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Continuous casting: make better steel and more of it!★

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Abstract – An impressive number of papers are published each year that report on continuously-cast steel quality issues and new machine equipment; few of them (if any) discuss productivity and cost issues as they should be addressed by plant management, caster operators, and scientists. At Management & Quality Control meetings in steel plants, much time is spent discussing tenth of percent rejections at the end of the processing line. But, little time is devoted to discuss slab direct-application ratios where rejections are several percents and penalty on the overall scheduling and organization of the steel production line very serious. At IPC & SOP review meetings (Integrated Process Control & Standard Operating Practices review meetings), much time is spent discussing upper and lower statistical (6-sigma) control-limit diagrams. However, no mention is made that such diagrams only prove process capability (process repeatability and reproducibility) and not product quality. There should be no comfort if center line is at 10% slab abnormality code month after month! It is the goal of the author to draw from an approach that combines 30^{+} years of research and plant experience. The result is the opportunity to "connect the dots" and a wide breadth of in-situ process understanding. The paper looks at continuous casting machines as tools for maximizing corporate earnings. It is about making good steel on the first attempt. Very systematically and practically, the paper discusses disturbing steelmaking defects, their causes, and how Electro-Magnetic Stirring technology can be used to eliminate them. It draws the attention to academics looking to validate or invalidate what they know or don't know, and provides in-depth, concise, practical explanations and guidelines to plant operators who are less interested or do not have the time to assimilate highly-technical presentations and publications.

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1 Making good steel at first attempt

Any redo costs money! This is shortly stated but it says it all. Any as-cast slab (or bloom or billet) that is not "direct" (i.e. is not maintained on the original customer order list) is a burden to the company's balance sheet.

There are multiple reasons. The slab may have just been suspected of being of poor quality in which case it is simply put aside for inspection. Any inspection costs money; not only in terms of personnel and yield, but also because it takes time (i.e., eventually heat as it will require additional BTUs/MJ at the slab reheating furnaces). In some worse situations, the suspected slab was indeed of poor quality, in which case it would be repaired (e.g., surface scarfing, cut to length), reinstated/redirected on the same order (e.g., the composition was slightly out of range but acceptable), applied to another less-demanding order (e.g., the missed composition was OK for another order), or simply sold on the secondary market.

In any circumstance, the corresponding penalty ranges from \$50 to \$100 per ton of product. This is huge. For a slab abnormality code ratio of 10% on a 200 000-ton per month caster, this represents a burden of 20 000 tons × \$100 = \$2.0 million per month! \$24 million a year!

A penalty of \$100/ton may look excessive to some of the readers. One should not forget, however, that the so-called secondary slab market is very volatile: with more producers now specializing in that marketplace, options to actually sell secondary slabs is becoming less and less possible.

★ This paper is based on a keynote address presented by the author at the 18th steelmaking conference of IAS (Instituto Argentino di Siderurgia) on November 1, 2011, in Rosario, Santa Fe, Argentina.

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A typical list of slab abnormality codes is presented in Table 1. It may affect up to 10–12% of the production of a slab caster. Alternatively, it constitutes an excellent list of projects for metallurgists and process engineers wishing to make a mark in their companies! Some plants refer to 5–6%; only because their list is less comprehensive!

Cast one ton, sell one ton! This statement sums up what any caster operator's goal should be. Easy to say!

- Caster operators are continuously under the pressure of preserving and extending the versatility of their machines; operations such as ladle change, tundish change, slab width change, casting speed change, submerged entry nozzle (SEN) change, mold taper change, and grade change are now routine and on-the-fly.
- Caster operators must make tons and simultaneously make sure that (1) nonmetallic inclusions and gas bubbles find their way out and (2) solidified steel is not mechanically and/or thermally stressed to a point that surface or internal cracks are generated. Discussing safety, a key attribute of any operation, is outside the scope of this paper.
- Caster operators are at the mercy of their product mix:
  - ✓ they must slow down for wide products (or would outpace the BOF/EAF furnaces and break the sequence);
  - ✓ they may not cast narrow slabs at maximum speed (or will lose lubrication near the narrow faces);
  - ✓ who wants to cast peritectic, TRIP-assisted, high-sulfur, or high-silicon grades?
  - ✓ who wants to cast (to lose) one full 250-ton heat to flush the ladle-to-mold refractory assembly of any oxygen traces before starting an ultra-clean D&I steel sequence?
  - ✓ who wants to cast a 250-ton reference heat to check machine alignment and/or roll gap before casting an internal-crack-sensitive sequence?
  - ✓ who wants to weld two 25-ton coils together to produce a 50-ton defect-free coil that will satisfy a highly-automated carmaker production line?

The list is endless. The consequence is a huge number of abnormality-coded slabs; and this is unfortunately at a dramatic cost as explained above.

What can we do about it? We did not start shipping slabs to the hot strip mill yet but we already lost 10% of our production! We will try to address this fundamental question in the next sections.

2 Collecting steelmaking defect data

For solving a problem there is a methodology to follow, the first step of which being to collect data. Simple to say, but more difficult to do as we will show below!

Collecting data on steel defects is no different than for example collecting data on machine productivity: it is frustrating! The issues are vocabulary, definition, and attributes. Table 2 presents a list of most "popular" steelmaking defects.

It immediately appears that this list does not allow any type of diagnosis. More information is needed. For example, is it an alumina- or a mold powder-based sliver? Or is it perhaps an argon-based sliver? And what about the longitudinal cracks? Are they mid-broad face or close to the slab edges? Defect characterization is key to defect analysis (i.e., problem solving). Table 3 shows some of the defects' most principal attributes.

It rests that frequency of occurrence still needs to be discussed. Here and there on the coil or everywhere; how many tons were rejected; on what steel grade; for what application; what was the coil size? At this stage of the conversation you might dare to ask: how many percent? I bet the number will always be low, say less than 0.20% for demanding automotive applications! This is precisely the point I wanted to make in the first section of this presentation: sometimes, to successfully ship one ton of steel with a zero defect rate to a particularly picky customers, it is necessary to cast 2 tons! But that is a number nowhere to be found! This is very frustrating as some American automotive customers I know, will ask for 50-ton coils while some Asian customers sometimes work out 5-ton

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Table 1. List of typical slab abnormality codes.

Abnormality Code	Impact
Slow casting speed (e.g., <1.0 m/min)	Sign of single-roll flow condition (see section 3.4)
High nitrogen pickup (e.g., >10 ppm)	Sign of steel reoxidation
Low aluminum (e.g., Al drop >0.010%)	Sign of steel reoxidation
Low tundish weight (e.g., <10 tons)	Slag entrapment
High mold level fluctuations (e.g., >6 mm)	Sign of instabilities in the mold
Long distance traveled by the meniscus (mm/min)	Sign of instabilities in the mold
Argon flush	SEN clogging alarm
Ladle change	Flow pattern change
Tundish change	Flow pattern change
SEN change	Flow pattern change
Casting speed change	Flow pattern change and tapered slabs
Slab width change	Flow pattern change
Grade change	Chemistry mix
Breakout alarms	Sign of loss of lubrication or taper
Ladle oxygen-open	Excessive amount of alumina
First and last slabs in a sequence	Cold meniscus
Reference heat	Check machine alignment and roll gap
Start heat	Flush oxygen in system (e.g., D&I)
Any other? e.g., SEN immersion depth change	See section 3.5

Table 2. List of most frequent steelmaking defects.

Slivers	Pinholes (argon)
Pencil pipe (blister)	Blowholes (hydrogen)
Longitudinal cracks	Subsurface cleanliness
Transverse cracks	Internal cleanliness
Corner (edge) cracks	Segregation
Internal cracks	Porosity
Slag patches	Ridging and Roping (stainless)
Scabs (scale)	Hook cracks (pipe line)

Table 3. List of the attributes that need to be collected to characterize the defects.

Position (vs. edges or center of strip)	Aspect (closed, open, with material or empty)
Position (vs. top or bottom, head or tail of strip)	Composition (powder, Al_2O_3, FeO, slag, gas)
Dimensions (length, width, depth)	Color (shiny, dark black)
Orientation (longitudinal, transverse, zigzag)	Shape (straight, tapered, large band, spotted dots)

coils. This makes an enormous difference in terms of tonnage rejection rates!

3 Connecting the dots

Now comes the time to take a look at the mold. Is it not said that: "the mold is the heart of a continuous casting machine?". In the next pages, we will see that laborious analysis of data over the last 10 years led to the development of what is now called *"the steel flow pattern concept"*. The concept explains why many steelmaking defects remained unsolved for many years. Alternatively, the concept introduces a new MM-EMS (Multi-Mode Electro-Magnetic Stirring) technology that literally eliminates steelmaking defects and fundamentally maximizes machine productivity.

3.1 The steel flow pattern concept – an overview

For nearly 30 years, the steelmaking community believed that the liquid steel exiting the bifurcated submerged entry nozzle (SEN) would travel to the narrow faces of the mold at high velocity where it would split into 2 loops, hence forming a double-roll (DR) flow (Fig. 1 left).

In the early 1990s at Hoesch Dortmund, where Amepa MFC sensors had been installed in a 2700 × 220 mm^2 curved mold, it was discovered [1] that single-roll (SR)

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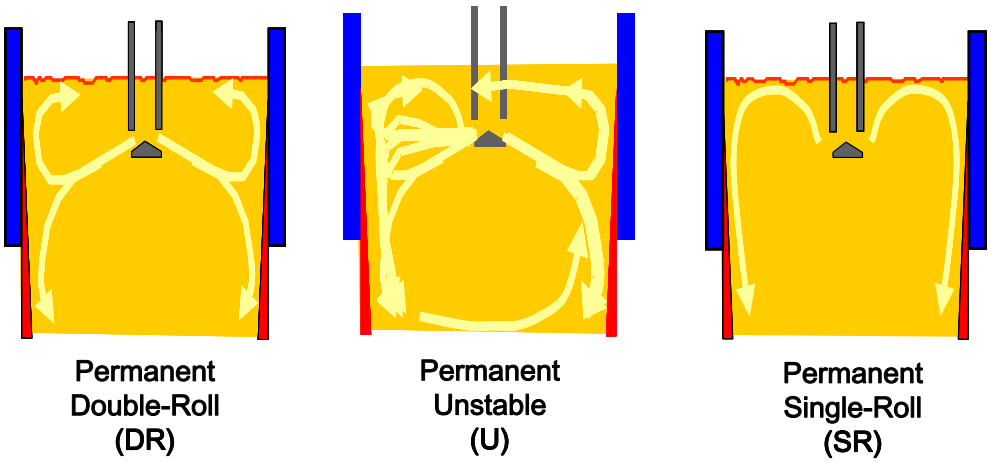


Fig. 1. There are 3 natural steel flow patterns in the mold: double-roll (DR), unstable (U), and single-roll (SR).

was also possible: for some baneful combinations of high argon flow rates and shallow SEN immersion depths, steel exiting the SEN ports would first travel up to the meniscus, then to the narrow faces at meniscus level, and eventually bore down deep into the liquid pool along the narrow faces of the slabs (Fig. 1 right). The authors also observed ephemeral/short-lived meniscus-roll and unstable flow conditions that they attributed mostly to SEN clogging or transitory casting situations.

