it can be deduced that the amount of inclusions is decreased.

It has been reported by Horigome, *et al.*¹⁰⁾ that the addition of a small amount of Te gave a marked effect on the ejection of aluminum clusters from the molten steel and that the addition of Se and S also showed similar effects, but that of Te was most remarkable among them.

Many investigations have been made as to the effects of impure elements on the C.C. steel. Desfofesez¹¹⁾ reported that the higher the contents of P, S and As in the cast steel were, the more the rate of vertical cracks in the C.C. slabs became. (Fig. 1)

1. Bubbling in the Ladle

In order to minimize the amount of inclusions and the clogging of tundish nozzle, it is desirable to maintain the temperature of molten steel in the ladle uniformly and to keep the temperature in the optimum range. In the case of 100-t ladle used at Keihin Works, Nippon Kokan K.K.,²⁾ the average temperature drop of the molten steel is 2°C/min even when inert gas pressure is less than 7 kg/cm² and its flowing volume is less than 1 Nm³, and it is helpful in the final control of the casting temperature.

As shown in Fig. 2, the effect of inert gas injection on the cleanliness of the steel can be revealed by the reduction of inclusions in relation to the variation of the total oxygen, and a marked increase in the cleanliness can be achieved by the injection of gas for 3 to 5 min.

According to the Nippon Steel Corp.'s report¹³⁾ on the reoxidation caused by the slags in the ladle during Ar bubbling of low carbon, Al-killed steels, it is revealed that the lower the FeO content in the slag is, the lower the total oxygen in the molten steel becomes, and that the total oxygen after Ar bubbling is reduced to less than 40 ppm and almost no inclusions larger than several tens of μ is observed when the content of FeO is maintained at about 1 to 2%. Similarly, in the case of Si-Al killed steel, it is expected that the defects which are detectable with ultrasonic inspector will disappear after 10 min of Ar bubbling because the total oxygen is reduced to about 30 ppm by this treatment. At the Ruhrort Works of August Thyssen-Hütte

Fig. 1. Effects of P, S and As on the vertical cracks occurring on C.C. slabs¹¹⁾

Fig. 2. Variation of O in the steel during the injection of inert gas into ladle²⁾

Fig. 3. Effects of Ar-bubbling on the temperature of the molten steel in the ladle during casting²⁰⁾

AG and other works,^{14,15)} the argon injection is made by immersing the lance into the ladle instead of injecting the gas through the porous brick lined at the bottom of the ladle. (Fig. 3)

III. Tundish and Tundish Nozzle

1. Tundish

The tundish must have a simple structure and it should be located in such a place so as to maintain and reheat easily. After casting of a certain number

of heats, the residual steel and slag in the tundish must be removed by cleaning with oxygen in order to prolong the life of tundish, and it is also necessary to investigate the quality of the refractory used for stamping and inner lining.

Table 1 shows the refractory used in the slab-caster at Kimitsu Works, Nippon Steel Corp.¹⁶⁾

In the casting of 113 mm ϕ billets for high carbon wire rods by the continuous-continuous casting (19 ch.) at Yawata Works, Nippon Steel Corp.,¹⁷⁾ electro-fused alumina refractory is used on the portion of tundish whereat the molten steel hits most severely and low-porous zirconia refractory on the nozzle to reduce the erosion of refractory.

Rutes, *et al.*¹⁸⁾ stated that the slag inclusions were greatly reduced when the depth of the moten steel-in the tundish was in the range of 300~400 mm to 500 ~700 mm as shown in Fig. 4.

It is reported by Mori, *et al.*¹⁹⁾ that in the case of multistrand caster the steel cast at No. 3 strand contained much inclusions than that cast at No. 1 strand.

This trend is due probably to the shorter holding time of the molten steel in the tundish and the insufficient floatation of inclusions since No. 3 strand is located closely to the steel stream than that of No. 1 strand. In the casting of billets having smaller sectional dimensions, open nozzles are usually used and their inner diameters should be determind on the basis of the static pressure in the tundish and the steel grade.

Nozzles of a definite size allowing the natural flow of metal ensure the smooth and sound teeming stream,

but when the size of nozzle is larger, it is apt to give a violent turbulent flow causing vertical cracks in the thin solid skin which is the source of breakout.

Mori, *et al.*²⁰⁾ reported that in the teeming of billets or blooms with open nozzles the fluidity of the scums becomes poor due to the temperature decrease at the meniscus as the cross sectional area becomes larger from 80 mm billet to 160 mm and 210 $\times$ 350 mm blooms, and consequently the slag inclusions become to increase.

As to the prevention of nonmetallic inclusions in the teeming of Si-deoxidized 0.50%C steel grade, Kenney²¹⁾ stressed the necessity of full protection against the oxidation of teeming stream in the tundish. Irwin, *et al.*²²⁾ mentioned that the most effective way was to prevent the oxidation of teeming stream as compared with other deoxidation methods.

Large inclusions observed in the billets cast with open nozzles are caused by clapping to the scums which are remaining in the mold into the molten steel or by warping of the scums due to the stirring of steel in the mold.²³⁾ According to Matsunaga, *et al.*²⁴⁾ such inclusions contain oxides which are independent of the equilibrium composition of the steel and tend to grow its volume by the collision of such oxides or by re-entering of scums. They noted the necessity of reducing the concentration of atmospheric oxygen to less than about 0.8% during the period of teeming.

