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Short Communication

Development of a large ingot continuous caster

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Abstract – A large ingot continuous caster (LICC) has been developed to increase international competitiveness in world steel markets by obtaining a higher yield and reduction of process for steelmaking industries as well as increasing quality by replacing the ingot casting process for production of an extra-large section size strand and high–alloy specialty steel. A conventional continuous caster of an extra-large section size needs a considerable amount of investment compared with a vertical semi–continuous caster such as the LICC. While the LICC is favorable for producing small lots for various steel grades, a conventional continuous caster is suitable for mass production of certain steel grades. The process of a conventional continuous caster and the process of a LICC from a ladle to a strand are similar to each other except for the withdrawer type and the standing below the LICC mold until complete solidification is achieved. At the end of the casting, the LICC bloom moves downward and stops at a certain distance below the mold, and then stands on a vertical position waiting for complete solidification. The LICC bloom is pushed horizontally to the tilter, the purpose of which is to set the bloom in a horizontal position. During the pushing stage, the bloom is separated from a well block. After a hot run of the pilot large ingot continuous caster (LICC), more than 90 heats of 12-ton liquid steel per heat for various steel grades were cast through the caster without any negative impact on the equipment or operations. From the LICC process developed by POSCO, most steel grades such as medium-carbon structural steels, stainless steels and tool steels have been cast successfully and confidently. Their surface and internal quality were found to be better than those of ingots and easily acceptable for the next process. We were able not only to design a continuous casting plant from concept design to detailed design but also to operate a new caster by ourselves. The equiaxed zone was much enlarged and its structure was found to be compactly composed of fine globular crystals. The shrinkage pipe was also greatly reduced from L to $0.23L$ by top heating and stirring. The casting speed, casting temperature, stirring and temperature gradient of the strand were found to be the "vital few" parameters affecting the internal quality based on investigations of the evaluation results of the macro-structure of the cast TD11 steel. The internal quality of the LICC strand for TD11 steel was much improved by using the optimum combination of these parameters, and the rolled bloom from the LICC strand has excellent internal soundness.

Demand for high profits and low costs in the steelmaking industry as well as other industries has increased recently with strong global competition. In order to meet this demand, a higher yield and reduction of processes for steelmaking industries are essential, as is attaining higher quality. The continuous casting process for steels has been a good solution until now, but there remains to be solved the problem of how to cast an extralarge section-size strand and highalloy specialty steel to replace the ingot casting process. Therefore, a large ingot continuous caster (LICC) has been under development since 2007 by POSCO's own engineering team along with its related groups such as POSCO E&C, POSCO ICT and POSCO SS. We created our own concept and basic designs, and a pilot caster, mainly composed of a mold size $700 \times 700 \times 800$ mm^3, a mold EMS, an oscillator, a withdrawer, the pusher, and the tilter, was built at the Melting and Casting Laboratories in the POSCO Pohang Works.

While the LICC process has the advantages of high recovery, eco-friendliness, and reduction of the next process which is skipping the forging step or simplification of the forging processes, the ingot process has the disadvantages of low recovery and high cost due to the forging process. It also has advantages such as good surface and inner qualities, due to the low casting speed of 0.05–0.2 m.min^{-1} and vertical strand. The LICC process of vertical semi-continuous casting has been developed to produce extra-large bloom section sizes ($700-770 \times 700-770$ mm^2) with a higher recovery and better quality than ingot casting.

During the preparation of the conceptual design of the LICC caster, computer simulation of the fluid flow and solidification using FLOW-3D®, a commercial CFD tool, was carried out and it was found that some defects such as macro-segregation, the top pipe, irregular solidification and remelting at the strand bottom could occur. Our own concept and basic design were prepared, incorporating solutions for these defects. Based on the designs, a pilot caster, the mold size of which was $700 \times 700 \times 800$ mm^3, was built at the Melting and Casting Laboratories in the POSCO Pohang Works. To date, more than 90 heats have been cast through the caster without any negative effects on the equipment or operations. Most steel grades such as mediumcarbon structural steels, stainless steels and tool steels have been cast successfully. Their surface and internal qualities were found to be better than those of ingots and easily acceptable for the forging or rolling process.

