Recent developments of electromagnetic actuators for continuous casting of long and flat products

Electromagnetic actuators for continuous casting machines can be divided into two categories: electromagnetic stirrers (EMS) and electromagnetic brakes (EMB). Although they may be described as mature technologies, recent developments of Multi-Mode® EMS and Multi-Mode® EMB intelligently control the liquid steel in the mould to drastically reduce the occurrence of steelmaking defects on as-cast and finished products. These developments cover the full range of slab thickness and casting speeds.

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ELECTROMAGNETIC ACTUATORS

Electromagnetic actuators for continuous casting machines can be divided into two categories, electromagnetic stirrers (EMS) and electromagnetic brakes (EMB). The abbreviations are used both for the processes, ie, stirring and braking, as well as for the devices, ie, stirrers and brakes. (The designation EMB refers specifically to the EMB systems commercialised by ABB.)

The common purpose of both EMS and EMB is to control the liquid steel flow during casting in order to improve productivity and product quality. The difference is that EMS uses dynamic magnetic fields which are rotating or travelling, ie, two- or three-phase inductors with AC currents like the stators of AC induction motors, whereas EMB uses static magnetic fields, ie, single-phase DC currents like the electromagnet of eddy current brakes. EMS is used for long and flat products, EMB for flat products only.

EMS and EMB were developed in the 1970s and 1980s, respectively, and are considered mature technologies. It might therefore be surprising that there are still recent developments worth describing. Moreover, in many meetings with caster suppliers and steelmaking companies, we have noticed a general lack of knowledge or even misunderstanding about the various EMS and EMB applications. The purpose of this paper is to review the different applications and to present recent developments.

EMS FOR BILLETS/BLOOMS

State of the art: For long products, EMS is used in the mould (M-EMS), in the secondary cooling zone or the strand area (S-EMS), and in the final solidification zone (F-EMS) [1]. All three applications use rotating magnetic fields with so-called rotative stirrers. Travelling magnetic fields for S-EMS and F-EMS have been abandoned because of poor efficiency. Historically, EMS started with S-EMS to improve the internal solidification structure in terms of equiaxed zone, centre segregation and centre porosity of billets and blooms. Today, however, approximately 90% of the applications are M-EMS. Its great success is due to the fact that it improves not only surface and subsurface quality of billets and blooms, but also its internal solidification structure (and even better than S-EMS). M-EMS always uses low frequency current below 10Hz. If 50Hz or 60Hz were used (which would be easier for the electrical power supply as there would be no need for a frequency converter) this would have practically no effect on the liquid steel because the major part of the magnetic field would be consumed for induction heating of the mould copper tube. S and F-EMS use either network frequency or low frequency current, depending on the section size. S-EMS on its own has been replaced almost completely by M-EMS, but is sometimes still used in combination with M-EMS to eliminate remaining centre porosities. The more frequently used combination is M+F-EMS to further reduce centre segregation in high carbon and high alloyed steel grades.

New jumbo stirrers: The recent tendency to cast ever larger sections led us to build larger stirrers that go beyond the common experience, and so cannot be designed by simple extrapolation from the smaller sizes.

For mould stirrers, one problem is due to the fact that mould height does not increase for these large diameters. As a result of the limited available space (height) the stirrers become flatter (the aspect ratio stirrer-diameter over stirrer-height becomes two or more) which is extremely unfavourable for magnetic performance and requires
great care in checking the design criteria. Danieli Rotelec has adapted the commercially available software tools that now show excellent agreement between simulation and measurements after the stirrer has been built (see Figure 1), and electromagnetic simulations followed by CFD simulations have been carried out to revise the design criteria.

For final stirrers, we do not have the problem of height limitation but, because of the longer and larger diameter stirrers in use, heat radiation from the bloom becomes another issue so that here also, we need new design criteria to avoid deformation of the stirrer casing.