Yawata Works of Nippon Steel Corp.²⁵⁾ has made various tests on the devices used for this purpose and has developed such a slit-type device as shown in Table 2, with which it was able to obtain a uniform gas distribution and also to observe the metal surface both in the mold and teeming stream. In view of the quality and the environment sanitation, it was necessary to keep the residual oxygen near the teeming stream less than 5% and N₂ flow at 1 Nm²/min.

Immersion nozzles, which have been developed by SAFE in France for the purpose of eliminating the oxidation of molten steel, the clogging of nozzle, and the involution of slags occurring by the use of open nozzles are now widely used in the casting of slabs and blooms having large sectional dimensions. The use of this nozzle in combination with mold powder has contributed to the reduction of inclusions and surface defects. (Fig. 5)

At Hamilton Works of the Steel Company of

Table 1. Example of tundish refractories¹⁶⁾

Parts name	Old type	New type	Note
Stopper head	Special Zr	Zr+fused silica	Dropping of the tip of head
Mortar for stopper	Medium Al	High Al	Increase in the adhesion strength of sleeve bricks
Nozzle collar	Pure Zr	Zr+fused silica	Counter-measure for non-stopping at the end of casting
Immersion nozzle	Fused quartz	Alumina graphite	Counter-measure for erosion

Fig. 4. Effects of the depth of molten steel and its temperature in the tundish on the slag inclusion¹⁸⁾

Table 2 Distribution of air-sealing gas flow rate for the stream from tundish (plane)²⁵⁾

Fig. 5. Casting by immersion nozzle and powder

Fig. 6. Device for Ar-sealing between ladle and tundish²⁾

Photo. 1. Comparison of X-ray photo of good and poor long nozzle and their cross-sections²⁷⁾

Canada,²⁶⁾ the argon protection has been applied to the steel stream from the tundish in the casting of Si-killed steel into 4 in. ϕ billets and has obtained an excellent cleanliness, but in the case of 6-strand machine, the application of argon protection was not so satisfactory because of the operational point. It has been found that the immersion nozzles were better than the argon protection for the operation and that it gave a good protection between the tundish and mold with a reduced amount of macro-inclusions.

As the material for the tundish nozzle, fused silica, zirconia, and corundum are commonly used, but since these materials easily cause erosion or clogging of the tundish nozzle due to the generation of less-soluble compounds, it is necessary to select the materials most suited for the grade of steel to be cast and the casting conditions. For the steel of relatively high in Mn, the immersion nozzles made of rubber-pressed alumina-graphite series have been used.

Photograph 1 shows the immersion nozzles made of fused silica. These nozzles are examined by X-ray before they are subjected for the use so as to prevent the accidents caused by the inferior quality and are

Fig. 7. Variation of sol. Al in teeming stream with or without air sealing.

graded by the degree of lamination and blowhole so that they can be used properly depending upon the grades of steel to be cast.²⁷⁾

There are many investigations as to the effect of casting steel with the immersion nozzle and powder, various means have been practiced by considering the prevention of oxidation and the flow pattern of stream in the mold.²⁸⁻³⁰⁾

The author, *et al.*²⁾ have cast a low-carbon, Al-killed steel by injecting the inert gas in a manner as schematically shown in Fig. 6, in which the inert gas was blown to the stream through a ring-like pipe attached to the bottom of the ladle by moving the sealing pipe made of refractory up and down by air cylinders. Figure 7 shows the comparison of the contents of sol. Al in the sample taken out of the teeming stream and that of the sample taken out of the tundish. From this it can be noted that the content of sol. Al in a heat of steel cast without this device is reduced 0.0013% while that of steel with this device is reduced 0.007%. It is also noted from Fig. 8 that the total oxygen of the steel without this device increases by 5 ppm while that of steel treated with this device decreases by 7 ppm. This makes the difference of 12 ppm and it shows how effective this device is.

According to the study made at Mizushima Works, Kawasaki Steel Corp.,³⁰⁾ the prevention of oxidation between the ladle and tundish showed a marked effect on the elimination of defects occurring on the cross-section of slabs as well as of nonmetallic inclusions.

Fig. 8. Variation of T(O) in teeming stream with or without air sealing

Fig. 10. Effects of sol. Al and temperature on casting⁹⁰⁾

According to the report of Yawata Works, Nippon Steel Corp.,²⁹⁾ alumina clusters in the slabs of low-carbon, Al-killed steel for tinplate manufacture have been eliminated almost completely by the application of argon sealings to the place between the ladle and tundish and to the detachable tundish nozzle.

2. Shape of Nozzle

Shape and dimensions of the immersion tundish nozzle affect not only the flowing condition of metal but also the surface quality and the internal solidification of the metal. Valuable informations for the actual casting operation can be obtained through the observation of the metal flow in the mold by the similitude of Froude value obtained by the water model studies by flowing water in a transparent plastic vessel or by the observations of the variations in the distribution of casting powder resulting from the changes in the angles of nozzle at outlet and the conditions of flow and stagnation, *etc.*¹²⁾ (Fig. 9)

3. Nozzle Clogging

In the casting of Al-killed steel, alumina clusters produced by the primary oxidation or by the air oxidation cause clogging of the tundish nozzle and make the casting operation difficult. In view of the casting conditions, clogging of the nozzle is affected by the casting temperature and by the content of

Fig. 9. Shapes of various types of immersion nozzle

Fig. 11. Cross-section of gas sleeve nozzle

sol. Al²⁾ as shown in Fig. 10. Many reports³¹⁻³³⁾ have been presented on the nozzle clogging and many tests have been carried out to examine the effects of the shape and the quality of the nozzle material on the clogging.

