ELECTROMAGNETIC STIRRING AND INDUCTION HEATING SYSTEMS

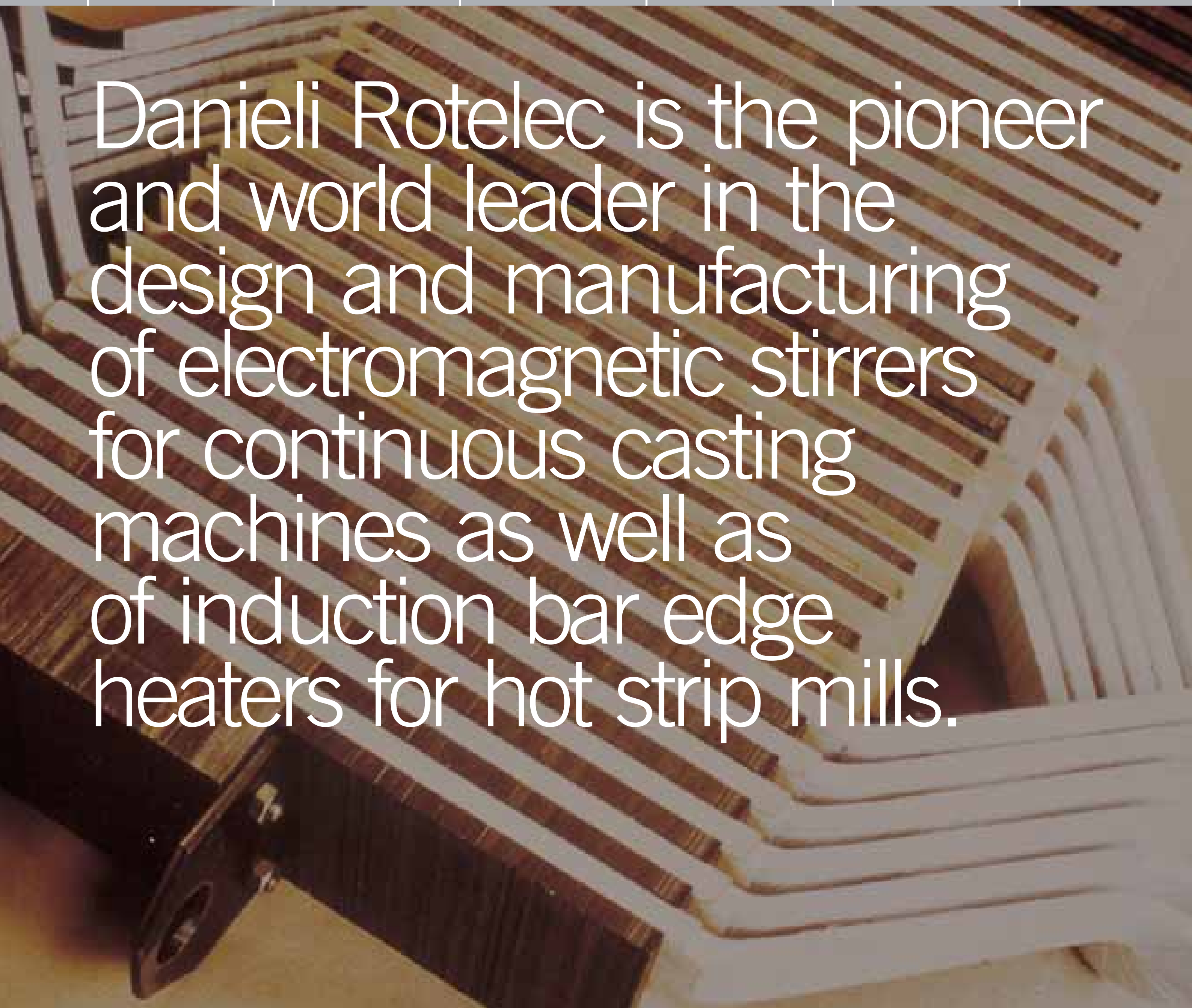
DANIELI ROTELEC

Danieli Rotelec

Electromagnetic Stirring
and Induction Heating Systems

France

Since 1977



Danieli Rotelec is the pioneer and world leader in the design and manufacturing of electromagnetic stirrers for continuous casting machines as well as of induction bar edge heaters for hot strip mills.

COMPANY PROFILE

Danieli Rotelec is a highly specialized supplier of electromagnetic technologies for the steel industry.

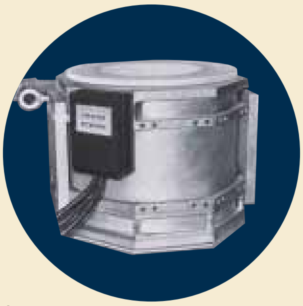
Danieli Rotelec's leading position goes back to the early 1970's when Irsid and CEM developed electromagnetic stirring (EMS) for continuous casting machines. Irsid was the world-renowned research center serving the French steelmaking industry. CEM was the Compagnie Electro-Mécanique, one of the two big electrical suppliers in France that later merged with its competitor Alsthom. Their world's first industrial application of electromagnetic stirring on a commercial continuous casting machine was a rotative strand stirrer in 1973 on the 240-mm square bloom caster of SAFE (now Ascométal) at Hagondange in France.
During the following years, the same partners developed mold and strand stirring of slabs and mold stirring of billets/blooms. The latter appeared the most promising in the immediate future and led to the creation of Rotelec.
In 1977, Rotelec was incorporated as a joint venture of Irsid, CEM, Arbed and Usinor to promote the newly developed mold stirring of billlets/blooms as a newly-patented technology under the name of Magnetogyr© Process. Arbed and Usinor (now both part of Arcelor) were two leading steel manufacturing companies in Luxemburg and France, respectively.
By its founders, Danieli Rotelec has the unique opportunity of combining in one same company metallurgical process know how (Irsid), feed-back of industrial results (Arbed, Usinor) and expertise in the designing and manufacturing of special inductors and electrical power supplies (CEM, Alsthom).
The name Rotelec stems from Rotation Electrique (Rotation Electrical) and reminds of the world's first industrial application of electromagnetic stirring in the mold on Arbed’s billet/bloom/round caster at Eschweiler (Germany) in 1977.