In 2001, one more step was made after a nail board (NB) measurement campaign was conducted on the LTV (now part of the ArcelorMittal group) Indiana Harbor vertical-bending machine (2235 × 260 mm^2). It was discovered [2] that an unstable flow (U) could establish itself, *steadily and naturally*, for some unfortunate combinations of slab width, casting speed, argon flow rate, and SEN immersion depth (Fig. 1 center)!

In 2002, after many more nail board measurements on several industrial slab casters, the *combined* effect of slab width, casting speed, argon flow rate, SEN design, and SEN depth on mold flow pattern was recognized across the board for all three DR, U, and SR flow patterns and Danieli Rotelec proposed an original 2D representation (Fig. 2) that clearly depicted the DR, U, and SR domains in a slab-width/casting-speed diagram [3].

At the same time, the link was made between flow pattern and slab/coil quality [3]. The specific attributes (flaws) of each flow pattern (DR, U, SR) were observed and the *"flow pattern concept"* was proposed: (1) steel flow pattern changes all the time during casting, (2) flow pattern affects steel quality, and (3) there is one preferred flow pattern for which steelmaking defects (both surface and internal) are minimum. Let us go through that.

3.2 Steel flow pattern – how do we know?

It is impossible to discuss steel flow pattern without first reviewing the various methods that exist to determine the way steel moves in the mold.

The preferred method for many years has been water modeling. Water is used to simulate liquid steel (freezing may be added to simulate the progress of solidification), dye and small particles are used to visualize water and inclusion movement, and air is used to simulate argon. Observations are visual, video-recorded, or use Particle Imaging Velocimetry (PIV). Inherent issues include: (1) the model scale that is necessarily small for wide slab casters at the risk of building a "monster", (2) the obvious limited number of slab widths that can be simulated, (3) the restricted length of the model that may jeopardize response to inclusion flotation, and more importantly, (4) the controversial possibility of simulating argon flow correctly

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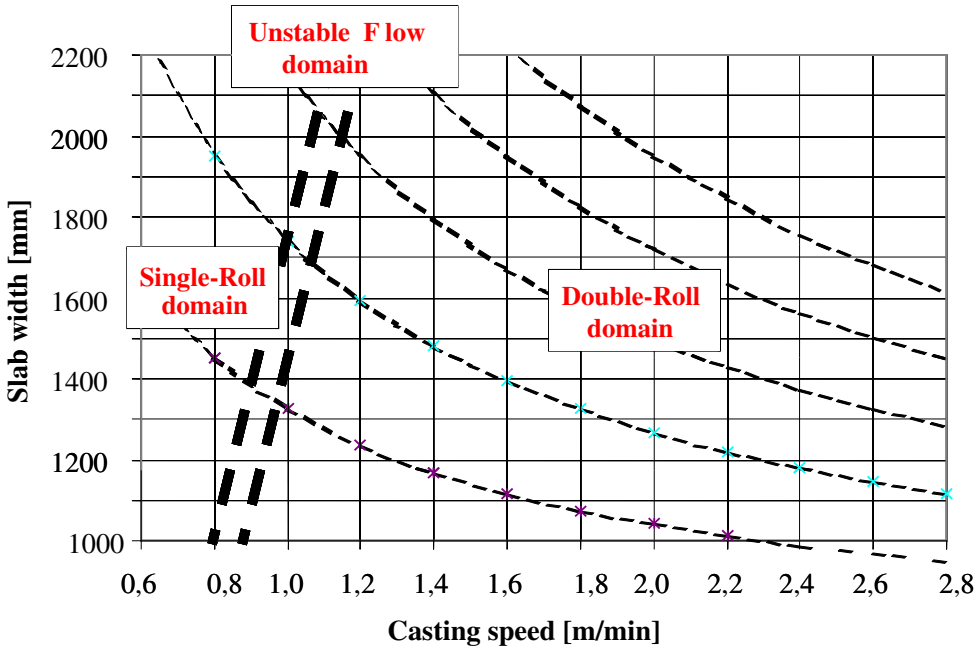


Fig. 2. Position of the 3 natural flow domains in a slab-width/casting-speed diagram; argon flow rate and SEN design/depth maintained constant to allow 2D representation [9]. Note the narrow unstable domain in this example.

(argon bubbles are not spheres with a uniform size [4]).

Mathematical modeling gained much interest in the last 15 years primarily because of the advent of new software and computer capabilities. This is a great tool that quickly became very popular at universities and research centers. One must not forget, however, that all those models must first be calibrated with *actual industrial* flow data.

In-the-mold, in situ, measurements remain the most appropriate method. They are made directly in the mold during normal operating casting conditions.

The Amepa MFC sensors use permanent magnets installed directly on the caster mold faces. The magnetic fields combine with the movement of the steel and induce eddy-current signals that can be converted into actual liquid steel velocities. They work extremely well. However, as the equipment is intricately built into the mold, it requires intensive installation efforts; a quick test is not possible. The equipment has been used on the Hoesch Dortmund (1994) and LTV Cleveland (1997) slab casters [1, 4]. The sensors are now offered on a limited basis for research projects.

Refractory paddles are interesting tools. They are immersed in the liquid steel at meniscus; their torque or angle of deflection is measured and converted into steel meniscus velocities. The issue is that the system is relatively cumbersome and does not allow several measurements to be made at the same time along the width of the slabs. Because unstable (U) flows go one direction at one point on the meniscus and another direction at different point, the method cannot be used to determine steel flow pattern. However, when flow pattern is known, the method works very well as it allows continuous, quantitative measurement of steel velocity over a long period of time (one hour).

Nail boards initially consisted [5, 6] of a simple piece of wood on which were arranged several sets of aluminum and steel nails (Fig. 3). At contact with liquid slag, the aluminum nails melt and, hence, indicate the position of the top of the molten slag layer. In contrast, the steel nails do not melt in contact with liquid steel, but rather a steel skull solidifies around them. The top of the skull indicates the position of the steel meniscus and the position of the bottom of the molten slag layer (hence, its thickness). The shape of

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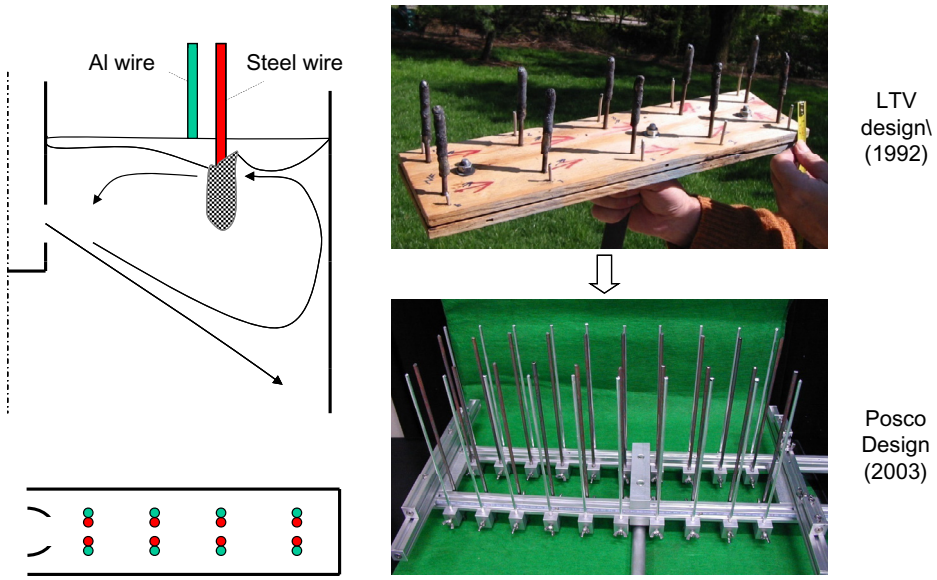


Fig. 3. Principles of the nail board measurements developed at LTV Steel. Note the POSCO new NB arrangement [6, 11].

the top of the skull (deflected to the narrow faces or to the SEN) is determined by the direction of the liquid steel at the meniscus (SR or DR). The height of the deflection (i.e., the height of the wave formed by the liquid steel as it hits the steel nail) is an image of the steel velocity. As a result, nail boards prove very useful to determine, right on the caster floor, the steel flow pattern and immediately assess its strength (DR^+, DR, DR^-, U, SR^-, SR, SR^+). They can be made by strand operators themselves and are a great learning tool to let them appreciate "what is going on in the mold". Nail board measurements do not look very scientific, although they received consideration at universities and research centers and were given an attractive look at Posco (Fig. 3) and Hyundai.

3.3 Steel flow pattern – it changes all the time during casting

With the definition of double-roll as indicated above (steel hits the narrow faces of the mold and splits into 2 loops), it is tempting to think that DR flows are favored by narrow slab widths and high casting speeds. As for single-roll (steel travels up to the meniscus first), we can add that SR flows are favored by high argon flow rates and shallow SEN immersion depths. It is with this in mind that Danieli Rotelec started analyzing information retrieved from nail board measurements conducted on the LTV Indiana Harbor and Cleveland East slab casters [3, 7].

- Table 4 shows that, indeed, DR flows are favored by narrow slab widths and high casting speeds.
- Conversely, SR flows are favored by wide slab widths and slow casting speeds (Tab. 5).
- Surprising, was the observation (Fig. 4) that the generation of a DR or SR flow did not depend on the slab-width x casting-speed product (i.e., did not depend on the machine throughput).
- Slow casting speed and more argon negate the impact of narrow width (Tab. 6).
- Slow speed and shallow SEN switch flow from DR to SR (Tab. 7).
- Shallow SEN and more argon switch flow from DR to SR (Tab. 8).

More importantly was the fact that for specific combinations of slab width, casting speed, argon flow rate, and SEN immersion depth, the flow would be neither DR nor SR as an unstable flow (U) would establish itself naturally (Tab. 9). This observation was quite alarming at the time since, as was explained later, unstable flow means mold

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Table 4. Narrow widths and high casting speeds promote DR flows.