1 Results of computer simulation

1.1 Liquid steel temperature during casting

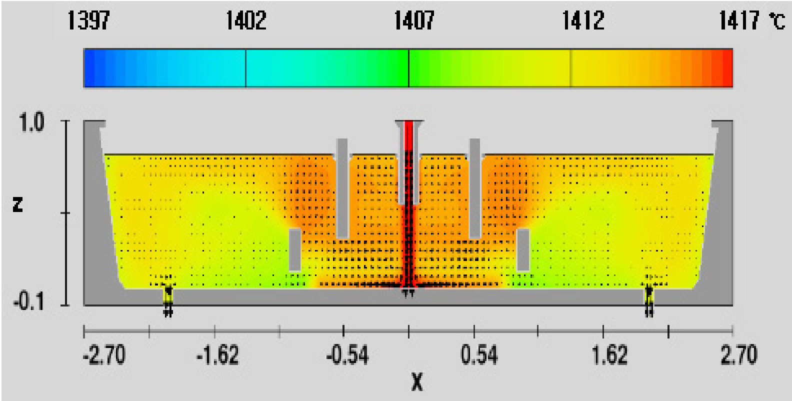
As the casting speed of the LICC is low (in the range of 0.05–0.2 m.min^{-1}), the temperature of the liquid steel at the exit of the tundish is important in order to prevent liquid steel from clogging the tundish nozzle. The calculated temperature at the exit of the tundish, obtained using ANSYSFLUENT (a commercial CFD tool), is shown in Figure 1. From the figure, one may see that this temperature dropped 5 degrees during a normal casting compared with the temperature at the exit of the ladle shroud nozzle and it dropped 7 degrees at the casting end after the ladle pouring was stopped. The total temperature drop of the liquid steel temperature is 12 degrees from when the pouring of the ladle begins to the end of casting. From the above results, it can be concluded that it is possible to successfully cast 30 tons of liquid steel with a superheat of 30 degrees to produce a 770×770 mm^2 bloom section size with a casting speed of 0.1 m.min^{-1} without tundish nozzle clogging.

1.2 Fluid flow in the mold

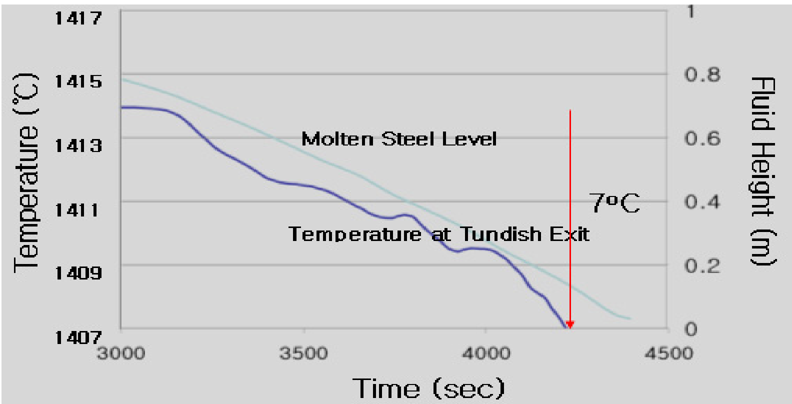
Calculations of the fluid flow in the mold are needed for various types of submerged entry nozzles (SENs) in order to reduce the mold-level fluctuation and obtain a homogeneous hot liquid steel surface below the mold powder since we have no experience with a continuous casting mold of extra-large section size.

The fluid flow and temperature in the mold were calculated for the three cases of single-, two- and four-port nozzles by using ANSYSFLUENT. We used the k-ϵ model for this simulation. From the results, we observed that a nozzle with all four ports facing up is found to be the most favorable among the three cases for maintaining the melt surface temperature with a lower melt velocity at the melt surface. The melt flow from both the four-port and two-port nozzles encountered a solidifying shell and either remelted the shell or retarded solidification. This calculation was needed to determine the proper submerged depth, angle of the ports and size of the ports.

The effect of various conditions such as the immersion depth, angle of the ports, inner and outer diameter, and area of the ports for the four-port nozzles on the melt flow and temperature in the mold was studied. These conditions were changed as shown in



(a)



(b)

Fig. 1. Temperature drop of liquid steel in a tundish. (a) The steady state, (b) after the close of a ladle nozzle.

Table 1. In the table, the immersion depth for case 2 is listed as 180 mm, which is deeper than those of cases 1, 3 and 4, all of which have the same depth (150 mm). The submerged entry nozzle port angle in case 4 is tilted 5° up with respect to horizontal and is smaller than those in cases 1, 2 and 3, which are 15° upward. The inner and outer diameters of the SEN in case 3 are greater than the corresponding diameters for cases 1, 2 and 4. The area of the ports in case 3 is greater than the corresponding port areas for cases 1, 2 and 4. The calculation results are shown in Figure 2. From the figure, it can be seen that more remelting of the solidifying shell occurred with decreasing the upward tilt of the angle of the ports, increasing the area of the ports, and decreasing the submerged depth such as in cases 4, 3 and 2 respectively, compared with case 1. Cases 3 and 4 were found to enlarge the remelting region. From the viewpoint of the homogeneous hot temperature of the melt surface in the mold, we observe that case 1 is the best of all the cases. Therefore, case 1 was selected as the SEN for the plant test without a mold EMS (electromagnetic stirrer).

The modeling with a rotational mold EMS was carried out in two steps as described below. The electromagnetic fields were calculated from the EMAG module in ANSYSFLUENT in order to consider the mold EMS effects and were tuned according to the measured data in the mold equipped with a mold EMS during the cold test. The fluid behavior of molten steel was analyzed by being coupled with the electromagnetic fields in ANSYSFLUENT. Using the calculated flow fields, we carried out solidification modeling, where we employed the enthalpy-porosity method. When a mold EMS was applied, the fluid flow