Recently, LECO Co. has developed a gas-sleeve nozzle. As shown in Fig. 11, Ar gas is introduced into the porous (60%) refractory buried in the zirconia nozzle (0.35~0.75 kg/cm², 2.4~11.8 l/min, for 1/2~1 1/2 in. nozzle diameter) to form a thin film of argon between the metal and the inner surface of the nozzle to prevent the solidification and the precipitation.

IV. Mold Powder

Mold lubricating oil is used currently in the casting of billets with small sectional dimensions. Recently, however, mold powder and immersion nozzles have become available for the casting of billets having larger sectional dimensions. In the case of lubricating oil, it is feared that hydrogen produced by the resolution of oil would cause pinholes in the billet, and hence the moisture content of the oil must be kept as low as possible^{34,35)} and the addition of paraffin would be effective to prevent the occurrence of pinholes.³⁶⁾ In view of the precipitation of carbide at the grain boundary of the cast steel caused by the use of lubricating oil, the amount of oil should be kept at a minimum; for example, carbide precipitation reached 0.04 in. even with 1 ml/in. of the circumferential length/min.³⁷⁾ and that of high-speed steel billets of 100 mm ϕ reached as deep as 0.15 to 3.0 mm from the surface of the billet.^{38,39)} Consequently, it is desirable to use mold powder.

According to the tests made by Klipov, *et al.*⁴⁰⁾ to measure the temperature curve in the mold with 100 pieces of thermocouple inserted, it was found that in

the case of mold powder, the heat transfer at the upper part of the mold was lower by 15 to 20% than that in the case of lubricating oil while the heat transfer of the former at the lower part of the mold was higher by 20 to 25% than that of the latter and that the thickness of the solidification layer of the steel was thinner by 2.5 to 5 mm at the upper part and thicker by 5 to 7 mm at the exit end. This indicates that the use of mold powder is better for the solidification of the steel.

It is also reported that the mold powder is effective for the reduction in the occurrence of corner cracks on the flat blooms because its use can minimize the delay in the solidification of steel at the corners.⁴¹⁾

The mold powder added to the meniscus of the steel in the mold produces a molten slag with low melting point covering the entire surface of the meniscus so as to prevent the radiation heat and the oxidation, melts the deoxidized products and the refractory particles accumulating on the meniscus, and acts as the lubricant as it moistens the gap between the mold wall and the solidifying shell of the steel uniformly. In order to obtain such effects of the mold powder, it is necessary to have a stable layer of the powder on the top of the molten slag layer so that the supply of the molten slags gradually compensates the loss of the molten slags; in other words, it is necessary to control the fusion rate corresponding to the casting rate. Generally speaking, to promote the fusion of oxides floating on the meniscus the casting powder should be of neutral slag composition of about $\text{CaO}/\text{SiO}_2=0.65$ to 1.1, and the flux which is capable of restraining the rise of the surface tension should be selected.

According to the tests made at Mizushima Works, Kawasaki Steel Corp.,⁴²⁾ (1) when the viscosity (η) is low, it causes the delay in the formation of solidifying shell and the local flow of fused materials, and due to the tension stress concentrated on these locality, cracks occur; (2) when melting rate (t_f) is slow, it causes the overflow of powder and consequently the vertical cracks occur. On the contrary, if the flow rate of powder is increased, it promotes the absorption and the fusion of Al_2O_3 floating on the meniscus and thus reduces the slag inclusions; (3) the vertical cracks and the slag inclusions are closely related to the value of η/t_f and therefore, a close control of this value is necessary to prevent such defects. When fly ashes are mixed with the powder, the mixing rate must be kept low because variations in the grain size and the chemical compositions of fly ashes (excess iron oxides and other elements which are hard to be fused) and the variations in the grain size of carbon in the powder are the main factors⁴³⁾ causing cracks on the cast steel.

As the severe oscillation marks appearing on the surface of the cast steel due to the oscillation of the mold often causes vertical cracks developing from transversal cracks, it becomes necessary to use the casting powder of special character so that the amount of the powder flowing into the gap between the mold wall and the steel shell is not affected by the changes in the casting conditions such as casting speed, *etc.*⁴⁴⁾

According to Leclerg,⁴⁵⁾ Al_2O_3 contained in the insulating material is enriched during the pouring in the casting of slabs for cold-rolled coils, although its rate varies depending upon the insulating material used and its saturation point is about 17 to 18%. This necessitates the periodical replacement of insulating material at least by 0.85 kg/t. With $\text{CaO}/\text{SiO}_2=0.96$, melting temperature of 1 000° to 1 050°C, and 7.5% of Al_2O_3 , a stable surface quality of the slabs for hot and cold-rolled coils has been obtained without the difficulties of surface conditioning.

At the initial stage of pouring, vertical cracks often occur on the bottom of the cast strand connected with the dummy bar due to the stress developed by the solidification and the contraction of the steel by the secondary cooling from the bottom of the mold. These cracks can be reduced greatly by controlling the secondary cooling and by the use of front-powder of relatively low-melting point at the initial stage of casting.⁴⁶⁾

Springorum⁴⁷⁾ has made the tests on the uniformity of fusion of the casting powder using a press-formed sample of 25 mm in diameter heated at 1 200°C for 4 min after forming, and from the uniform external appearance of the test pieces, the availability of the powder for the casting of slabs used for plate products has been determined.