Event No.	Slab Width mm	Casting Speed m/min	SEN Depth mm	Argon Flow l/min	Flow Pattern
3	1397	1.65	127	9.6	DR
5	1422	1.50	142	9.6	DR

Table 5. Wide widths and slow casting speeds promote SR flows.

Event No.	Slab Width mm	Casting Speed m/min	SEN Depth mm	Argon Flow l/min	Flow Pattern
21	1879	1.12	122	10.5	SR
23	1879	1.12	109	10.5	SR

Table 6. Slower and more argon negates the impact of narrow width; flow switches from DR to SR.

Event No.	Slab Width mm	Casting Speed m/min	SEN Depth mm	Argon Flow l/min	Flow Pattern
3	1397	1.65	127	9.6	DR
1	1168	1.16	144	20.4	SR

Table 7. Slower and shallower switch flow from DR to SR.

Event No.	Slab Width mm	Casting Speed m/min	SEN Depth mm	Argon Flow l/min	Flow Pattern
8	1422	1.52	162	30.3	DR
9	1422	1.16	144	31.7	SR

Table 8. Shallower and more argon switch flow progressively from DR to U to SR.

Event No.	Slab Width mm	Casting Speed m/min	SEN Depth mm	Argon Flow l/min	Flow Pattern
10	1448	1.14	165	19.8	DR
11	1448	1.16	155	31.7	DR/SR
9	1422	1.16	144	31.7	SR

Table 9. The steadily unstable flow is easy to understand as natural transition between DR and SR [3].

Event No.	Slab Width mm	Casting Speed m/min	SEN Depth mm	Argon Flow l/min	Flow Pattern
3	1397	1.65	127	9.6	DR
5	1422	1.50	142	9.6	DR
6	1422	1.47	144	25.5	DR
7	1422	1.57	155	26.9	DR
8	1422	1.52	162	30.3	DR
10	1448	1.14	165	19.8	DR
11	1448	1.16	155	31.7	DR/SR (U)
12	1525	1.27	150	15.8	DR/SR (U)
14	1525	1.16	173	20.4	SR/DR (U)
16	1575	1.65	173	28.3	SR/DR (U)
17	1600	1.19	137	18.7	SR
19	1778	1.14	111	18.4	SR
21	1879	1.12	122	10.5	SR
23	1879	1.12	109	10.5	SR
25	2133	1.14	137	17.0	SR
26	2133	1.12	137	17.0	SR

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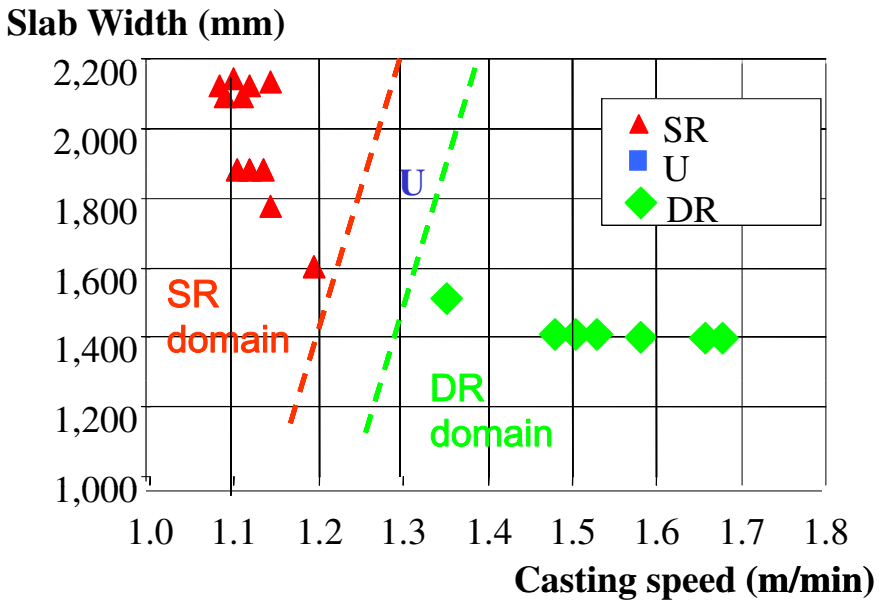


Fig. 4. For a same throughput (approx. 4.4 t/min here), mold flow pattern can be SR, U, or DR [3].

level fluctuations (i.e., mold powder shearing, mold powder entrapment, and formation of slab surface defects; mold powder-based slivers and longitudinal cracks). Also troubling was that none of these "turbulent" flow conditions would be noticed on Quality Control report cards as all operating parameters would apparently be maintained constant (no slab width change, no variation of casting speed, no SEN immersion depth change, no variation of argon flow).

3.4 Steel flow pattern – there is a preferred flow

At first, it did not seem obvious at all that there would be a preferred flow pattern. Again, it was a question of connecting the dots: observing the operations at the casters, talking to the operators, analyzing the data, determining the composition of the defects, and trying to relate the data to the newly-acquired information on steel flow pattern.

The very first piece of information that became available was in 1991 when NKK (now JFE) published a paper [8] stating that there was an optimum meniscus velocity to achieve to minimize coil defects (Fig. 5). For too-low meniscus velocities, steel meniscus would be too cold and alumina-based slivers would be generated. For too-high meniscus velocities, steel would tear the molten slag layer, and mold powder-based slivers would be generated. The information related to the Fukuyama high-speed casters that were casting relatively narrow slabs (1600 mm) at fast speed (2.0–2.5 m/min) with low argon flow rate (5–6 l/min for throughput of 4–6 tons/min): a true double-roll machine!

In 2000, LTV Steel had just converted one of their Indiana Harbor curved mold machines into vertical/bending and were surprised to collect 6 pencil pipe defects within the first 6 months of operation of the new machine design. An analysis of the defects (in position vs. width of the slabs) triggered a nail board measurement campaign and showed that all defective coils had been cast in single-roll flow conditions (Fig. 6).

Came 2001, when it was realized at LTV Steel again, that unstable flow can establish itself naturally and permanently for some unfortunate combination of slab width, casting speed, argon flow rate, and SEN immersion depth. It was quickly observed that high-speed vortices can be generated in unstable flow conditions (Fig. 7) and lead to all type of defects, mold-powder slivers at slow casting speed to name one!

The loop was looped: each flow pattern has its own inherent flaws and propensity to generate defects (Tab. 10). There is one

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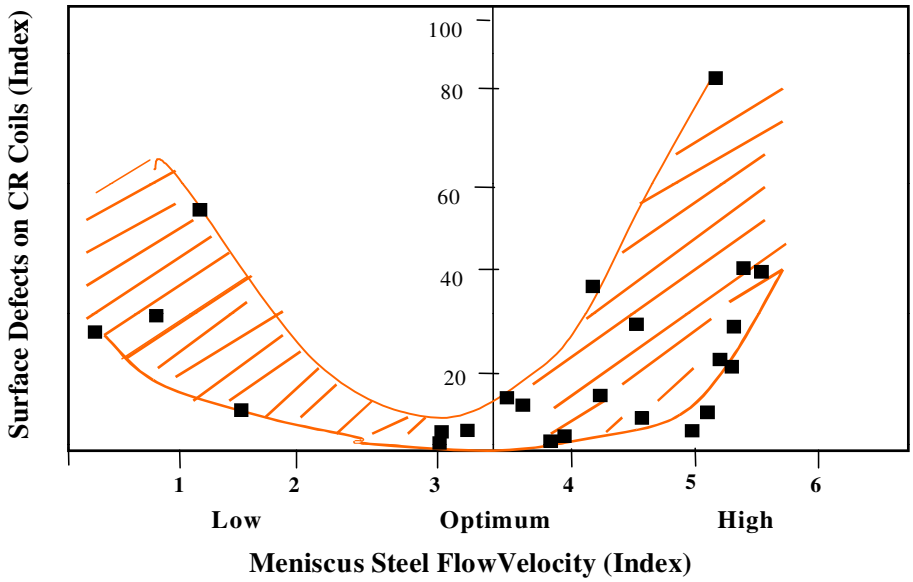


Fig. 5. At NKK Fukuyama [8], it was found that the preferred flow pattern is a not-too-strong, not-too-weak Double-Roll flow.

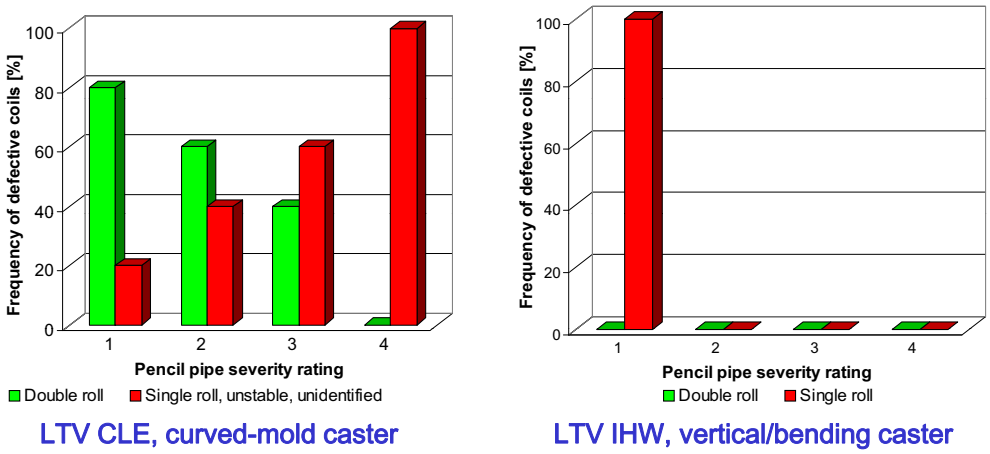


Fig. 6. At LTV Steel Indiana Harbor [4], it was found that pencil pipe defect frequency and severity increase dramatically in the Single-Roll flow domain.

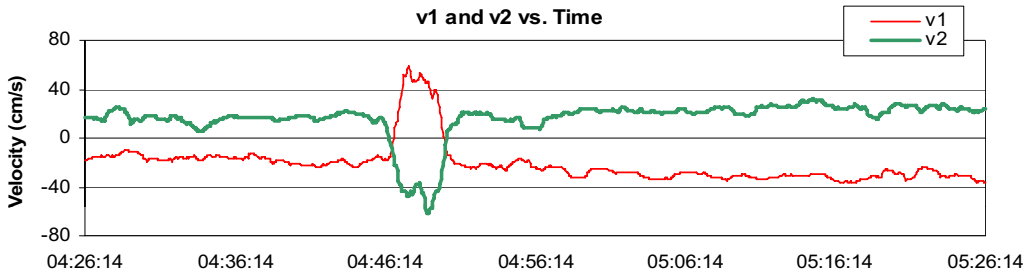


Fig. 7. High-velocity vortices are generated in the unstable domain (60 cm/s vs. 20 cm/s) which explains the formation of mold powder-based slivers even at low casting speeds. Key: meniscus velocities V1 and V2, at right and left of SEN; 1 400 mm wide slabs, 1.10 m/min, 14 l/min argon [4].

