Advances in Strip Surface Quality from Thin Slab Casters

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Abstract

Minimills with thin slab casting have become rivals to those with conventional slab casting. Today, very few conventional slab casters are being built or planned. The reasons for this are, among other things, the thin slab process is more cost-effective in that less rolling reheating and rolling are required. Other advantages include the potential replacement of cold rolled band by hot rolled band, location, often requiring less transportation and staffing, where minimills often operate with an extremely thin organization.

A major advantage for the conventional slab casters has been steel quality, especially in terms of cleanliness and mold powder entrapment. However, this concern has been dramatically reduced for thin slab casters with the introduction of the ABB ElectroMagnetic BRake (EMBR). The first EMBR test installation for thin slabs was made at Nucor Steel, Crawfordsville, IN. That equipment was later moved to Nucor Steel Berkeley, SC and subsequently, the second CSP strand installed in Berkeley was also equipped with EMBR. As the Berkeley plant uses an optical surface defect detection system after the hot rolling, it is an ideal installation for checking the effectiveness of the EMBR. Recent results show that with the EMBR, mold powder entrapment in hot rolled coil can be reduced by as much as 95%, all the while casting at higher casting speeds. These quality improvements coupled with operating cost reductions, for example, increase of mold life, enables Nucor to compete more effectively with the conventional slab casters.

Within ABB, substantial efforts have been made during the 90's to understand and optimize the use of EMBR (and stirrers) by computer simulations. As the different casting processes create turbulence in the mold, transient simulations are required. ABB has developed a simulation package that allows us to run transient simulations within reasonable computer time. A video will be presented showing how steel flow in a thin slab caster with a tapered mold is influenced and calmed down when using the EMBR. This video explains a great deal of the results obtained from thin slab caster installations.

The result of the introduction of the EMBR to the thin slab casting process is that today, thin slab casters can compete very effectively with the conventional slab casters, particularly on quality levels.

1. The development of thin slab casting

After the introduction of CSP® by SMS Schloemann Siemag (today SMS Demag), the start of the first CSP plant followed in 1989 at Nucor Steel, Crawfordsville, IN, USA. Plant engineering and the degree of automation together with caster productivity and metallurgical results have since then been developed further so that today practically only thin slab casters are being considered for installation. At present, some 35 thin slab plants are in operation or scheduled, worldwide, of which 25 are CSP plants. With the start-up of the Terni CSP plant in Italy, thinslabs are also used for stainless steels.
By increasing casting speed to above 6 m/min and by extending plant utilization time, the annual production volumes have been continuously increased. Today, the standard achieved with regard to product quality and output in CSP plants can be compared with those of integrated steel plants. An essential prerequisite here is the funnel-shaped mold developed by SMS-Demag (Figure 1).

![Figure 1. CSP mold with submerged entry nozzle.](image1)

In spite of the optimized mold and Submerged Entry Nozzle (SEN) geometry obtained by water modeling (Fig. 2) and computer simulations, the increase of the casting speed beyond 6 m/min leads to increasingly unstable flow conditions which might adversely influence the surface quality.

By using the ElectroMagnetic Brake (EMBR), the flow conditions in the mold can be controlled as a function of the casting width, the casting speed, the steel grade, the superheat and the SEN geometry. This means that by using an ElectroMagnetic Brake it is possible to achieve a good and reproducible surface quality within a wide range of casting speeds and steel grades while ensuring a high operational safety.

2. EMBR function and equipment

Production of steel with high demands on cleanliness requires good control of both chemistry and fluid flow in the continuous casting process. The problem with too high flow speeds in continuous casting and associated problems with non-metallic inclusions was addressed by ABB and KSC (Kawasaki Steel Corp) at the beginning of the 1980s during the pioneering work on the electromagnetic brake technology for normal slabs.

The EMBR brakes the steel flow by applying a static magnetic field across the mold, perpendicular to the casting direction. The steel flow induces voltages and thus electric currents in the melt and these currents together with the static field produce a braking force opposite to the steel movements. The higher the casting speed, the higher will be the speed of the steel and the larger will be the braking force. The reduction in steel velocity and turbulence provides many benefits, such as increased cleanliness, fewer rejects and a possibility to increase the casting speed.