V. Mold

Two types of molds are in use at present; they are block-molds and built-up molds. As the material for molds, copper or copper alloys are used since they are easily obtainable and provide a uniform and rapid heat transfer from the molten steel to the inner wall of the mold and to cooling water behind the wall.

It is recognized that the smaller the cross-section of billet is, the larger the diamond-shaped deformation grows, and the heavier the said deformation grows, the more the vertical surface cracks occur on the corners with an obtuse angle and their vicinity, and that the thickness of the solidification occurring on the wall is thinner than that of the solidification occurring on the corners with an acute angle. This is presumably due to the uneven cooling within the mold, and in the case of the blooms of 200×220 mm cast by a curved mold machine, if the difference in the inner diameter of the mold and that of the molten steel level is over 1.2 mm because of the deformation of the mold caused by the wear, it causes cracks on the corners of the bloom. Therefore, the inner surface of the mold must be kept precisely by grinding, re-forming, and by the replacement of the mold.⁴⁸⁾

According to the report presented by Topi Industries, Ltd.,⁴⁹⁾ the vertical corner cracks appeared on the cast blooms were originated in the inner corner cracks already presented in the blooms during the casting, and such blooms did not have sufficient shell thickness capable of withstanding the internal stress developed when the blooms were withdrawn from the mold wall. To prevent such internal corner cracks, they used the molds equipped with cooling pipes (10 mm) and succeeded in reducing the vertical

corner cracks because the use of such a mold provided wider chilled crystal zones at the corners

As the results of the tests made by Kure Works, Nisshin Steel Corp.⁵⁰⁾ on the alteration of the taper angle of the mold having wider top end, the bulging of the narrow side of strand has been eliminated with the resultant reduction in the vertical corner cracks on the cast strand. If the said angle becomes larger, it produces a greater friction between the strand and the mold and increases the horizontal cracks on the surface, and there exists such a taper angle that both the vertical and horizontal cracks become minimum.

Figure 12 shows an example of the methods enabling a rapid change of mold width.⁵¹⁾ Free longer copper plates are fixed to, or detached from, the shorter copper plates with a light tap of push-button of an oil-jack. Since this is arranged to provide the prescribed taper angles in accordance with the changes in the mold width, smaller width slabs of 750 to 950 mm can be produced safely with a high efficiency.

The twin mold casting method developed by the Mannesmann is now used at Fukuyama Works, Nippon Kokan K.K.⁵²⁾ On its wide molds, a copper plate partition and the tundish with two immersion nozzles per strand are equipped with. Special heads are used for the dummy bars and the side rollers are equipped directly under the shorter copper plate. But, no side roller is used beneath the copper plate partition.

Presently, almost all of the molds used for the casting of slabs are constructed with the plates, and as seen in the case of Keihin Works, Nippon Kokan K.K.,¹²⁾ the life of the copper plates in the curved molds can be prolonged for 1 700 to 1 800 heats if their inner surfaces are kept in good order by hand grinding.

Cracks and fissures such as turtle-shells occurring on the surface of cast strand are considered to be caused by the mechanical scraping of the surfaces of copper plates in the mold resulting from the poor internal dimensions and the irregular shape of the mold, by the malalignment of the mold with a roller-apron, and by the improper stripping of the steel off the strands, *etc.* The resultant invasion of scraped copper into the grain boundary of the metal surface layer gives the adverse effects on the high temperature strength of the metal.⁷³⁾

Deoxidized copper has been commonly used as the material for the mold, but in recent years the precipitation-hardening, high strength copper alloys which are able to withstand for heats more than those for the other materials have been developed.⁵³⁾

As for the oscillation of the mold the sine curve method based on a simple mechanism which is free from troubles is now widely used, and the relationship between the negative strip and the amplitude, the frequency of oscillation is shown in Fig. 13.⁹⁰⁾

Good surface quality is generally obtainable with a small amplitude and a large oscillation number even the negative strip is constant.

According to the results obtained at Kure Works, Nisshin Steel Corp.,⁵⁴⁾ the defects arising from the

Fig. 12. Mold width changing device⁵⁰⁾

Fig. 13. Relation between amplitude $\times$ oscillation and time of negative strip⁹⁰⁾

oscillation marks can be greatly reduced when the oscillation strokes are smaller than, or equal to, the thickness of the slag layer.

VI. Secondary Cooling

The thin shell commenced in the mold is rapidly cooled by secondary cooling and at the same time the compression of steel takes place at this stage, but the compression of solidifying layer of steel is hampered by the static pressure developed in the inner liquid phase and thus the fracture of steel is taken place by the severe strain arising from the static pressure. When the steel has a thinner shell because of the longitudinal cracks or the slag inclusions, the inner liquid phase flows out therefrom and breakout occurs.

The secondary cooling zone is a critical point and most of severe strain is produced here. Therefore, it is necessary to maintain a proper temperature gradient at the secondary cooling zone and to control the amount and the distribution of spray water so that the steel can be cooled uniformly. If the cooling stress is not uniform or excessive, the cast steel is warped or bent or twisted, and both the vertical and horizontal cracks occur.

The longer the distance from the mold is, the larger the static pressure of molten steel becomes, and the bulging of the cast strand between the supporting rolls of the secondary cooling zone increases by fourth power of the roll pitch of the supporting rolls. Consequently, it is necessary to decrease the roll pitch to prevent the internal defects of the cast steel, and the supporting rolls must be rigid and strong enough to withstand the loads developed by the static pressure of the molten steel.