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Table 10. Inherent flaws of each steel flow pattern [7].

Flow	Attributes of Each Flow Pattern	Impact/Consequences
DR^+	Thinning of molten slag layer near narrow faces High meniscus velocities High mold level fluctuations	Lack of lubrication; *Sticking alarms* Mold powder entrainment *Mold powder-based slivers*
DR	Equal distribution of molten slag layer over entire width of mold	Optimum casting conditions Minimum (zero) steelmaking defects
DR^-	Cold meniscus Slow meniscus velocities Insufficient washing of solidification front	Long solidification hooks; *subsurface inclusions* *Slag patches on slab surface* *Alumina-based slivers*
U	Vortexing (high meniscus velocities locally) Uneven molten slag layer thickness High mold level fluctuations	*Mold powder-based slivers (at slow speed!)* Uneven solidification shell *Longitudinal cracks*
SR	Thinning of molten slag layer at SEN Unobstructed propelling of inclusions and argon bubbles deep into the slab Strong descending loop counteracts flotation of ascending inclusions and argon bubbles	*Mid broad face longitudinal cracks* *Pencil pipe defects* *Subsurface inclusions*

preferred flow pattern and that is a not too-strong (DR^+) and not too-weak (DR^-) double-roll flow.

3.5 Mold flow pattern – when electro-magnetic stirring is the solution for caster operators

Steel flow pattern changes all the time during casting but steel flow pattern determines slab and coil quality (Tab. 11 below). What are the options?

Caster operators must continuously adapt their practices to product mix (width), BOF tap-to-tap time (casting speed), refractory wear (SEN depth), and inertization of operation (argon flow). They must maintain the versatility of their operations, but still make sure that liquid steel will follow the preferred path and inclusions and gas bubbles will find their way out! What can they do about this?

As an example, Figure 8 highlights the effect of SEN immersion depth [7]. This is an operating parameter that is changed all the time during casting to distribute refractory wear and extend SEN life. In some plants, SEN depth is changed in steps (e.g., 3–4 steps during the life of an SEN); in some other plants, SEN depth is changed continuously during casting (e.g., sinusoidal or triangular movement). Unsuspected from the operators, SEN depth affects steel flow pattern; its impact on steel quality is disastrous. It should be added to Table 1, to the already long list of slab abnormality codes!

Figure 9 is relative to a tundish change operation [4]. It is interesting to observe that although the operation only took 7 min, it took 15 min for the meniscus velocities to again reach stable levels: that is the time necessary to cast 1.5 slab/strand (i.e., 3 slabs or up to 75 tons downgraded per operation for a 2-strand machine)!

Slab width and casting speed are key to steel flow pattern; SEN (depth and design) and argon flow are no less important. Their impact is well observed in Figure 10 where, for some particular combination of operating parameters (compare with Fig. 2), the defect-prone SR and U domains have been dramatically widened.

MM-EMS stands for Multi-Mode Electro-Magnetic Stirring: it is a technology (developed by Danieli Rotelec, based on the NKK EMLS/EMLA) [8–12] that can force the liquid steel to follow the preferred path independently from casting conditions (i.e., reduce steelmaking defects to zero)! The technology consists of 4 stirrers that are installed 2 by 2 on each broad face of the mold on each side of the SEN (Fig. 11). A detailed description of the technology is outside the scope of the present paper. It suffices here to list its capabilities that are to slow-down or accelerate steel as it exits the SEN or even put it in rotation at the meniscus (i.e., the EMLS, EMLA, or EMRS modes, respectively). Table 12 lists

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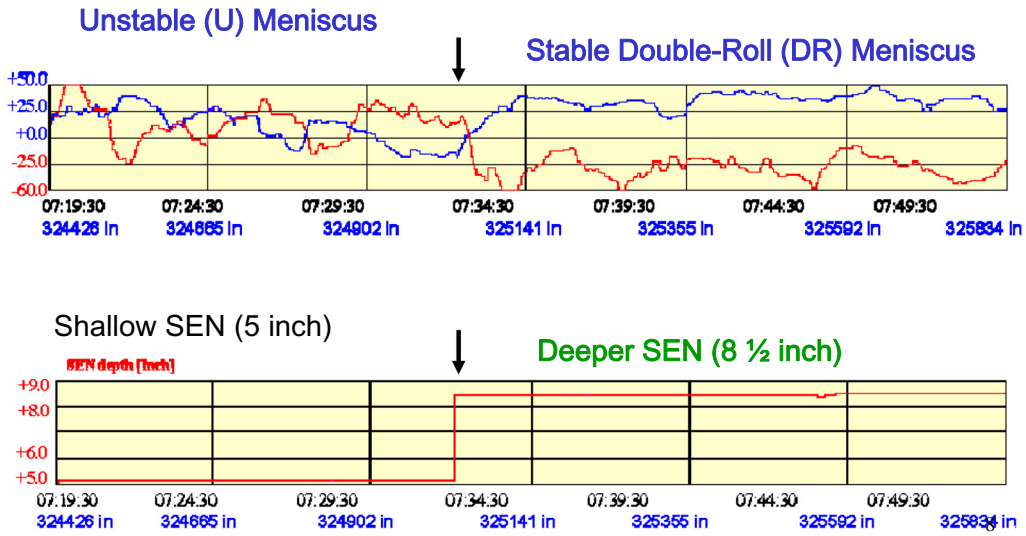


Fig. 8. Increasing SEN immersion depth from 5 to $8^{1/2}$ inches (125 to 215 mm) changed flow pattern from U to DR [4].

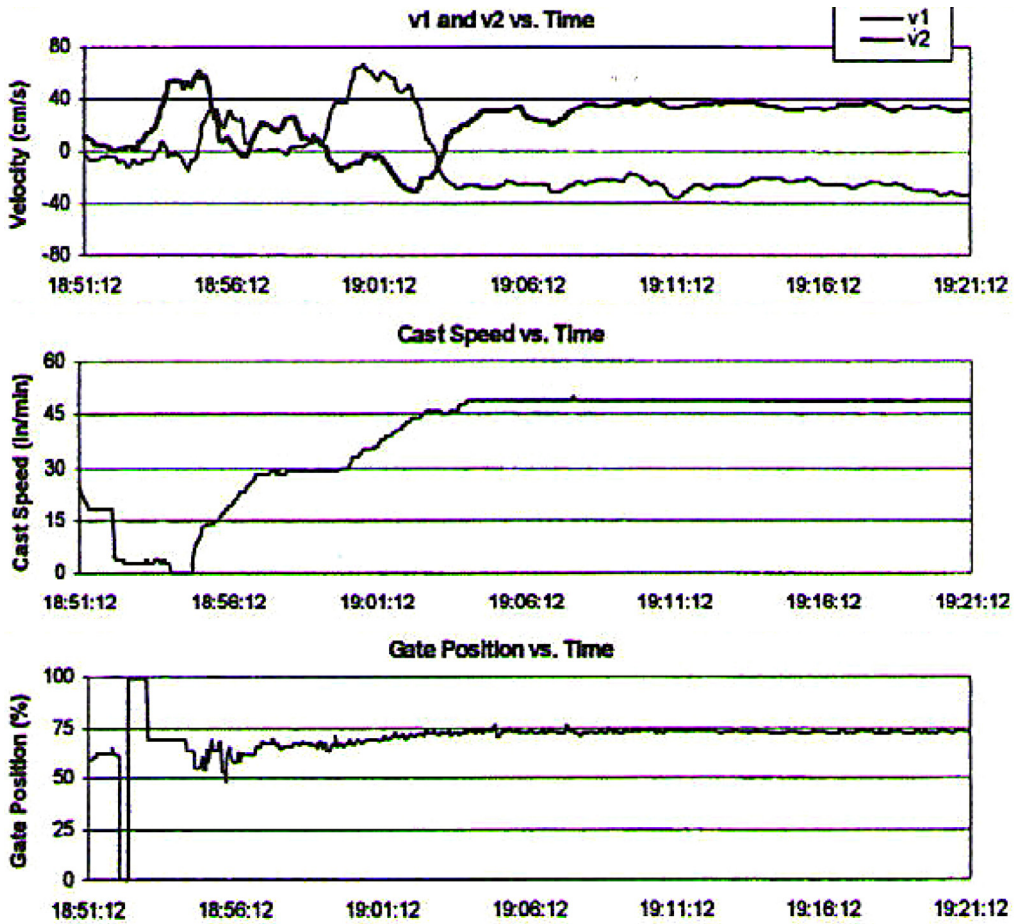


Fig. 9. Tundish changes generate instabilities in the mold that may last 15 min, the time to cast 1.5 slab on each strand. They are temporary in contrast to U flow conditions that are permanent. Key: 1650 mm wide slabs, 1.25 m/min, 12 l/min argon [4].

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Table 11. Example of steel flow-related steelmaking defects [9].

Steelmaking Defects	Most probable causes
Mold powder-based slivers at high casting speed	Powder shearing/entrainment High steel meniscus velocities/high mold level fluctuations Fast casting speeds (typical on narrow slabs) *Too strong, too fast double-roll*
Mold powder-based slivers at slow casting speed	Powder vortexing, biased flow, shallow SENs *Unstable flow*
Alumina-based slivers	Cold meniscus, long solidification hooks Slow meniscus velocities, slow casting speeds (typical on wide/double-width slabs) *Too weak, too slow double-roll or single roll flow*
Slag spots on slabs cast at slow speed	Unmelted mold powder, cold meniscus *Weak/slow steel flow*
Non-metallic inclusions Insufficient internal cleanliness (defective D&I steel cans)	Dirty steel, inclusions propelled into the liquid pool *Inappropriate SEN design* at reduced casting speed (typical of wide-automotive and narrow-D&I combined product mix)
Pencil pipe (blisters) in a 30-cm band along the slab edges on vertical/bending machines	Un-opposed drive of argon bubbles and inclusions to the narrow faces and deep into the liquid pool *Single-roll*
Argon-based pinholes (porosities)	Too much argon Sluggish meniscus flow; insufficient washing of the solidification front *Weak/slow steel flow*
CO-based blowholes e.g., on pseudo-rimming, enameling steels	Slow-moving meniscus flow ; insufficient washing of the solidification front *Weak/slow steel flow*
Longitudinal cracks at slab mid broad face	Thinning of molten powder layer near SEN *Single roll*
Longitudinal cracks anywhere in slab width	Mold level fluctuations Temperature gradient, uneven molten slag layer thickness *Unstable flow*
Transverse corner cracks	Lack of lubrication in the corner of the mold *Too fast double-roll*
Various slab abnormality codes	Casting speed variations (e.g., at ladle change, at cast start/end, wait for steel, maintain cast sequence, broken rolls) *DR/SR/DR reversion*
Various unexplained defects in so-called steady casting conditions	Unfortunate combination of slab width, casting speed, argon flow and SEN depth *Permanent unstable flow*

the specific attributes of each of those stirring functions.