At the beginning of the 1990s, development leading to a further improvement of the EMBR was made with a single magnetic field covering the total width of the thin slab or the EMBR Ruler (Figure 3). The corresponding configuration with surrounding yoke and two...
iron cores with part coils is shown in Figure 4. The first commercial installation in a thin slab caster used the EMBR Ruler and today, it is used in most thin slab casters.

Currently, there are two designs for the EMBR ruler:

- **Integrated design** (Figure 5), the old design. The part coils, the magnetic cores and yoke are built into the mold and go in and out of the caster with the mold. This principle gives a small air gap with corresponding lower power demand, but the EMBR part coils have to be (dis)connected at mold exchange and the oscillation mechanism has to support the extra weight, typically 5–10 tons. This design is normally used for existing casters.

- **Window design** (Figure 6 and 7). A non-oscillating magnetic yoke surrounds the mold. From this yoke, movable magnetic iron cores are guiding the field to the mold. The part coils are mounted on the iron cores that move in through windows in the water jackets to minimize the non-magnetic gap. These windows are large enough to allow for the oscillation to take place. The non-oscillating iron cores and part coils are retracted and remain in the caster during mold exchange. This design is normally used for new casters.
The EMBR normally used today for thinslabs is of the Ruler type, window design. The mechanical equipment involved is shown in Figure 7 below. Although this equipment weight is several tons, there is no harmful effect on the mold oscillation as the oscillation mass is not increased thanks to the window design.

![Figure 7. The EMBR mechanical equipment for a thinslab caster](image)

An alternative solution, especially for the integrated EMBR type in order to reduce the carry on weight, is the original **EMBR Local Field**, where the magnetic fields cover only part of the strand width (Figure 8). This solution has received renewed interest for existing thin slab casters. The corresponding configuration has no yoke surrounding the mold and, consequently, it is less heavy (Figure 9).

![Figure 8. EMBR Local Field. The left part is shown without EMBR and the right part with EMBR. Important differences are highlighted.](image)

![Figure 9. EMBR Local Field with two yokes and four cores with part coils guiding the magnetic field towards the mold.](image)
The main EMBR electrical equipment consists of a power transformer, thyristor converter, control cubicle, EMBR coil(s) and a cooling water station (Figure 10).

![Figure 10. The EMBR electric and cooling water equipment.](image)

The EMBR coil (for one mold) converts the direct current from the thyristor converter into a static magnetic field. The EMBR Ruler coil consists of two part coils, one on each side of the mold. The part coils together with iron cores and magnetic yokes form a magnetic circuit with a 200-400 mm long non-magnetic gap across the mold. The magnetic field in the non-magnetic gap covers substantially the entire width of the mold.

The part coils contain the electric windings and are enclosed in austenitic stainless sheet steel cases. They are normally designed to fit each individual mold. The electric windings (hollow copper sections) in the different part coils are electrically connected in series and cooled by de-ionized water from the closed loop cooling water system.

3. Metallurgical results

Thin slab casting imparts increased demands on the casting process. The casting speed compared to conventional slab casting is up to six times higher, which means meniscus turbulence increases leading to mold powder entrapment. Likewise, steel residence time in the mold will become too short for separation of normal-sized inclusions and argon bubbles. The steel in thin slab casting is therefore always Ca-treated so that the inclusions coming with the steel do not clog the SEN but remain very small and thus harmless. Consequently, no clogging of the SEN occurs and thus argon use is not required. Further, the narrower the mold thickness, the greater will be the tendency for asymmetric steel flow, which leads to a wave generation at the mold narrow sides resulting in risk for mold powder entrapment.

The EMBR results from thin slab casting show the same beneficial effects as has been established for normal slab casting, but with the difference that the need for an EMBR is still further increased for thin slab casting. Thus, most of the new thin slab caster installations have included EMBR.

By using an EMBR, the steel flow speed is lowered and the “standing” wave close to the mold narrow side is reduced. An imprint of the meniscus profile can be obtained by dipping down a thin steel sheet in the mold and letting it melt off (Figure 11). As reported by Nucor Steel, Berkeley, casting at 5 m/min through a 4-port nozzle without EMBR produces a 15 mm wave. With EMBR, the maximum wave is 4 mm.
Figure 11. The standing wave close to the narrow side in a thin slab is reduced when using the EMBR.