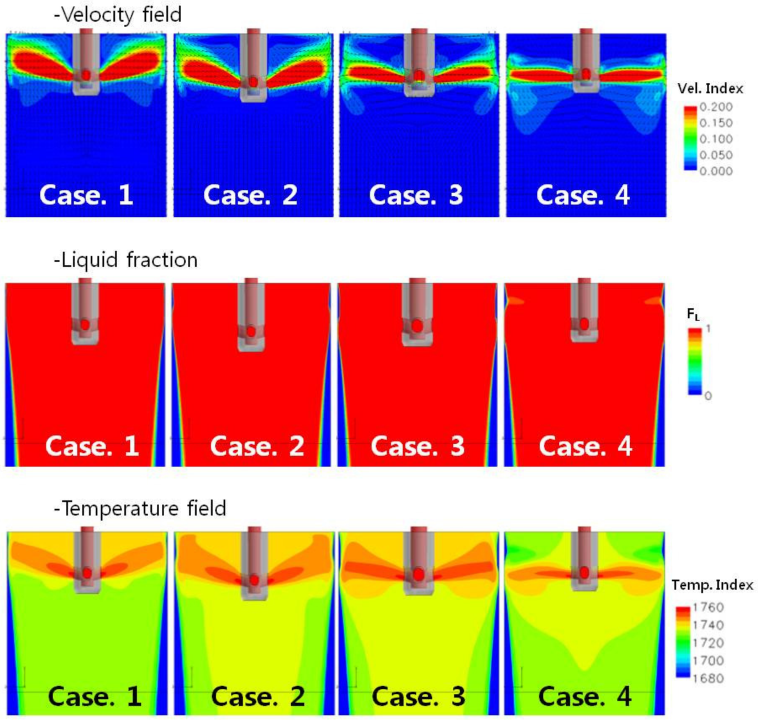


Fig. 2. Contours of the velocity and temperature fields in the mold with the various submerged entry nozzles (SENs).

Table 1. Various SEN conditions for the calculation.

Conditions	Case. 1	Case. 2	Case. 3	Case. 4
Immersion depth	150 mm	180 mm	150 mm	150 mm
Port angle	15°	15°	15°	5°
SEN I.D	55 mm	55 mm	75 mm	55 mm
SEN O.D	120 mm	120 mm	140 mm	120 mm
Port size	55 × 38	55 × 38	65 × 48	55 × 38

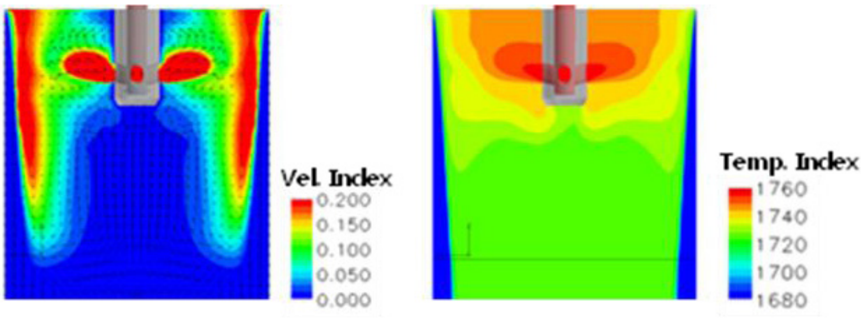


Fig. 3. Contours of the velocity and temperature fields in the mold with the adopted submerged entry nozzle (SEN).

and temperature in the mold were calculated for various submerged entry nozzles on the basis of case 1 in Figure 2. By selecting the proper submerged entry nozzle with the mold EMS, the stability of the liquid steel level and the homogeneous hot liquid temperature below the mold powder could be obtained as shown in Figure 3.

1.3 Solidification profile

In order to understand the solidification of the extra-large section size continuous casting, computer simulations by FLOW-3D® were carried out for various casting conditions such as cooling zone length, casting speed, mold electromagnetic stirring and top heating. We used a latent heat recovery method for this simulation. From the calculated results it can be seen that there exist certain casting speeds where the casting operation remains safe.

Figure 4 shows the contours of the solid fraction profiles with secondary cooling zone lengths. As the cooling zone length increases irregular solidification can easily occur causing central defects such as segregation, porosities and V-segregation where the resulting forms are referred to as mini-ingots as reported by Alberny [1]. It was also found that another irregular solidification occurred in the upper region of the LICC ingot without top heating and insulation regardless of the cooling zone length. It is thought to be necessary to overcome the irregular solidification in the upper region of the LICC ingot by applying heat from the outside, insulating heat from the top, or stirring the residual liquid in the upper region.

Therefore, we tried to simulate solidification when applying input heat and stirring to the region. The solid fraction profiles with top heating and stirring are shown in Figure 5. We note that (1) the shape of the solidification profile on the top of the strand is desirable and (2) the minimum top shrinkage pipe is expected.

1.4 Bulging amount

In order to decide whether or not to adapt supporting rolls to the strand, it was necessary to calculate how much bulging would occur in the strand of the LICC during casting. The amount of bulging was calculated based on the calculated solidification profile, and we then estimated whether cracks could occur or not during casting without supporting rolls, as shown in Figure 6. From the investigation of the amount of bulging of the solidifying shell from the viewpoint of crack occurrence, it was found that it could be ensured that there would be no crack in the LICC strand without supporting rolls because the calculated amount of bulging strain for the solidifying shell in the LICC strand was as small as in the bloom strand of the Pohang Works.