3.6 Electro-magnetic stirring? Is this a profitable investment?

In discussions with quality control and process specialists, many people argue that they cannot find many incentives to install Electro-Magnetic Stirring as their average coil defect ratios are in the range of 0.15–0.20%. The simple example below shows that this is ignoring (1) diversions that occur right at the caster and (2) casting speed constraints that reduce machine productivity.

Money savings is on the side of the machine performance e.g.,

(1) increased machine productivity because of casting speed maximization on narrow slabs;
(2) increased slab *direct* application ratios because of the possibility to maintain the preferred flow pattern in the mold independently of casting condition changes;
(3) waving the need to reduce speed on some reduced-speed difficult-to-cast grades;

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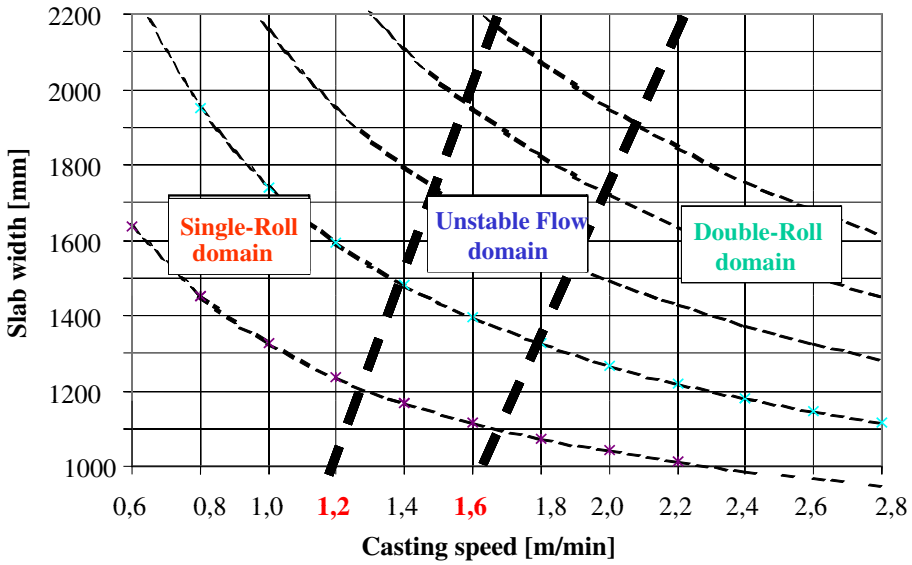


Fig. 10. Compare with Figure 2. Note the wide defect-prone SR and U domains in this example with an alternate SEN design, shallow immersion, and high argon [9].

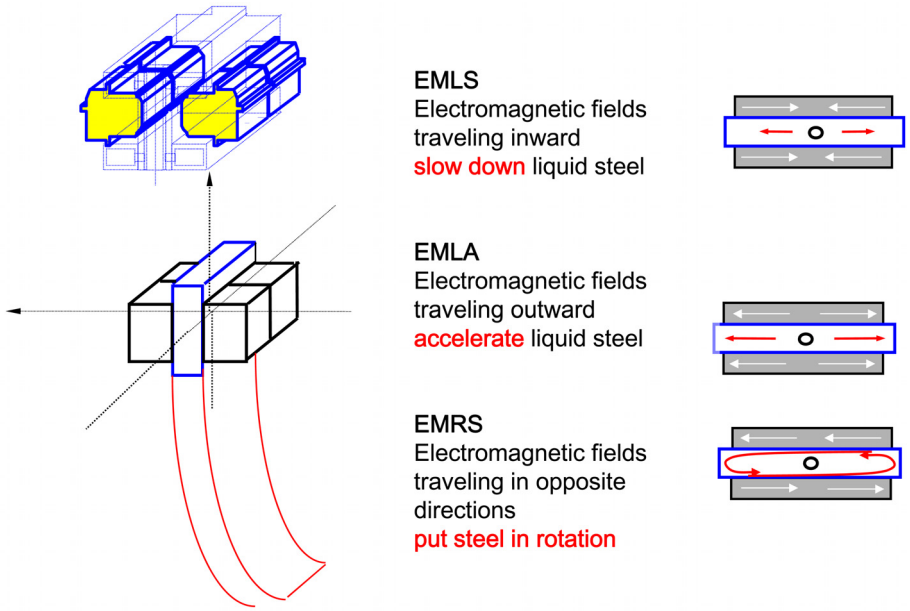


Fig. 11. Multi-Mode EMS (MM-EMS) consists of 4 stirrers creating 3 functions: slowing down, acceleration, or rotation of the steel that oblige liquid steel to follow the preferred flow pattern independently of casting conditions [9].

(4) making better slabs and more of them because of the elimination of the need to sometimes cast 2 tons of steel to be able to ship one, and;
(5) reduction of defects after rolling.

An example of return-on-investment is discussed below. It considers investment cost and money-saving items for a 2-strand slab caster producing 2.4 Mtpy [10]. It concludes that the annual savings obtained ($21.2 M in the present example) easily outweigh its investment ($ 12–15 M)! [13].

Investment

– A complete MM-EMS installation with license fees, services, all specific power

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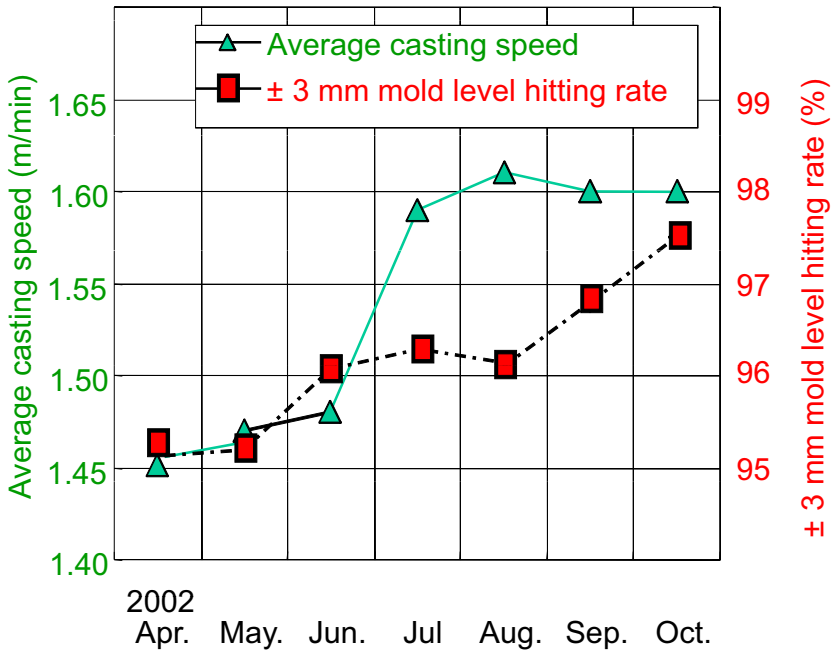


Fig. 12. At Posco Pohang [11] average casting speed was increased 10% (0.15 m/min) after MM-EMS implementation mid- May. Reason: elimination of restricted speeds on narrow slabs and specific grades.

and control equipment, stirrers for 4 molds, and 6 modified molds (presuming that the existing machine structure around the mold and the oscillation mechanism need no revamping) represents a capital expenditure in the range of 8 to 10 M Euros (12–15 million dollars).

Money-savings

- Let us assume a slab abnormality code rate of 10% on the 2.4 M tpy machine and a penalty of $100 per ton of downgraded/redirected slab.
  - ✓ This represents a penalty of 2.4 Mtpy × 10% × $100 = $24 million per year.
  - ✓ Assuming, cautiously, that MM-EMS decreases the slab abnormality codes by one-third, this item would generate earnings of $8 million per year.
- Let us assume that 50% of the production of the machine consists of reduced-speed grades and/or narrow slabs that cannot be naturally cast at full speed.
  - ✓ It was reported [9, 11, 12] that MM-EMS improves the average casting speed by approximately 10% while simultaneously improving mold level control performance 3% (Fig. 12).
  - ✓ This represents 2.4 Mtpy × 50% × 10% = 120 000 tpy of additional slabs.
  - ✓ Assuming a margin of $100 per ton, this item would generate additional earnings of $12 million per year.
- Let us assume that 25% of the product mix of the machine is demanding grades on which coil rejection rate is 2% at a penalty of $200 per ton.
  - ✓ Assuming, cautiously, that MM-EMS decreases coil rejections by 50% (Fig. 13), this item would save 2.4 Mtpy × 25% × 1% × $200 = $1.2 million per year.

3.7 When do we know flow is ok?

When do we know that steel flow pattern in the mold is OK? Well, that is simple: when coil defects are zero!

The problem with this approach is that we may only find out 4 or 5 weeks after the cast! The real question of interest to the caster operators is rather: "When do we know *while casting* that the flow that is being generated in the mold is the preferred one?".