In the casting of billets and blooms, the bulging

occurs less and hence, the structure of the guiding rolls may be a simple one. The solidifying shells at the exit end of the mold grow as the steel travels to the secondary cooling zone. Since the heat transfer from the center to the surface of the steel becomes smaller gradually, the amount of spray water can be reduced accordingly.⁵⁵⁾ (Fig. 14)

The parameters for the secondary cooling zone should be determined by considering the grades of steel to be cast. As they are influenced by such factors as the liquidus and solidus lines, the latent heat, the heat dispersion rate, and the high temperature strength of the steel, it is necessary to divide the cooling zone into several sections so as to be able to change the cooling pattern for each section even for the casting of low and medium-carbon grades.

The center part of the cast steel should be solidified before it enters into the pinch rolls and therefore, the casting rate of the materials having larger cross-section naturally becomes low or the length of the secondary cooling zone becomes longer. The length of the non-solidified core of the molten steel varies depending on the thickness of the slab and the rate of withdrawal as shown in Fig. 15.⁵⁶⁾ In order to obtain good surface quality of the slab, the casting speed must be increased as much as possible, but the casting speed is restricted by the distance of the secondary cooling zone from the mold to the pinch rolls.

As to the types of the internal cracks appeared on the slabs, there are the cracks resulting from the impurities concentrated in the weak interdendritic structure caused by the heat strain developed on the solidifying shells before reaching the pinch rolls and those caused by the pressing action of the pinch rolls for the steel solidified incompletely. In the former case, the location of the secondary cooling zone whereat such internal cracks occur can be predicted based on the location of the internal cracks and on the formular for the rate of solidification. In the later case, *i.e.*, cracks caused by the pinch rolls, they are characterized by being perpendicular to the sur-

Fig. 14. Relation between heat transfer and amount of spray water at the secondary cooling zone⁵⁵⁾

face contacting with the pinch rolls.

When it is preferred to adopt a faster casting speed from the stand point of the surface quality, the distance between the mold and the last pinch roll may be made longer than 20 m and the cooling plates can be applied directly under the mold in order to maintain the accurate shape of slab at this particular location as well as to prevent the bulging and break-outs.^{57,58)}

Between the upper and lower supporting rolls, whereat the unsolidified portion of the slab tends to come, the spacers are inserted so that an adequate torque keeping a good balance with the bulging power may be applied to their driving rolls (Fig. 16), and the multi-drive system, in which most of the upper rolls act as the driving roll, is used to reduce the tensile stress in the interior of the slab so as to obtain good interior quality.

This system is particularly desirable for the high speed casting machines causing larger stress within the solidifying shells.^{59,60)}

In the curvilinear curved type machine recently developed in Russia, indirect cooling by cooling plates is applied to the arched secondary cooling zone, and either inside or outside bar cooled with water always contacts with the slab surface to facilitate the movement of slab.⁶¹⁾

Since the distribution of spray water influences the solidification of the slab, it is necessary to check whether the spray nozzles are in good order.

VII. Factors Affecting Solidification

1. Structure of Solidification

It is generally recognized that when the casting

Fig. 15. Depth of unsolidified core, thickness of slab, and withdrawal rate⁵⁰⁾

Fig. 16. An example of multi-drive system⁶⁰⁾

temperature of blooms or billets and their withdrawal rate are raised, slag inclusions produced become less because the fluidity of scums becomes better due to the higher temperature in the mold.^{18,62-64} On the other hand, it is also recognized that the higher the casting temperature is, the longer the columnar crystal becomes.^{27,65,66} The crystalline structure of the cast steel is affected greatly by the degree of the superheat of the molten steel and therefore, the lesser the superheat is, the larger the equi-axial crystal becomes. However, the degree of the central segregation is not necessarily determined only by the superheat of the molten steel, and a considerable center segregation occurs even in the case of equi-axial crystals. This may be attributed to the contraction of the residual steel accompanying the solidification or the movement of the said residual steel to the voids produced by the bulging due to the static pressure of the molten steel.⁶⁷⁾

According to Takaishi, *et al.*,⁶⁸⁾ there is a close relation between the degree of the central segregation and the columnar crystals developed inside of the bend. Since the latter is sensible to the temperature of the molten steel and rapidly grows when the superheat is over 20°C.

According to the results of the tests made by Mori, *et al.*⁶⁹⁾ on the structure and the segregation of square billets ranging from 80 to 250 mm and blooms of 260×370 mm, it has been revealed that the columnar crystals become longer as the casting temperature rises excessively, the shape of the center porosity changes from wide pore to pipe pore toward its axis, the V-segregation changes from band to line, and the width of the center segregation becomes larger. The dense center segregation can be reduced by controlling the superheat of the molten steel, by making the cross-section of the strand larger and by maintaining the degree of the section flatness over 1.3.

The conditions of the center porosity correspond with that of the center segregation, and therefore the center porosity is harmful when the steel as cast is further processed with the said porosity left as it is, but the said porosity is not so harmful since it is pressed down with a rolling ratio between 3 and 5.⁷⁰⁾

Figure 17 shows the relations between the equiaxial crystals and the superheat of the molten steel in the tundish under the regular secondary cooling conditions of 200×1 600 mm slab.⁹⁰⁾ From this diagram it is noted that the width of the said crystal becomes larger than 53 mm when the superheat in the tundish is less than about 12°C. The temperature of the molten steel decreases while it is teemed into the mold from the tundish and the relations of superheats between the tundish and the mold are shown in Fig. 18.