2 Hot simulation results

12 tons of liquid steel were poured into the ingot mold of dimensions 710–770 × 710–770 × 3000 mm^3, and the basic design data for the pusher was obtained. The position and pushing force of the pusher were determined from computer simulations and

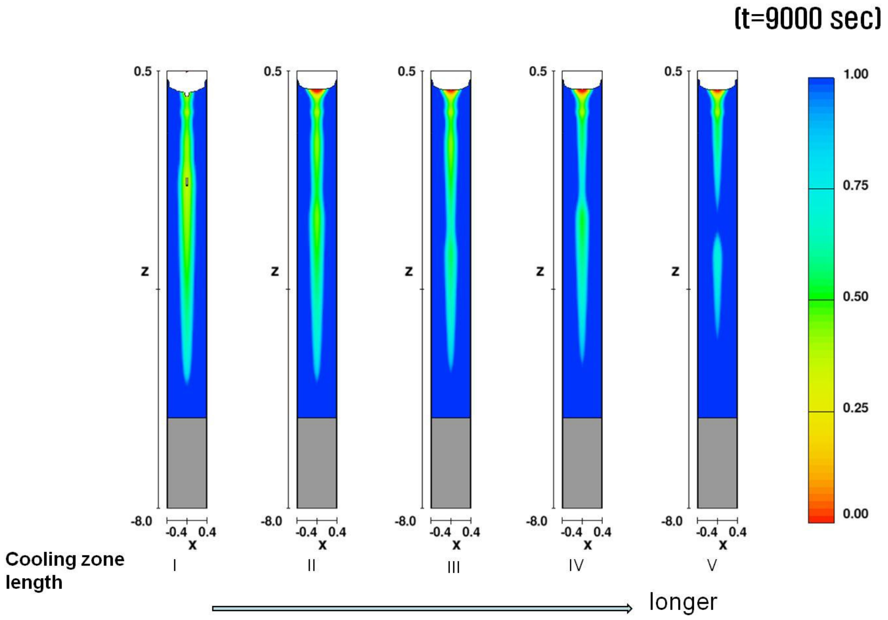


Fig. 4. Solid fraction profiles for various secondary cooling zone lengths.

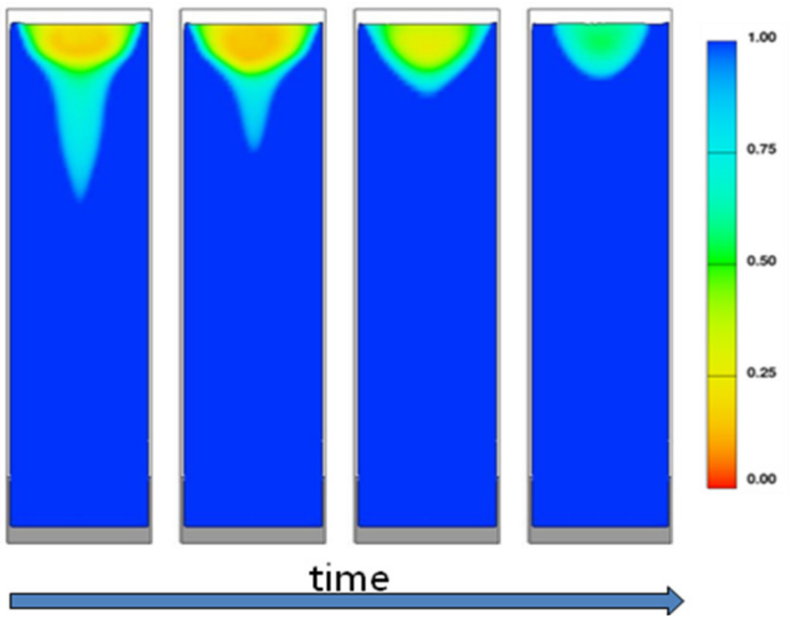


Fig. 5. Evolution of the solid fraction profiles with top heating & stirring.

the hot simulation results. The proper two positions of the pusher on the ingot were determined after computer simulations by testing various combinations of two positions using Adams, the dynamic analysis simulation tool. In the calculation, the important factor represented by the friction coefficient between the ingot and the well block during the separation of the ingot from the well block was estimated from the variation of the measured force with time from the hot simulation tests. The starting time of the separation was 300 min after the end of the casting, based on observations of the complete solidification time at an ingot plant. This assumption was proven afterwards to