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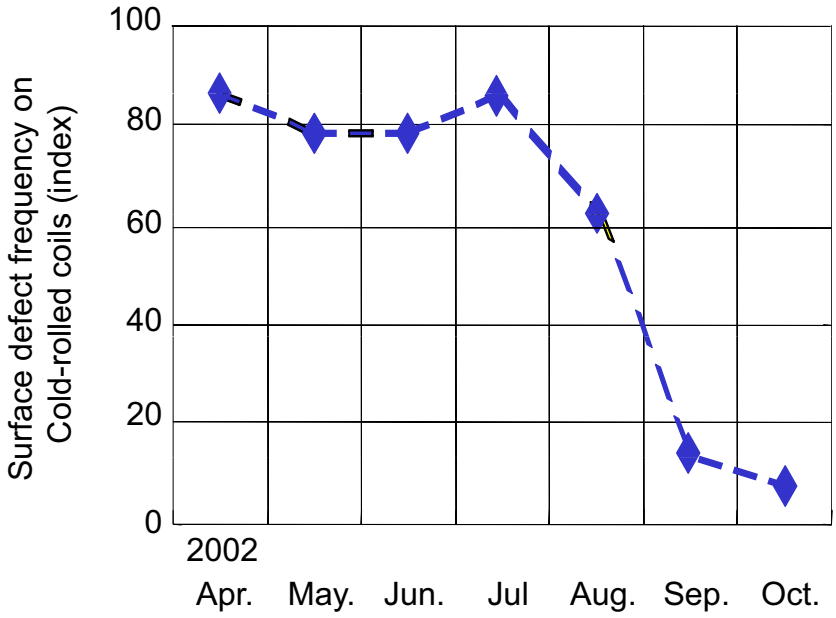


Fig. 13. At Posco Pohang [11] steelmaking defects were reduced 80% at cold-mill inspection line with MM-EMS implementation. Note the 4-week delay vs. Figure 12.

The answer is found in Table 10, more specifically in Figures 14 and 15. It is shown that molten slag layer is thinner (1) near the SEN when a strong SR flow establishes itself in the mold and (2) near the narrow faces when a strong DR flow is in the mold. The preferred flow is when the molten slag layer is consistently thick over the entire width of the mold! So, the answer to the above question is actually very simple: make nail board measurements, determine the position of the SR/U/DR domains, and measure molten slag layer thickness!

Note that the nail-board measurement method is also applicable while using Electro-Magnetic Stirring. Figure 16 refers to a 915-mm wide slab cast at 2.0 m/min: a strong standing wave is observed near the narrow faces with concomitant slag thinning in that area [11]. After activation of the slowing-down EMLS function (Fig. 17) the narrow face wave has been eliminated and the molten slag layer thickness is uniformly distributed over the entire width of the mold. Alternatively, the figure confirms one of the benefits of MM-EMS i.e., the possibility of casting narrow slabs at maximum casting speed without sticker alarms or breakouts; Table 12.

3.8 Beware of statistics

In our pursuit of generating a not too-fast, not too-weak double-roll flow pattern in the mold, it results that slow SR and unstable U flows need be accelerated and fast DR^+ flows need be slowed down. The impact on steel quality is shown in Figure 18. Again, this is something that looks simple. Not so simple, however, as it really shows that when conducting statistics over a large number of slabs and coils in an attempt to identify the impact of casting speed on defect occurrence, no relationship will be found at all! Statistics need be conducted flow pattern domain by domain! Increasing casting speed is beneficial in the SR and U domains; it is detrimental in the DR^+ domain.

Figure 19 refers to another error commonly made. It refers to the so-called 6-sigma (σ) diagrams that often are discussed at cost meetings to assess steel quality. The evolution of a parameter (slab abnormality rate or sliver rejection for example) is monitored over time, and upper and lower control limits (ULC and LCL limits) are defined. Everyone is happy as long as the parameter in question does not "exit" the control limit diagram for say 3 measurements (3 months) in

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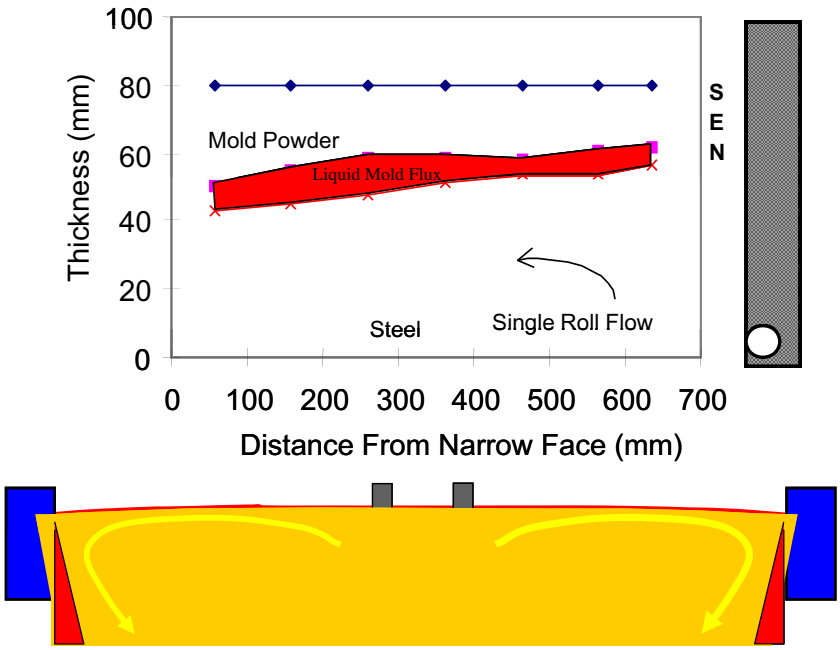


Fig. 14. Molten slag layer thinning near the SEN is observed when casting in the single-roll domain.

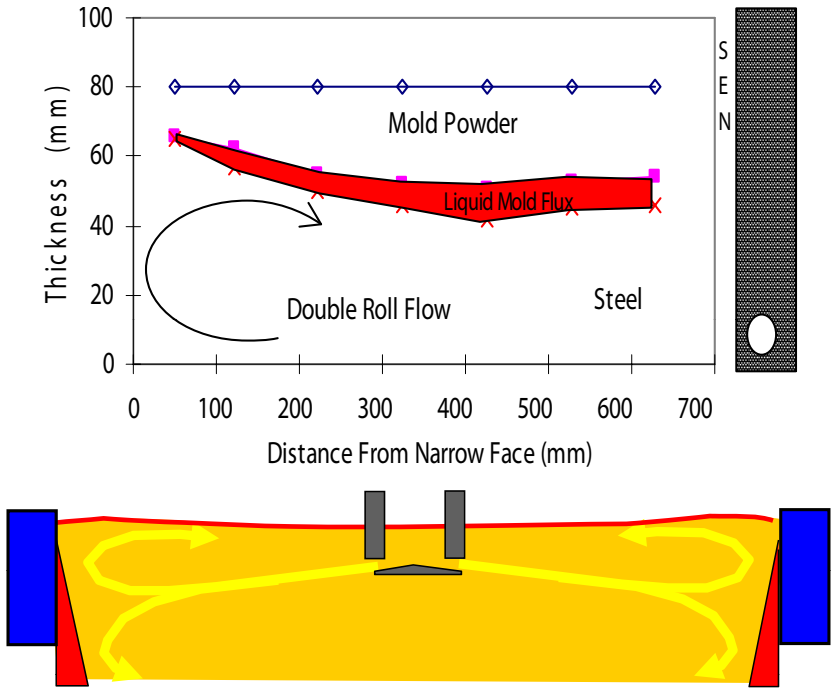


Fig. 15. Molten slag layer thinning near the narrow faces is observed when casting in the strong (DR⁺) double-roll domain.

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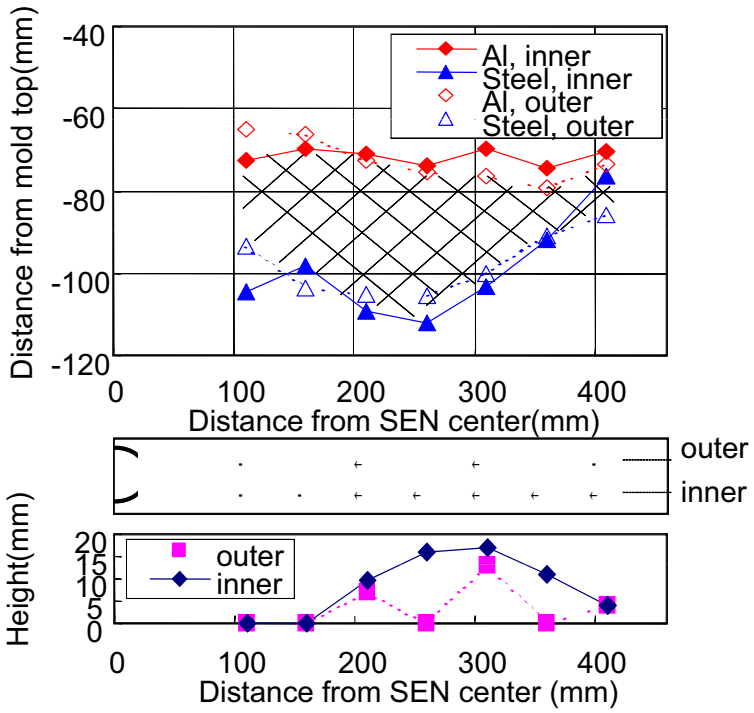


Fig. 16. In natural DR⁺ flow conditions (typical of narrow-width slabs cast at high speed) high standing waves are generated at the narrow faces with concomitant thinning of the molten slag layer i.e., loss of lubrication [11].

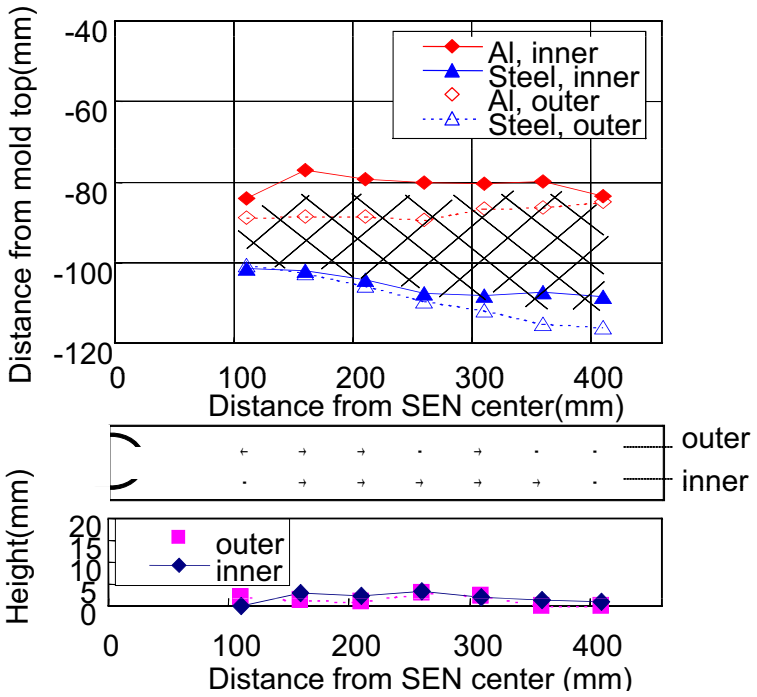


Fig. 17. Compare with Figure 16. EMLS activation slows down meniscus velocities, eliminates narrow-face standing waves, and restores a consistent molten slag layer thickness over the entire width of the mold independently of casting speed [11].