When the superheat of molten steel in the tundish is less than 12°C, that in the mold becomes lower than 0°C. Under this condition the structure of solidified steel is fairly good.

Adjustment of the casting temperature may be made by the addition of cooling agents to the steel or by the gas-bubbling in the ladles, but it is necessary first of all to control the steel temperature at the

Fig. 17. Equi-axial crystals and superheat of molten steel in the tundish⁹⁰⁾

Fig. 18. Relationship between superheat of molten steel in the tundish and that in the mold⁹⁰⁾

tapping out of the steelmaking furnace.

According to Yurev,⁷¹⁾ by the addition of pig iron powder of 0.3 to 1.0 mm in diameter at the rate of 1.5% for the weight of molten steel to the mold, the temperature has been reduced by 23°C per 1% of the powder added and the center segregation of 175×420 mm bloom has been reduced.

Premiov, *et al.*⁷²⁾ reported that when the steel was vacuum treated in a ladle, the teeming at a reduced temperature had become possible because of the improved metal fluidity and the reduction in the total oxygen from 70~80 ppm to 30~35 ppm and thus the center porosity of 120 mmφ billet had been reduced because the width of its equi-axial crystal was increased.

2. Thickness of Solidified Shell

It is possible to improve the casting conditions and the interior quality of the cast strand by observing the solidification occurring throughout its length. Figure 19 shows the results for the slab of 200 mm thick measured by the author, *et al.*⁹⁰⁾ Considering the effect of the casting temperature on the solidification rate, comparative heat of molten steel is far lower than the latent heat, and the casting temperature does not give much effect on the duration of solidification.

To calculate the solidification rate of steel, the mathematical method, molten steel discharge method, and identifying materials adding method are available, but in view of the reliability and the economics, the method by which the solidification rate is determined by measuring the thickness of solidified shell

(Photo. 2) is commonly used. In this method, such identifying materials as the radio active-isotopes (RI) of Au, S, and W are thrown into the mold, and after the steel is solidified, the cross-sectional radioactivity is measured by the autoradiographic inspection. With any of the methods mentioned above, however, it is difficult to clarify the solidus-liquidus interface of the solidification front and therefore the high-speed rivetting method⁷⁴⁾ is used as a simplified method. In this method a nail is driven into the casting strand at any desired location and a sample is taken out of the place where the nail is driven for the examination of liquidus and solidus lines after solidification so that the secular change on the solidified interface can be measured.⁷⁵⁾

Figure 20 shows the distribution of Cr in the neighbourhood of the location whereat a nail with 1.10%Cr was driven.

VIII. Productivity

1. Improvement of Productivity

The productivity per unit time of casting for the C.C. process has been improved by enlarging the sectional dimensions of the cast strand, the development of multistrand, and by increasing the withdrawal rate, etc. Further improvement of the operating efficiency has been aimed at by the adoption of continuous-continuous casting, the reduction of the preparation time, and the improvement of the techniques for maintenance and repair.

Fig. 19. The state of solidification measured by ¹⁹⁸Au and theoretical mathematics⁹⁰⁾

2. Continuous-continuous Casting

Continuous-continuous casting (abridged as C.C. C.) has the advantages: improvement in the casting efficiency, improvement of the yield, reduction in the material cost.

1. C.C.C. Process

In the C.C.C. process, the exchange of ladles and tundish must be done quickly. To exchange the ladles, cranes have been used mostly, but recently, there are many instances where ladle cars are used for the exchange of ladles in view of the rapidity and the economics.

It is desirable to change tundish while steel in the ladle is still sufficient so as not to reduce the temperature of molten steel, and therefore tundish cars are generally used for this purpose.

The turn table which was capable of changing ladle or tundish more faster has been developed in FR Germany. In this method a ladle filled with molten steel is put on the empty end of the arm projecting to the ladle yard, and by turning the table halfway the ladle on the arm comes over the tundish. After teeming the empty ladle is carried away by a crane installed in the yard opposite to the teeming yard. (Fig. 21)

In order to improve the operating efficiency of C.C. machine, it is necessary to establish a close coordination between the steelmaking furnaces and the casting machine and to have complete end-point control on the furnace side.

2. Time Schedule for C.C.C.

There is a limit in the heat numbers to be cast in terms of the life of the tundish. Therefore, the

Fig. 20. Cr distribution in the neighbourhood of the nail driven (XMA result)⁷⁵⁾

← Solidifying Boundary
at the 1st RI addition
500 mm below the meniscus
← Solidifying Boundary
at the 2nd RI addition
1000 mm below the meniscus

Photo. 2.
Autograph of cast strand
cross-section⁹⁰⁾

tundish must be replaced occasionally in the practical operation, but in this case it is necessary to provide some means which is possible to prevent the solidification occurring on the meniscus of steel in the mold because the supply of steel is suspended while the tundish is being replaced. It also causes the gaps between the strand and mold due to the contraction of steel resulting from the solidification and produces the double skins due to the entry of steel into the gaps when the supply of steel is resumed. However, according to the experiments made by the author *et al.*, the degree of such surface defects appeared on the slab of 200×1600 mm becomes smaller when the suspension of the steel supply is less than 1 min and these defects can be removed completely by scarfing.⁷⁶⁾