However, the most important advantage of having a flat meniscus is that the metal flow speed below the meniscus is reduced and therefore, so is the risk for vortices and mold powder entrapment or inclusions. Without EMBR, these inclusions increase considerably at high throughput (>3.5 tons/m) as shown in Figure 12. These inclusions are trapped below the surface of the slab and are brought towards the surface during rolling. Therefore, the best possibility to detect them is after hot rolling. The use of an automatic surface inspection system is then vital for reliable detection, failure classification and statistical treatment.

Figure 13 and Figure 14 are prints from an optical surface inspection system showing the top surface (left parts) of two coils, where corresponding slabs were cast at a high speed without and with EMBR, respectively. The red marks are mold powder entrapment. The scales on the top and left of the print show the longitudinal and transverse distribution of the defects in the coils.

Figure 13. Coil upper surface defects after hot rolling. Without EMBR.

Figure 14. Coil upper surface defects after hot rolling. With EMBR.
Results from normal operation show that the decrease of surface defects resulting from the use of EMBR can give savings in customer rejects of about 1.75 USD per ton. This achievement has enabled Nucor Berkeley to enter new market segments, namely white products. Reliable product quality to these more demanding market segments could not have been realized without the use of EMBR.

As EMBR reduces the turbulence in the molten steel, the heat transfer to the solidified shell is also reduced, resulting in a higher steel temperature (Figure 15). Here, the steel superheat is shown as a function of the tundish superheat, with and without EMBR. The average temperature increase using the EMBR is approximately 10° F (5.5° C).

![Figure 15. Meniscus superheat versus tundish superheat with / without EMBR](image)

![Figure 16. EMBR increases the lifetime of the mold copper plates due to less temperature cycling](image)

Another equally important result of a flatter and more stable bath level profile is that the temperature cycling of the mold copper plates at meniscus level is reduced, see Figure 16. The lubrication between the solidified shell and copper plate is more uniform, resulting in a reduction of the mold copper plate distortion. Results from operations show that the life of the mold copper plates can be significantly increased at high throughput, and with corresponding savings.

4. Computer simulations

Over the years, a great deal of experimental and computational work has been done to optimize the EMBR for different casting situations. Metallurgical feedback from full-scale installations, in combination with ABB’s 3D computer simulations of the electromagnetic field and the fluid flow, has resulted in a good understanding of how the EMBR works and how to optimize it.

The mathematical modeling of turbulent flow and the numerical solution of the resulting partial differential transport equations have reached robust and reliable engineering levels today. Computer codes that solve the 3D turbulent fluid flow fluid have been available for several years.

Mathematical modeling of fluid flow in the continuous casting mold involves utilization of Navier Stoke's equations, a turbulence model modified for transient simulations, transport equations for gas bubbles, inclusions, temperature, etc., together with Maxwell's equations for the electromagnetic field.
The turbulent recirculating flow in the mold gives rise to characteristic low-frequency (0.05-0.15 Hz) velocity and meniscus level oscillations. Transient Large Eddy Simulations (LES) are needed to model these phenomena (Figure 17). This figure shows the meniscus velocity for a thin slab (50x1300 mm at 5.5 m/min, EMBR switched on at 400 seconds) and is the results from an ABB-LES transient model and illustrates how the EMBR dampens these oscillations.

![Figure 17. LES simulation showing the reduction of low-frequency oscillations in a thin slab mold when the EMBR is switched on at 400 seconds.](image)

**Conclusions**

Since the introduction of the CSP® by SMS Schloemann Siemag (today SMS Demag) and the start of the first CSP plant in 1989, this thin slab technology has achieved commercial success and today nearly 30 million tons/year are cast. The reason for this is the worldwide patented funnel-shaped mold and well proven equipment, that ensures reliable high production and good product quality. Today, the CSP technology features a high degree of process automation as well as hydraulic oscillation, hydraulic segment adjustment, liquid core reduction and soft reduction.

The introduction of the EMBR to high-speed thin slab casting has made it possible to maintain the high quality standards in terms of mold powder entrapment achieved in conventional slab casting. This has opened up new market segments for the minimills and allowed them to compete effectively with the integrated mills for more demanding grades and applications. With EMBR, the bath level profile becomes flat and stable, which ensures a uniform mold powder distribution and improves the lifetime of the mold copper plates.

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