The largest mould stirrer we ever built has an external diameter of 2m yet is only 610mm high (see Figure 2). It is used on a semi-continuous vertical caster for 700-770mm square blooms. At the end of the cast, the bloom is stopped below the mould to complete solidification, the stirrer is then moved below the mould and continues to stir the top of the bloom during its ongoing solidification. The equiaxed zone width obtained with this process is almost 100% and the top shrinkage cavity is reduced to 300mm from 800mm typically (see Figure 3).

STRAND EMS FOR SLABS

State-of-the-art S-EMS: As for long products, strand EMS for slabs is used to improve the internal solidification structure in terms of increased equiaxed zone and decreased centre porosity and centre segregation[2]. Unlike long products, however, slabs require linear inductors with horizontally travelling magnetic fields that generate a thrust pushing the liquid steel horizontally across the slab width, thus generating the so-called butterfly stirring pattern. Such an effect can be produced either with box-type EMS positioned on the inside radius of the machine behind the mechanical guiding rolls, or with in-roll EMS where two stirring rolls are positioned either side on the inside radius or face-to-face on the inside and outside radii. In-roll EMS has far better efficiency because of the reduced distance between stirrer and slab – its electrical power consumption is approximately three times less than that of the box-type EMS. It is particularly recommended, therefore, for double-stage EMS, ie, one pair of rolls in an upper and one in a lower position. Double-stage EMS with box-type design would mean excessive investment and running costs.

Double-stage EMS does, however, generate a triple zero stirring pattern (see Figure 4) that moves the liquid steel over a longer distance in the strand and therefore achieves better metallurgical results, particularly when casting at higher superheat.

New In-Roll EMS for wide slabs: Historically, in-roll EMS was limited to conventional slab casters with slab
widths up to 1,650mm because the stirring rolls had no intermediate bearings. For larger widths there would be excessive roll deflection because of increased bearing distance, but a mechanical arrangement with back-up rolls to limit the deflection of the stirring rolls is not a satisfactory solution because of maintenance problems for the back-up rolls and short life time for the roll sleeve of the stirring rolls.

To take advantage of stirring rolls for wide slabs, a new version has been developed that permits installation of stirring rolls with intermediate bearings. With this new design, in-roll EMS can be used on large and very large slab casters with roll deflection of less than 0.5mm. A 2,400mm wide slab caster has been equipped with this new design and has been operating successfully for more than two years (see Figure 5).

MOULD EMS AND EMB FOR SLABS

State of the art: EMS or EMB in slab moulds is used to decrease or eliminate the defects generated directly or indirectly by the liquid steel flow in the mould. The defects are related to mould powder entrapment, gas bubbles, non-metallic inclusions, insufficient or inhomogeneous meniscus temperature or insufficient meniscus lubrication, and accumulate mainly in the surface and subsurface region of the slabs. They translate into casting slowdowns due to sticker and breakout alarms and poor slab and cold-rolled coil quality. These defects are generated by inappropriate steel flow in the mould which cannot be controlled by the caster operator, because the flow itself is determined for a given cast by the SEN geometry and slab thickness and during the cast by the actual conditions of casting speed, slab width, SEN immersion depth and argon flow rate that change all the time\[3\]. Therefore the purpose of EMS and EMB in the mould is to correct the naturally existing steel flow and to force it into an optimised flow pattern by using electromagnetic forces.

Two technologies are available:

- **ABB’s EMB**, evolved since the 1980s from EMBr and EMBr-Ruler into different FC-Mould generations and used on thin and thick slabs. This paper will not go into its details, since abundant articles can be found in the literature.

- **Danieli Rototec’s Multi-Mode® EMS**, used for medium thick slabs. It provides three functions for slowing down, accelerating and rotating the liquid steel in the mould (electromagnetic level slow down EMLS, level acceleration EMLA and rotative stirring EMRS). Details of this technology and its results are described in reference \[3\].