It has been long since C.C.C. equipment was de-

veloped both in Europe and the United States and multiple heats including 84 heats recorded by McLouth Steel Corp. have been cast. Casting of a small number of heats by C.C.C. has become common practice. The first multiple heats in Japan was cast with its slab caster for 28 heats at Keihin Works of Nippon Kokan K.K. in June, 1970 based on the time schedule shown in Fig. 22⁷⁶⁾ and then 270 heats by C.C.C. in August, 1974. In March, 1972, Yawata Works of Nippon Steel Corp. cast 56 heats by C.C.C. and in May of the same year, it succeeded in casting of 34 heats of billet materials. In the latter case the substituting metals were charged in the mold while the supply of steel is suspended and after the metals were cooled and solidified, subsequent heats were poured.⁷⁷⁾

Fig. 21. Recent slab caster⁵¹⁾

Fig. 22.
Data for C.C.C.
for 28 heats⁷⁶⁾

3. Sizes of Mold and Cast Strand

In the C.C.C. process, it is necessary to cast many heats with the same mold and hence the size of cast strand becomes the same. In order to meet the demands for different sizes and shapes for subsequent rolling mill products even for the same grade of steel, the direct rolling method, which is capable of rolling the cast strand into the desired semi-finished products by in-line rolls, has been introduced. The followings are some examples where the direct rolling is being applied for making billets:

Gebr Böhler & Co. AG in Austria, from 140 mm ϕ to 96 mm ϕ ; ⁷⁸⁾ Badische Stahlwerke AG in FR Germany, from 130 $\times$ 190 mm to 100 mm ϕ ; ⁷⁹⁾ Inland Steel Co. in U.S.A., from 190 mm ϕ to 127 mm ϕ ; Georgetown Steel Corp. in U.S.A., from 133 $\times$ 95 mm to 100 mm ϕ ; The Timken Roller Bearing Co. in U.S.A., from 241 $\times$ 305 mm to 241 mm ϕ . ⁸⁰⁾

The direct rolling in the field of billet casting mentioned above is now carried out either by the combination of a pinch roll and a rolling roll or by a rolling mill installed right after the pinch rolls, and is expected to improve the interior quality of the cast strand as well as to achieve the merit of continuous processing.

Hot and cold-rolled sheet available on the market generally have the width ranging from 600 to 2 000 mm with increments of 50 mm. In order to cast slabs for hot strips continuously with 50 mm pitch, the change of the width of mold or the change of the width of slab with in-line rolls is considered.

Molds with adjustable width has already mentioned before and is illustrated in Fig. 12. The widths of these molds are adjustable in the range of 900 to 1 500 mm within 15 min, but it is necessary to shorten the time needed to change the width as much as possible so as not to interrupt the casting operations due to the suspension of steel supply caused by the change of the mold width. The circulating dummy bar inserting system (Fig. 23), which can reduce the time necessary for the preparation and the change of the width of dummy bar inserted from the upper part of the mold, has been developed and is now subjected to the use. ⁸¹⁾

The change of slab width by in-line rolls is now used at the U.S. Steel Corp. ⁸²⁾ In this method, the continuously cast strand is heated up to 1 200°C in a reheating furnace installed just behind the pinch rolls and then it is rolled to various widths by the in-line rolls consisting of 3 stands of horizontal roll and 4 stands of vertical roll; the latter being used to adjust the width. The mold being used on this installation

Fig. 23. Circulating dummy bar system ⁸¹⁾

is only of two types; 9.3'' $\times$ 76'' and 9.3'' $\times$ 56''. The smallest slab available from the former is 7'' $\times$ 56'', and 5'' $\times$ 30'' from the latter.

For the C.C.C. process, it is equipped with two ladles cranes and two tundish cars as shown in Fig. 24 and with a rapid tundish nozzle changing device.

4. Automation

Utilization of analog analysis and automatic control for the C.C. process has made a significant progress in recent years. At the initial stage of C.C. operation, most of the devices used for this purposes were of compressed air type, but now the solid-state electronic transmission and other devices have become available. ⁸³⁾

The purpose at the initial stage was to facilitate a smooth and consistent control of the driving equipment, particularly of the pinch rolls, but later, with the need for further automatic control of C.C. operations and labor saving, such operations as (1) mold and cooling water spray, (2) inserting and drawing of dummy bar and (3) withdrawal of cast strand have become automatically controlled. Presently, the automatic control systems on (1) level of the meniscus in the mold, (2) adjustment of the slab thickness and (3) cutting of the cast strand, *etc.*, are being developed, and the introduction of a computer control system is being considered in order to improve the productivity and the stability of C.C. operations. ⁸⁴⁾

It is practiced to automatically control the meniscus in the mold using cobalt 60, revolution of pinch rolls, and pouring of steel into the mold geared with automatic opening of tundish nozzle and also computer control of the transportation of cast strands and the storage yard operations are introduced. (Fig. 25)

Fig. 24. The layout of continuous caster at Gary Works of the U.S. Steel Corp. ⁸²⁾

Fig. 25.
Computer control system
for continuous casting⁹¹⁾

5. Maintenance of Equipment

To support the casting of sound steel from high temperature molten steel continuously and in a large quantity, it is necessary to establish an adequate maintenance system. In this sense the maintenance personnel must be trained to cope with many problems never experienced in the conventional ingot casting such as mechanical, electrical, oil, water, and instrumental, *etc.*, and the operating crew must be educated so as to have the knowledge which is able to handle the problems associated with metallurgy, refractory and maintenance.

The improvement of the productivity can be attained by preserving the mold, the secondary cooling zone and the nozzles in good conditions by the regular inspections based on the check-list prepared, by the maintenance and repair of the components exposed to high temperature and by the capacity of maintenance personnel to take necessary actions for break-outs at the secondary cooling zone and overflow of metal at the mold which are peculiar to the C.C. operation.