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Table 12. Specific attributes and impact of each electro-magnetic stirring function.

Mode	Attributes/Characteristics	Impact
EMLS	Transform DR$^+$f lows into optimized DR; Slow-down excessive meniscus velocities	Eliminate narrow-face standing wave Eliminate slag thinning at narrow faces Maintain maximum casting speed on narrow product Eliminate high mold level fluctuations Eliminate powder shearing
EMLA	Transform SR flows into optimized DR; Accelerate stagnant meniscus velocities	Promote heat transfer to the meniscus Eliminate cold meniscus situations Eliminate slag thinning at SEN Prevent inclusions and argon bubbles from being entrained deep into the liquid pool
EMLA	Transform U flows into optimized DR; Accelerate liquid steel to eliminate flow instabilities due to specific combinations of casting conditions	Eliminate high mold level fluctuations Eliminate powder slag vortexing Equalize molten slag layer thickness Equalize solidification shell thickness
EMRS	Put liquid steel in rotation at meniscus; Generate soft, genuine stirring conditions	Homogenize temperature distribution around meniscus Equalize solidification shell thickness Promote heat delivery to narrow faces on thick, wide slabs Neutralize impact of tension-active elements in specific steel grades (see section 4.3) Wash solidification front from inclusion and argon bubble impurities
EMLS EMLA	Eliminate unbalanced right/left mold flow conditions (is distinctive of 4-stirrer configuration)	Maintain preferred mold flow in SEN clogging situations Offset impact of tundish flow control specificities (see section 4.2)
EMRS	Optimize right/left thrust settings (is distinctive of 4-stirrer configuration)	Equalize steel velocity around meniscus Prevent vortex formation at narrow faces

Table 13. MM-EMS projected savings ($ 21.2 M) compare extremely well to investment ($12–15 M) [8, 9, 11, 12]; 2-strand slab caster; 2.4 Mtpy; 25% surface-demanding quality grades; 50% slow-speed conditions.

Source of Diversion Loss of Production or CR rejections	Slab Abnormality Codes	Slow-Speed Narrow Slabs Speed-Restricted Grades	Cold Mill rejections	Total
Typical rejections or loss	10%	10%	2%	–
% of production affected	100%	50%	25%	–
Annual production affected	2 400 000 tpy	1 200 000 tpy	600 000 tpy	–
Tons rejected or lost	240 000 tpy	120 000 tpy	12 000 tpy	–
Penalty per ton or margin	$100	$100	$200	–
Penalty per year	$24 M	$12 M	$2.4 M	$38.4 M
Minimum (%) MM-EMS improvement	33.3%	100%	50%	–
MM-EMS savings ($/year)	$8 M	$12 M	$1.2 M	$21.2 M

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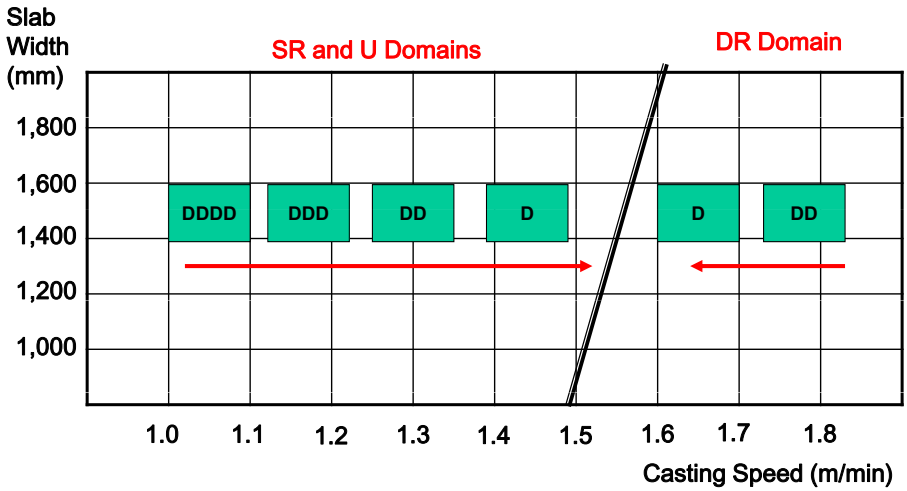


Fig. 18. Increasing casting speed is beneficial in the SR and U domains, and detrimental in the DR$^+$ domain rendering across-the-board statistical analyses irrelevant. Key: D for defect; the more D, the more defects.

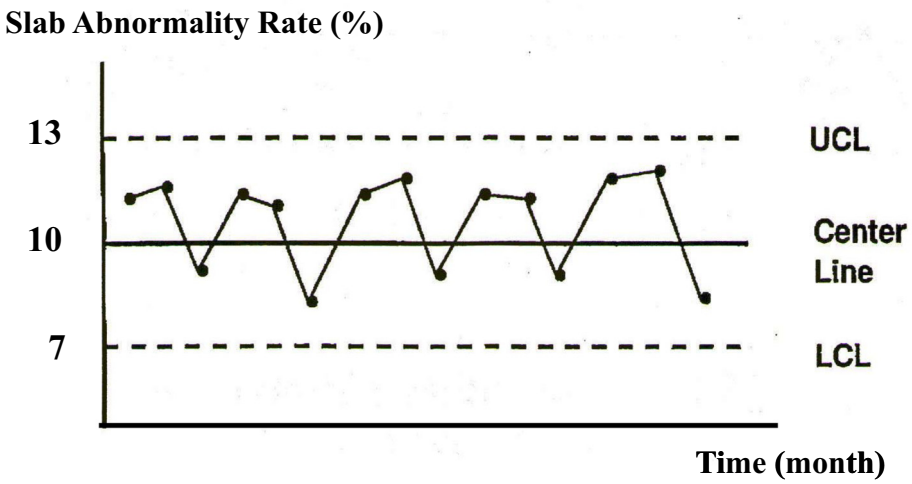


Fig. 19. IPC statistical/conformity diagrams prove process repeatability and reproducibility, not product quality. There should be no comfort if centerline is 10% slab abnormality/downgrade. Key: UCL and LCL, upper control and lower control limits at 6-sigma distance.

a row. One should remember that such diagrams are developed to assess process reproducibility and repeatability only, not product quality. There should be no comfort for example if the slab abnormality code index (the centerline on the diagram) remains at 10% month after month!

4 Going back to the basics

"When everything else fails, read the manuals". This sounds familiar, doesn't it? Steelmaking is not different from other industries, except that here the manuals are chemistry and physics textbooks, phase diagrams, Fast Fourier Transforms, the Bernoulli equation, the Nernst equation, calculus derivatives, etc. The amount of information that can be extracted from the table of Mendeleyev or the Ellingham's oxide free energy of formation diagram is also amazing. The 3 examples below will confirm how important it is to "go back to the basics" to solve some of the most frustrating steelmaking projects we have to deal with.

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4.1 SEN clogging vs. refractory composition

We all know the detrimental effects of SEN clogging when casting aluminum-killed steels e.g., increased mold level fluctuations and asymmetrical distribution of inclusions. Countermeasures such as argon flushes and SEN changes are not welcome: they all result in unacceptable increase of slab abnormality codes at the prohibitive cost discussed in Section 1.

A first countermeasure to SEN clogging comes from the ceramists who made the observation that SEN refractory material contains C, Na_2O, and K_2O. Now come Ellingham and Bernoulli (Fig. 20):

- the Ellingham diagram tells that carbon can reduce Na_2O, and K_2O at high temperature; resulting in CO gas;
- the Bernoulli principle tells that the SEN is a vacuum pump: the high velocity of the steel that travels through the SEN bore sucks the CO inside the SEN where, tells Ellingham again, it can react with aluminum and form the highly non-desirable Al_2O_3 that will induce clogging!
- The response of the ceramist was immediate. They manufactured carbon-free SEN linings and clogging disappeared, or at least was drastically reduced (there are indeed other unfortunate sources of alumina). The technology was used at several locations, including LTV Steel, where SEN life was increased 50% consistently (from 4 to 6 heats/SEN).

Quality control personnel must make sure this breakthrough technology is used as it is intended to be. One option is to maintain SEN life at 4 heats and, indeed, reduce clogging and abnormality-coded diverted slabs. The other option is cost-driven: it will schedule 6 heats per SEN (a 20% cost reduction of SEN refractory cost) but, in fact, with only minor effect on slab abnormality/clogging frequency!

4.2 SEN clogging vs. electro-magnetic stirring

MM-EMS operators know that the EMLS and EMLA functions automatically adjust to maintain the preferred flow pattern in the mold *even in presence of SEN clogging*. The explanation results from mathematical considerations exclusively [14]. We have to go back to the basics of the Electric and Magnetic Fields theory to explain why:

- Physics says that when an electrical multi-phase alternating current circulates through a multi-coil inductor it generates a magnetic field that moves.
- Faraday's law tells that a magnetic field that moves creates eddy currents in any nearby conductor.
- Lorentz' law tells that the magnetic field and eddy currents will combine to create a force that goes into the direction of the moving field.
- The force can be calculated. It is directly proportional to the electrical conductivity (σ) of the materials, the square of the magnetic field (B), and the difference between the speed of the steel and the speed of the field (ΔV):

$$\vec{F} = \sigma \Delta \vec{V} \vec{B}^2$$

If we examine this equation in closer details, we notice that F, ΔV, and B^2 are all vectors; more specifically ΔV. The observation is not without consequences:

- In the EMLS slowing-down mode for example, when the magnetic field goes *against* the steel flow, it means that the absolute value of ΔV will result from the *addition* of the absolute velocity values of liquid steel and magnetic field.
- In the EMLA accelerating mode, when the magnetic field goes *with* the steel flow, the absolute value of ΔV will result from the *subtraction* of the absolute velocity values of liquid steel and magnetic field.