So, what is new in this field?
NEW CONCEPT FOR ALL SLAB SECTIONS INCLUDING EMS AND EMB

Controlling slab quality means controlling steel flow in the mould. This general idea is largely accepted now, however, the question of which technology should or should not be used – EMS or EMB, and for which application – still raises opposing views and confusion that might persist due to commercial reasons or ignorance of physics and metallurgy. The following facts should be well understood:

The common belief that liquid steel flow can be stopped with EMB is wrong. Unlike the solid disc of the eddy current brake in trucks and buses, the liquid flow does not go through the ‘obstacle’ of the magnetic field that generates the braking force. Instead it goes around it. If the braking force is strong enough, ie, magnetic field must be strong and liquid velocity must be high, the EMB can act like a wall that changes the flow direction, but neither the flow is stopped nor the direction is controlled.

EMB is a DC electromagnet with a static magnetic field that only generates braking forces in opposite direction and proportional to existing steel velocity. EMS, however, is an AC inductor with a travelling magnetic field that generates braking or accelerating forces parallel to the field velocity and proportional to the differential velocity of steel and field.

Danieli Rotelec’s collaboration with NKK, which started in the 1990s, has confirmed that medium thickness slabs need the meniscus flow to be optimised into a right-left symmetrical double-roll flow, which means one has to accelerate or slow down (brake) the flow exiting from the SEN with electromagnetic forces that push steel symmetrically outwards (from SEN to narrow faces) or inwards (from narrow faces to SEN). This can only be achieved by travelling magnetic fields of EMS with the functions EMLA (acceleration) and EMLS (slow down), respectively. The conventional EMB, whatever the generation is, can only brake; it cannot impose right-left symmetrical forces and cannot accelerate.

Based on this experience we have applied the most recent knowledge on steel defect analysis, fluid flow mechanics and magneto-hydrodynamics calculations, to develop impressive technologies called Multi-Mode® EMS (MM-EMS) and Multi-Mode® EMB. These intelligently control the liquid steel in the mould in order to drastically reduce steelmaking defects occurring on as-cast and finished products. MM-EMS can generate new flow in the selected direction, hence transform arbitrary, unstable or bias flow into stable and right-left symmetrical flow. EMB cannot do this.

Moreover, we propose a concept that evidences which type of flow control must be applied according to slab thickness and casting speed (see Figure 6). This concept...
covers the full range of slab thickness and casting speeds, and is as follows:

- Only braking for very high casting speeds (typically above 5m/min) and thin slab casters
- Braking/accelerating/rotating for high to medium to low casting speeds (in the range ~ 1-3m/min) and medium to thick slabs (in the range 150-300mm)
- Only rotating for very low casting speeds (<1m/min) and very thick slabs (>250mm).

This concept is based on the following considerations:
Steel flow in the mould is, of course, a three-dimensional phenomenon. However, flow control operating in all three dimensions would be extremely difficult, space consuming and expensive. Therefore, we reduce the three-dimensional reality into a two-dimension view, which means we focus either on a plane parallel to the broad slab face or on a plane parallel to the meniscus, depending on which plane the predominant flow is found.

Slab thickness and casting speed are the two parameters that favour one or the other plane:
- For thin slabs, the predominant flow is in the plane parallel to the broad slab faces and for very high casting speeds the flow in the mould is always too fast. Hence, we need only braking forces acting in that plane.
- The thicker the slab and the slower the casting speed (which are related), the more flow goes out of this plane into the direction of slab thickness. Hence, for very thick slabs and very low casting speeds, the plane parallel to the meniscus becomes relevant, and thus the flow control uses electromagnetic forces in that plane, which means it generates rotative flow.
- Between these two extremes, we have the most frequently used medium to thick slabs and medium to high casting speeds. This is the domain of MM-EMS that uses the accelerating/braking/rotating functions of EMLA/EMLS/EMRS. These are used alone or in combination, with the correct mode automatically selected relative to steel grade, section size and casting speed.

According to this concept, the following guidelines can be expressed:

**Thick slabs ~200-300mm, casting speeds ~1-3m/min:** This is the most frequently used range, and we recommend the most flexible tool, ie, MM-EMS, with all three accelerating, braking and rotating functions: EMLA, EMLS, EMRS.