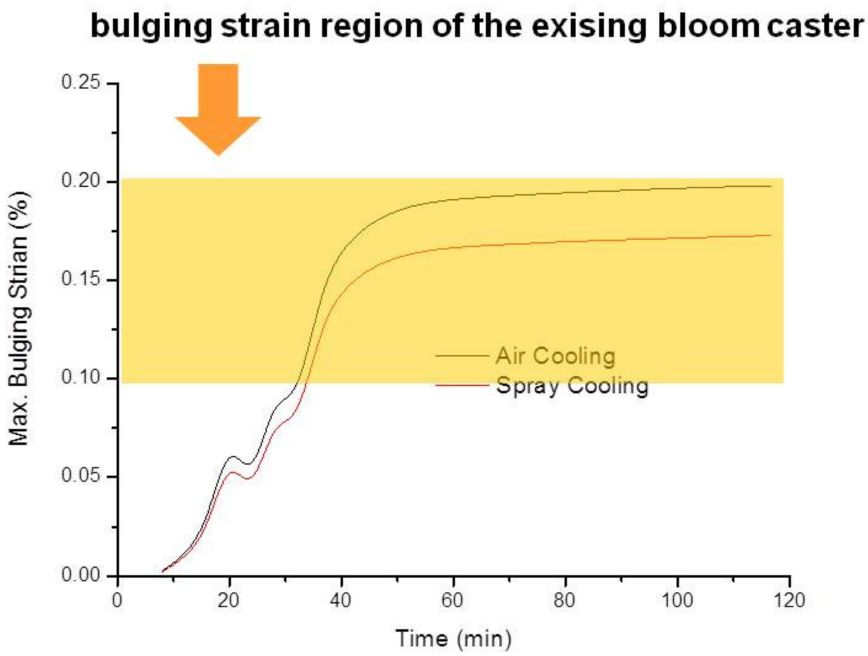


Fig. 6. Evolution of the calculated maximum bulging strain with casting time.

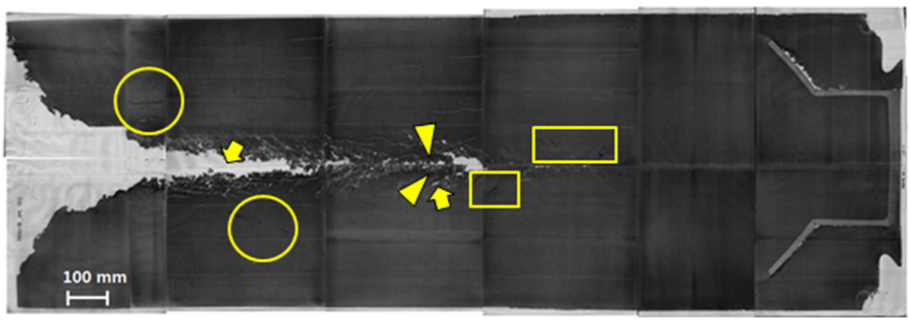


Fig. 7. Cast structure of the 12-ton ingot simulator, which is similar to the LICC strand.

be correct from an examination of the lack of movement trace in the macro-structure of the ingot sections.

The cast structure of a 12-ton ingot similar to the shape of the LICC strand was investigated from the macro-structure of entire longitudinal slices taken from the ingot. In Figure 7, the A-segregation and V-segregation explained by Flemings [2], center porosity or the pipe including the top pipe, and center segregation are marked with the symbols ○, ▭, ⇨, and ▷, respectively. The length of the top pipe including the center porosity for a 12-ton TD11 steel ingot was found to be about 1200 mm and A-, V-, and center segregation existed as well.

3 Operational results

Our own concept and basic design were prepared and a pilot caster, the mold size of which was $700 \times 700 \times 800$ mm^3, was built at the Melting and Casting Laboratories in POSCO's Pohang Works. Figure 8 shows a 3-D representation of the pilot LICC composed of a mold EMS, an oscillator, a withdrawer, the pusher and the tilter. The hot test scene is shown in Figure 9, and it can be seen that the molten steel was fed directly into the mold without a tundish. To date, more than 90 heats of 12-ton liquid steel per heat for various steel grades have been cast through the caster without any negative effects on the equipment or operations.

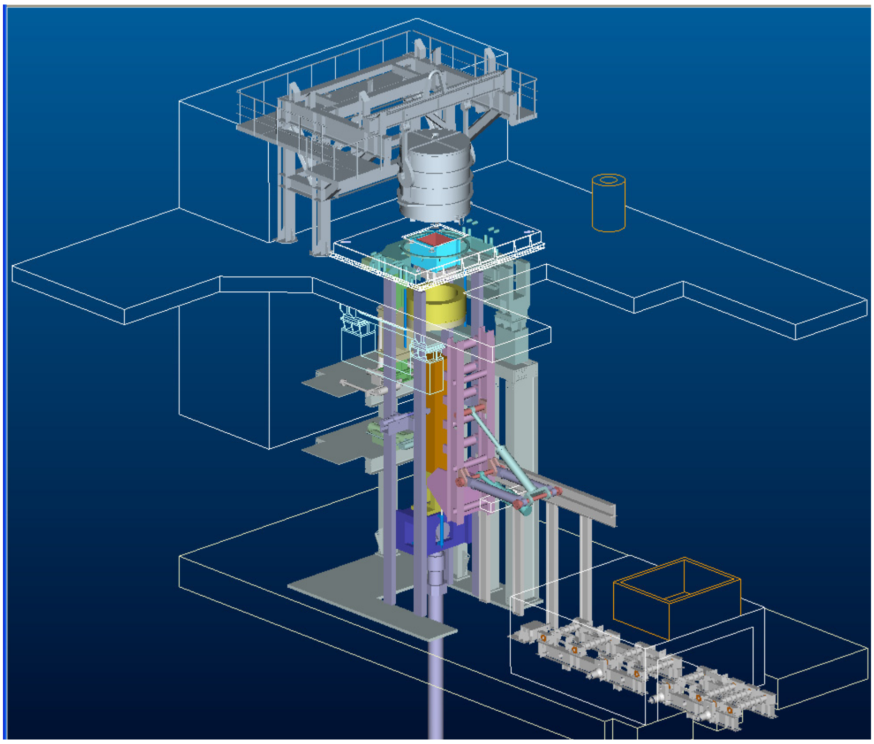


Fig. 8. 3-D diagram of the pilot LICC.