In case of SEN clogging, the observation means that the forces applied in the EMLS and EMLA modes will, for an unchanged current setting, mathematically increase or decrease and, consequently, automatically restore a balanced, non-biased steel flow in the mold without the operator having anything to do:

- In the EMLS mode (*addition* of the absolute velocity values), if liquid steel goes faster on one side of the SEN because of

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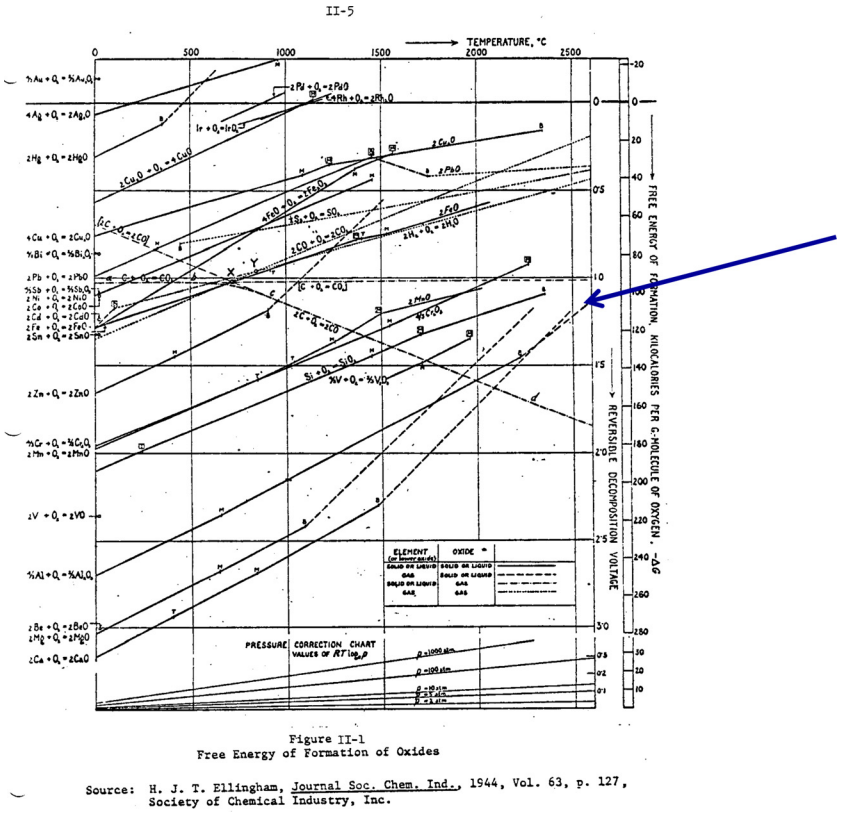


Figure II-1
Free Energy of Formation of Oxides

Source: H. J. T. Ellingham, Journal Soc. Chem. Ind., 1944, Vol. 63, p. 127, Society of Chemical Industry, Inc.

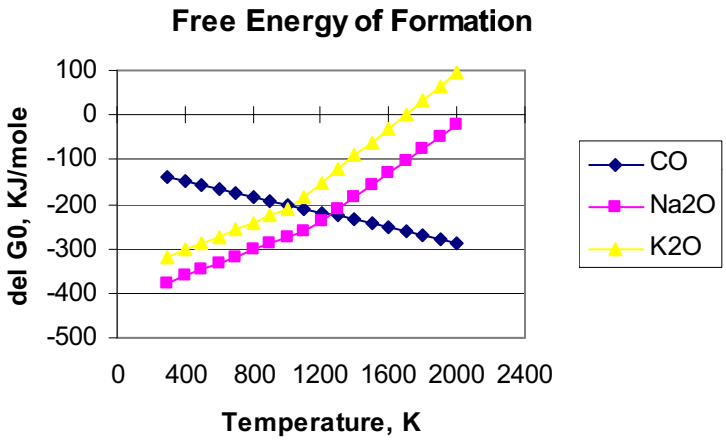


Fig. 20. The Ellingham oxide free energy of formation diagram shows carbon can reduce CaO, MgO, and Al_2O_3 at high temperatures making SEN clogging more frequent.

clogging, $\Delta\vec{V}$ and hence force $\vec{F}$ automatically become larger on that side of the SEN.

– In the EMLA mode (*subtraction* of the absolute velocity values), if steel goes faster on one side of the SEN because of SEN clogging, $\Delta\vec{V}$ and hence force $\vec{F}$ automatically become smaller on that side of the SEN.

The reasoning also applies when comparing stopper rods and slide gates. Mathematical simulations say that tundish slide gates may generate biased flow in the mold i.e., a flow that would go faster on one side, slower on another side and flip/flop all the time. In this instance also, the EMLS/EMLA modes will adapt automatically to the situation and

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maintain a uniform flow in the mold eliminating the predicted slide-gate's drawback.

The comment is of particular application in the EMRS mode: the 4 stirrers that generate the rotative movement of the mold adapt automatically to any variation of flow velocity and establish a very uniform distribution of steel i.e., of heat at the meniscus in the first solidifying shell.

4.3 Argon bubble pinholes – the surprising effect of steel composition

In Section 3.4, we have seen that mold flow pattern determines slab and coil quality. This is the reason why MM-EMS control models have been developed [10] that: (1) predict what the natural flow pattern in the mold is (in function of the slab width, casting speed, argon flow, SEN design, and SEN immersion depth), (2) determine the stirring mode that must be applied (EMLS, EMLA, or EMRS), and (3) calculates the electromagnetic force that is needed to generate the preferred flow.

Recently, it was observed that quality of some specific steel grades was better addressed with EMRS (the rotative function) than with EMLA (the accelerating function). In a sense, this is not surprising. Indeed, Physics tells us that all steel grades are not the same: some steels for example have the tendency to naturally collect and entrap argon bubbles! The result is what is now called "argon-based or pinhole-based slivers".

- ULC steels are known to form solidification hooks that are longer than on LCAK grades [15]: the lower the carbon, the longer the solidification hooks (Fig. 21), and the higher the propensity to collect argon bubbles in subsurface (Fig. 22).
- High-sulfur (0.018%) ULC grades were observed to specifically attract gas bubbles and entrap them in the slab subsurface because of a surface tension phenomenon [16].
- More surprising was an article W. Kesternich published in 1985 [17] which reported that titanium should be added to steels used in the nuclear industry because this would "introduce precipitates within the matrix as trapping centers for helium." It was tempting to extend the observation to argon bubbles that, indeed, are more frequent on Ti-stabilized (0.040%) ULC steels than on ULC grades with little or no titanium! We had to wait until 2006 to have this effect of titanium confirmed by Japanese steel researchers [18]. However, it is only in 2011 that Postech researchers [19] offered the well-awaited explanation: argon bubble entrapment in the solidified shell is a 2-step process that includes: (1) a heat gradient that literally pushes the argon bubbles to the solidified shell, and (2) a gradient of surface tension forces that catch/trap them. Sulfur and titanium are similar in the sense that their surface tension is low. We may apply the concept to explain the beneficial effect of EMRS on pinhole-based slivers: because of its homogenization effect of temperature near the solidification front, EMRS reduces the heat gradient and, hence also, argon bubble entrapment (one should not overlook the additional washing effect of EMRS, however).

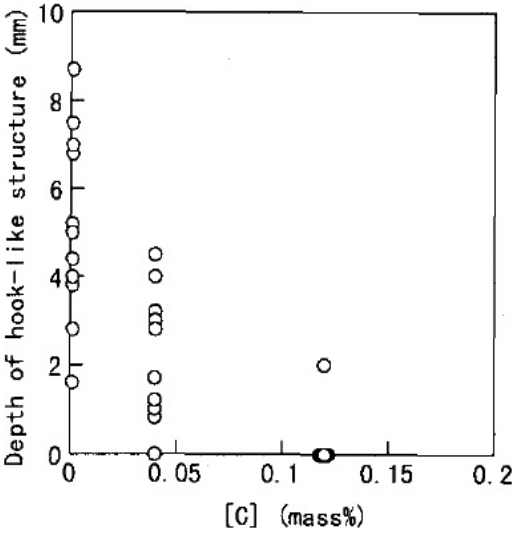


Fig. 21. The lower the steel carbon content, the longer the solidification hooks [15]. Note the ULC steel data very close to the y-axis.

The thing to remember from this section is that statistical analyses can be very tricky. We already learned that statistical analyses have to be performed flow-pattern domain by flow-pattern domain; now we learned that they also have to be done steel grade by steel grade! All other conditions being equal,

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Steel	Chemical compositions (mass%)					Solidifying temp. (K)		Temperature Gap Liquidus/Solidus
	C	Si	Mn	P	S	Liquidus	Solidus	
Ultra-low-carbon	0.001	0.10	0.50	0.01	0.01	1 805	1 801	**4**
Low-carbon	0.040	0.10	0.50	0.01	0.01	1 802	1 785	**17**
Medium-carbon	0.120	0.10	0.50	0.01	0.01	1 796	1 751	**45**

Fig. 22. Longer hooks and shorter liquidus/solidus intervals increases argon bubble and inclusion entrapment frequency [15].

ULC grades will contain more pinhole-based slivers than LCAK grades with a peak on high-sulfur, titanium-stabilized grades. This is frustrating!

5 Conclusions

The following highlights a number of bullets and key points that were discussed in this paper.

- Connecting the dots is key to knowledge advancement.
- The events we observe every day on our caster floors, the information we read in the literature, the conversations we exchange with our colleagues are pieces of a gigantic jigsaw puzzle that need to be put together to solve our quality, productivity and cost issues (safety is not addressed in this publication).
- A new way of looking at continuous casting machine performance is needed.
- *Cast One Ton, Sell One Ton* should be everyone's goal.
- Any cast ton that is diverted from its original order is a financial burden to the company.
- Any ton that is not cast at maximum speed is a production loss.
- Slab diversions at the caster are as detrimental (if not more detrimental) than rejections at the cold mill.
- Making good steel on first attempt is mandatory.
- Casting narrow slabs at maximum speed is mandatory.
- Steel flow pattern (i.e., the way steel moves in the mold) determines slab and coil quality.
- Reporting steel flow pattern in a slab-width/casting-speed diagram is very effective for solving puzzling steel-quality issues.
- There are 3 steel flow pattern domains: single-roll, unstable, and double-roll.
- The permanent unstable flow is undetectable on slab report cards; it results from specific combinations of casting speed, slab width, argon flow rate, SEN design, and SEN immersion depth.
- The permanent unstable flow is real and responsible for large amounts of unexplained steelmaking defects.
- SEN immersion depth must be added to the already long list of slab abnormality codes.
- Impact of steel composition (e.g., C, Ti, S) may not be overlooked.
- Statistical regression analysis must be conducted flow domain by flow domain, steel grade by steel grade.
- Being within 6-sigma IPC/SOP statistical control limits is of no comfort.
- Only one type of flow pattern (a not too-weak, not too-strong double-roll) can guarantee zero-defect product.
- Water models, mathematical simulations, and actual mold results are only identical for zero-argon casting conditions making in-situ, in-the-mold steel flow measurements indispensable.
- Electromagnetic stirring technology exists that can generate the optimum steel flow pattern independently from casting conditions; return on investment may be just one year. What is the industry waiting for?

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