The natural steel flow is either double-roll (high casting speed), unstable (high argon flow) or single-roll (low casting speed and high argon flow). The optimised flow
will be double-roll flow with meniscus velocity in the range 0.2-0.3 m/sec and stable right-left symmetry. This is achieved with the braking (EMLS) function slowing down the too-strong double-roll flow, or with the accelerating function (EMLA) accelerating the too-weak double-roll flow or transforming single-roll and unstable flow into double-roll flow, the stirrers being located at mid-height of the mould.

Certain steel grades develop gas bubbles that are trapped in the solidification front close to the meniscus. For such cases, the rotative stirring (EMRS) is the preferred application. To obtain an efficient rotative flow at the meniscus, the required stirring power is higher than for EMLS and EMLA, the slab must not be too thin, the casting speed not too high, and the stirrers must be close to the meniscus. In these conditions, an additional design called ‘up and down’ mechanism is provided that shifts the stirrers automatically up into a position close to the meniscus for EMRS operation and down to mid-mould height for EMLS/EMLA operation.

Medium thick slabs ~150-220 mm: These sections are too flat and do not allow generation of an efficient rotative flow at the meniscus. Therefore, the EMRS function and the up and down mechanism can be ignored, which reduces the investment as well as the operating cost (because the EMRS function requires the highest electrical power). The flow control purpose here is only to obtain the optimised double-roll flow with meniscus velocity in the range 0.2-0.3 m/sec and stable right-left symmetry under all casting conditions.

Very thick slabs >300 mm: The thicker the slab, the lower the casting speed, and the natural flow in the mould does not require braking. Here, the purpose of flow control is ‘washing’ the solidification front to eliminate gas bubbles and particle inclusions in the surface and sub-surface region and to equalise the meniscus temperature. This is achieved with the EMRS function of MM-EMS located in a high position close to the meniscus.

We have developed two additional stirring modes for generation because we have four independent stirrers around the mould (see Figure 7). The first mode, Optimised EMRS, modulates the stirring force on the same broad mould face between right and left side to achieve more regular flow velocity around the meniscus and avoid turbulences in the corners near the narrow faces. The second mode, Double EMRS, produces two rotating flow loops where the meniscus rotates clockwise on one side and counterclockwise on the other side of the SEN. Both, optimised and double EMRS are currently used on a very thick 400 mm slab caster.

Thin slabs <150 mm: The natural flow is either double-roll or unstable; single-roll flow does not exist because no argon is used on thin slab casters. These casters aim at high productivity, hence use high casting speeds, but double-roll flow in most cases is too strong, hence meniscus flow velocity must be slowed down. Acceleration is not required and rotational flow cannot be generated with such flat sections, therefore EMS with magnetic travelling fields is not needed as the static magnetic field of the EMB is good enough. However, conventional EMB can only provide a global braking function, therefore a new EMB has been developed that, thanks to a multiple pole arrangement with three independent electrical power supplies, has three distinct functions. These are: braking the horizontal meniscus velocity, damping the vertical meniscus fluctuations and stabilising the right left bias flow instabilities (see Figure 8).

NEW MULTI-MODE® EMB

This new EMB has been built and extensively tested for slab sections 100 x (900-1,800) mm and casting speeds up to 10 m/min (for 1,200 mm width) on a full-scale caster simulator operating with a closed loop low melting point alloy. Horizontal meniscus flow velocity and vertical meniscus fluctuations have been measured with a laser scanner on both the right and left side of the SEN with and without EMB (see Figure 9). The results have validated the three functions of braking, damping and stabilising, and the new EMB was commercialised in 2013 under the name of Multi-Mode® EMB and will, we believe, be a breakthrough in terms of flow control on thin slab casters.

One industrial unit is under construction and will be commissioned in 2014. Details will be presented at the 8th European Continuous Casting Conference in June 2014 in Graz, Austria.

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