Fig. 9. Hot test scene on the casting floor.

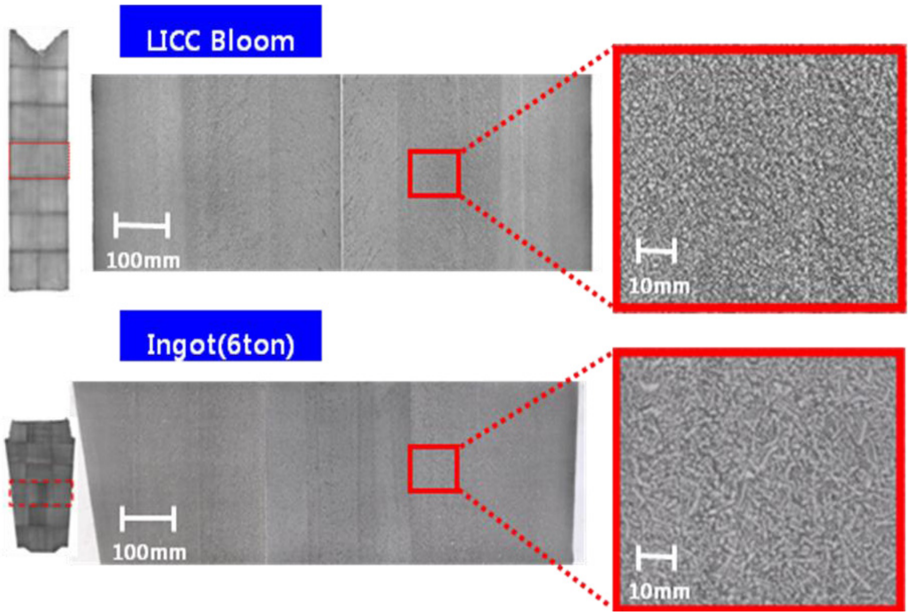


Fig. 10. Cast structure of the LICC bloom and 6-ton ingot.

Both the surface and inner qualities of the LICC strand were found to be better than those of the ingot. The equiaxed zone was enlarged and its structure was found to be compactly composed of fine globular crystals (Fig. 10). From heating and stirring of the molten steel in the upper region of the LICC strand, the shrinkage pipe was also greatly reduced from L to $0.23L$ by applying the top heating and stirring methods (Fig. 11).

It was thought to be necessary to improve the internal quality in order to produce TD11-grade steel containing very high levels of carbon and chromium through the LICC process even though internal defects such as A-, V- and center segregation, and center porosities or the pipe are apt to occur during an ingot process. After various trials in which more than 60 heats were cast, the LICC ingots were cut along the longitudinal center plane from top to bottom and the specimens taken from them with a thickness of 20 mm were machined, polished and etched in order to determine their macro-structures. To evaluate the internal quality from the macrostructures, standard grades were introduced from 1 to 5 representing evaluations of “very bad”, “bad”, “normal”, “good” and “very good”, respectively for four categories of internal quality which are thought to be A-, V- and centersegregation, and the center porosities or the pipe including the top pipe. Segregation spots around the top pipe were included in the category of A-segregation in this evaluation. The total sum of each grade for a macrostructure (where this sum is in the range 4–20) was used to express the internal soundness of the LICC strand. From investigating the evaluation results of the macrostructures, the casting speed, casting temperature, stirring and temperature gradient of the strand were found to be the vital fiew parameters representing the internal quality.

The test results are shown in Figure 12. It can be seen that the internal quality of the LICC strand was improved by decreasing the casting speed and casting temperature as reported in the papers on continuous casting strands [3–6]. Stirrings could deteriorate or improve the internal quality depending on the conditions of the particular case, which suggests that proper stirring conditions are necessary for the LICC process. The LICC strand moves downward at the end of casting, stands at the given position, and stays until complete solidification. During this time, the mold EMS under stirring operation also moves downward following the strand and it stands at the upper part of the strand until solidification occurs, and stirring stops at the end of solidification.

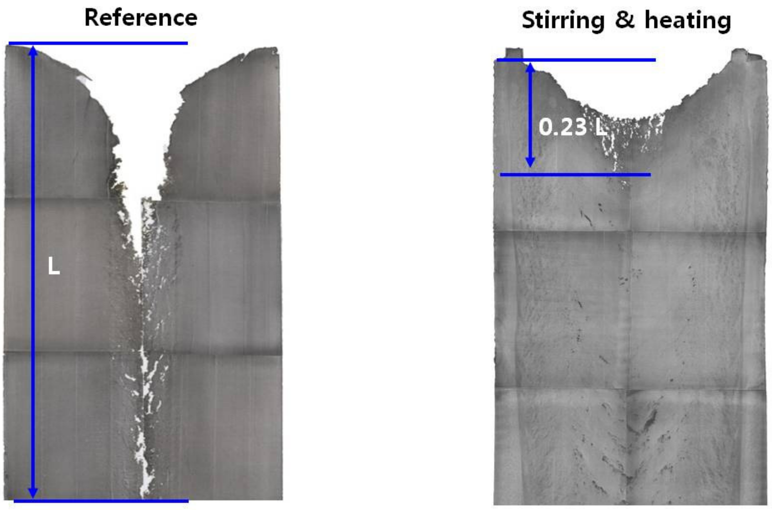


Fig. 11. Effect of top heating and stirring on the shrinkage pipe of the LICC strand.