As an example of the stable operation of C.C., the slab caster at Keihin Works of Nippon Kokan K.K. may be cited. This installation had no breakouts for more than 10 000 heats during three years since it was commissioned in March, 1967 and this outstanding record was the results of the extensive training of the operators and good maintenance of the equipment.

Not to mention the operating process, special attentions must also be paid to the refractories used in the ladle and tundish since these are subjected to a high temperature for a long time.

IX. Cross-sectional Shape of the Cast Strand

In addition to the square mold, the molds having various cross-sectional shapes such as round, octagonal, hollow circle and I-beam shape are available. At Mannesmann's, a considerable amount of hollow blooms over 400 mm in diameter has been cast with a

Fig. 26. C.C. mold being used for casting H-beam blank at Algoma Steel Corp.

vertical machine in which a bar was inserted in the mold, and at SCEC round billets up to 200 mm in diameter are being produced by rotating the round mold on a horizontal plane.

H-beam blank, which was developed by BISRA for H-beam application, is now commercially produced at Algoma Steel Corp. in Canada⁸⁹⁾ by using the dumbbell-shape mold in Fig. 26. The largest size of the said blank so far cast is 301/2" × 14" × 4" and it is reported that by the use of this dumbbell shape mold the number of breakdown at rolling has been greatly reduced as compared with the case of the ordinary type molds. It is also reported that because of the complexity in the cross-sectional shape of the mold, special attentions are being paid to the maintenance of the mold as well as to the cooling rate at the secondary cooling zone to prevent the occurrence of cracks and bulging on the corners of billets.

X. Improvement of the Internal Quality of the Cast Strand

As mentioned previously, the internal quality of the cast strand is influenced by the operation practice followed from the refining of steel at the steelmaking furnaces to the solidification of strand at the secondary cooling zone, but some experiments are being done to improve the internal quality of the strand while it is being solidified.

1. BSR Method

The method being practiced at Böhler Company is to press down the strand with a pair of rolls while it still has an unsolidified core. This method is based on the fact that if the molten steel solidifies without convection at the end of unsolidified portion, the segregation occurs on its arbor and so the steel is rolled down at the state having a molten steel pool in its center. This method is called BSR method (Böhler-Strang-Reduzier Verfahren).

2. Electromagnetic Stirring

Since a patent was granted to Junghaus on his electromagnetic stirring process used for the continuous casting steel, many experiments have been made on this process. According to Alberny,⁸⁵⁾ the electromagnetic stirring of molten steel in the crater is effective in improving the inner quality of finished products, particularly that of billets, because the stirring of columnar crystals assists to increase the equi-axial crystals in the center of the steel.

According to Poppmeier, *et al.*⁸⁶⁾ the columnar crystals found in the round billets with 130 mm diameter made by C.C. has become shorter and its steel structure has become finer when the electromagnetic stirring was applied to cast steel during solidification and thus the center porosity was dispersed.

Nishiwaki, *et al.*⁸⁷⁾ reported that the growth of the columnar crystals existing in the slabs of 210 mm × 1 250 to 2 050 mm was stopped as the result of the stirring of nonsolidified portion of the steel with a three-phase alternate magnetic induction field, and that the sulfur prints of heavy center segregation have either disappeared or become lighter as the result of the stirring of unsolidified portion of the steel. They also stated that the white band appeared by the stirring, and that the growth of columnar crystals extending from the surface of the steel was stopped when they reached the boundary of this white band.

3. Supersonic Vibration

Abramov, *et al.*⁸⁸⁾ conducted the tests to ascertain the effect of supersonic treatment for the improvement of the quality of cast strand. Supersonic waves were added to the cast strand of 150 × 640 mm incross-section by water cooled emitter made of copper, and it was found that the columnar crystals in the macro-structure decreased and the tensile and impact strengths improved at the cast steel, but no change in the character and the distribution of non-metallic inclusions as well as in the gas composition did occur.

XI. Conclusion

Continuous casting which was started from the operation of a small quantity of special steel, has now proved to have the merits for improving the yield and the quality of steel and for saving the labor, and its application to the production of full line of carbon steels is being considered as a means to modernize the conventional ingot casting. Its functions to omit the conventional rolling such as blooming or slabbing is attracting much attention.

In order to make further improvement, its productivity and efficiency, establishment of better combination with the steelmaking furnaces, particularly with BOF and electric furnaces, extension of available sectional dimensions of strand, increase in the withdrawal rate, reduction of the preparation time and adoption of the continuous-continuous casting, *etc.* are being studied along with the introduction of a computer control system in not only the operations but also the handling and transportation of cast strand.

The techniques of engineering of casting machines, operation and refractories have made a remarkable progress in recent years.

For the improvement of the productivity of the C.C. process it is also necessary to establish the standardized operating practice to satisfy the wide diversity of steel grades suitable for mill products, an extensive training system for the operating personal to uplift their working moral and good maintenance system for the facilities.

It is also noted that the advanced techniques to cast any types of high quality steel have been developed in combination with the developments in the iron and steelmaking techniques such as desulfurization of raw materials, refined end-point control at the steelmaking furnaces, and vacuum degassing of molten steel, and that automatic process control aiming at the improvement of quality of steel, stabilization of operation and saving of labor as well as systematization of integrated operations of subsequent rolling have been in progress.

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