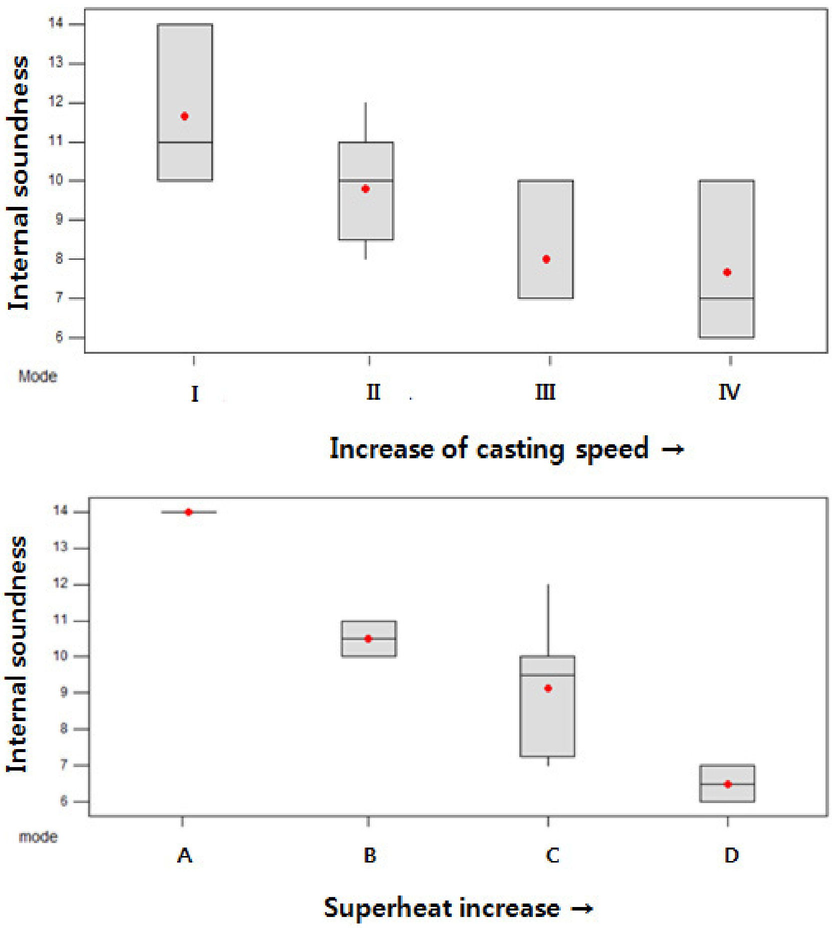


Fig. 12. Effect of the casting speed (top) and superheat (bottom) of the molten steel on the internal soundness of the LICC strand.

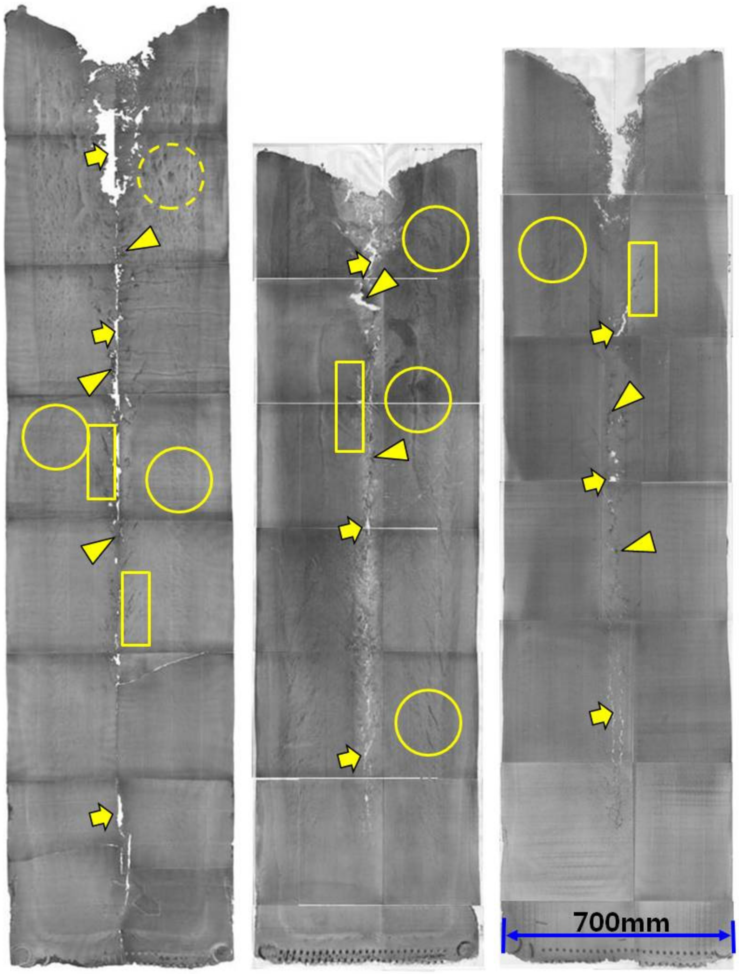


Fig. 13. Improved longitudinal macro-structure of the LICC strand (700 × 700 mm^2 cross-section size).

Stirring in one direction during this period was found to deteriorate the internal soundness as many segregation spots around the top pipe were formed (see the photograph of Ref. [1] in Fig. 13). The segregation spots are thought to be a different type of segregation compared with those in other ingots or CC strands. It is presumed that they could be formed by a constant flow pattern during solidification, and solute-enriched residual melt could penetrate into the solidification shrinkage in the direction of the magnetic force. In cases where the direction of stirring was alternated during the period, this alternating stirring direction was found to improve the internal soundness considerably and resulted in a lack of the segregation spots. The temperature gradient in the final stage of solidification was found to have an effect on the pipe formation [7,8] in the center region of the LICC strand.

From the proper combination of these conditions, the internal quality was much improved. The macrostructure with the proper combination of the vital few parameters is shown in Figure 13 together with those of the references In the figure can be seen examples of A-segregation, V-segregation, center porosity or the pipe including the top pipe, and center segregation marked with the symbols ○, ▭, ⇨, and ▷, respectively. There are segregation spots around the top pipe marked with the symbol ◌ in the macrostructure of reference [1]; they

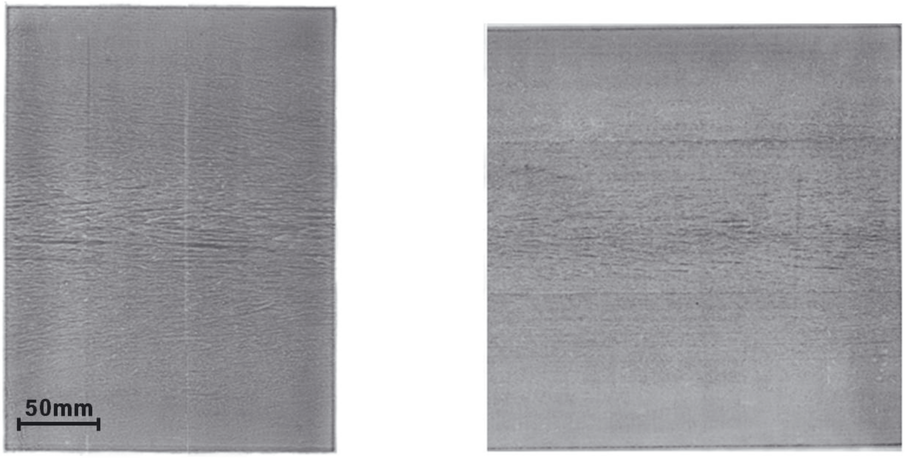


Fig. 14. Macro-structure of a forged bloom from a 6-ton ingot (left) and of a rolled bloom from the LICC strand (right).

were included in the A-segregation category in this paper for practical reasons from the viewpoint that the positions where they most frequently occur are similar to those of the A-segregation around the top pipe and since they have not been previously reported under any particular name. From examination of the macrostructures, it was found that A-segregation even appeared along the perimeter of an entire line around the strand and some center porosities occurred after solidification without any accompanying segregation. Aside from the situation described above, the macro-structures in the top region were similar to those in a conventional ingot while the macro-structures below the top region were similar to those in a continuously cast strand. As shown in the figure, it can be seen that the A-, V- and center segregation and center porosities or the pipe (including the top pipe) with the proper combination of the vital few parameters were remarkably reduced compared with the references.

The macro-structure of the rolled bloom for TD11 steel from the LICC strand is shown in Figure 14, and it can be seen that the rolled bloom has excellent internal soundness compared with that from the ingot.

4 Summaries

From the large ingot continuous caster (LICC) developed by POSCO, most steel grades such as mediumcarbon structural steels, stainless steels and tool steels could be cast successfully and confidently. Their surface and internal qualities were found to be better than those of ingots and easily acceptable for the forging or rolling process. We were able not only to design a continuous casting plant from concept design to detailed design but also to operate a new caster by ourselves. The equiaxed zone was much enlarged and its structure was found to be compactly composed of fine globular crystals. The shrinkage pipe was also greatly reduced from L to $0.23L$ by top heating and stirring.

The internal quality of the LICC strand was improved by decreasing the casting speed and casting temperature as reported in the papers on continuous casting strands. Stirrings could deteriorate or improve the internal quality depending on the conditions of the particular case, which suggests that proper stirring conditions are necessary for the LICC process. The temperature gradient in the final stage of the solidification was found to have a dominant effect on the pipe formation in the center region of the LICC strand. The internal quality of the LICC strand for TD11 steel was much improved by using the optimum combination of these parameters and the rolled bloom from the LICC strand has excellent internal soundness.

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