In 1987, the company made the decision to apply its electrical/electromagnetic know-how to another section of the steel industry, namely the reheating (by induction) of the steel transfer bars as they enter the finishing stands of the Hot Strip Mills.
In cooperation with Irsid and Sollac-Fos (now also part of the Arcelor group), a C-type inductor with automatic gap adjustment was developed and patented. A breakthrough in the business, the design rapidly superseded and replaced the traditional U-type concept.
Since 1991, Rotelec is part of the Danieli team and, with its technology and equipment, strengthens the billet/bloom and slab casting activities carried out by Danieli Centro Met, Danieli Davy Distington and Danieli Wean United, respectively. It also cooperates with the other machine builders on customer demand.
Danieli Rotelec's philosophy is that of tailor-made process and equipment technology with priority to best metallurgical results and highest equipment efficiency and life time.
It commercializes three product lines:

- Electromagnetic stirrers for billet and bloom casters.
- Electromagnetic stirrers for slab casters.
- Induction bar edge heaters for hot strip mills.

1 Danieli Rotelec Headquarters at Les Tours Mercuriales in Bagnolet/Paris.
2 Strand stirring on a bloom caster.
3 Induction Edge Heating for hot strip mills.

Danieli Rotelec technological milestones



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1968 First trials of electromagnetic stirring (EMS) for billets and blooms below the mold by Irsid and CEM. **1**

1973 World's first industrial application of electromagnetic stirring on a commercial continuous casting machine; rotative strand stirring on the 4-strand 240-mm square bloom caster of SAFE (now Ascométal) at Hagondange, France.

1974 First trials of EMS for billets and blooms in the mold by Irsid, Usinor, Arbed and CEM. **3**

1977 World's first industrial application of mold electromagnetic stirring on a commercial continuous casting machine; rotative mold stirring on the 4-strand billet/bloom square/round caster of Arbed at Eschweiler in Germany. **4, 5**

1977 Creation of Rotelec and commercialization of in-mold EMS under the name Magnetogyr© Process. **2**

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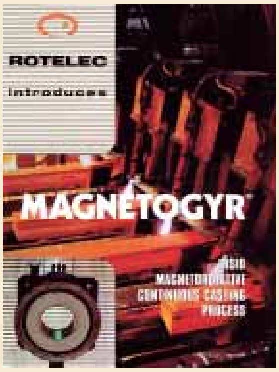

1978 Developments of In-Roll and in-mold EMS for slab casters by Irsid and CEM. **6, 7**

1979 World's first successful industrial application of In-Roll EMS on a commercial continuous casting machine; traveling magnetic fields in the rolls on the Usinor-Dunkerque slab caster in France. **8**

1980 Collaboration agreement between Rotelec in France and Kobe Steel in Japan; joint

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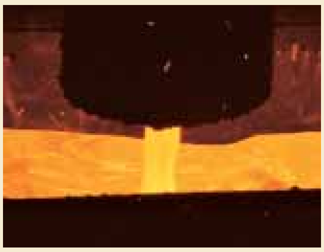

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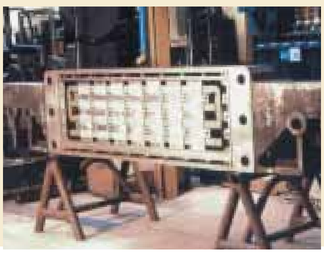

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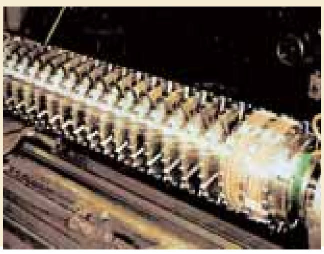

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licensing and marketing of the billet/bloom M + F (mold + final) combined stirring configuration under the name of Kosmostir-Magnetogyr Process. **10**

1981 Granting license to JME of Canada (now part of ABB) for joint marketing of billet/bloom EMS in North America.

1985 Merger of CEM and Alsthom.

1986 Rotelec becomes a subsidiary of Alsthom and covers the entire field of EMS activities i.e., in the mold and below the mold, for billets, blooms and slabs. Arbed, Irsid and Usinor/Sacilor remains as minority shareholders.

1987 Rotelec takes over the Alsthom activity that deals with induction heating; this includes steel bar edge heating in hot strip mills and steel/aluminum strip heating in coating and annealing lines. **9**

1991 Rotelec becomes a fully-owned subsidiary of Danieli.

2000 Collaboration agreement between Rotelec and Nippon Kokan Kabushiski Kaisha (NKK, now part of JFE); joint licensing and commercialization of the EMLS/EMLA mold stirring technology for slabs that allows slowing down or acceleration of the liquid steel stream at the exits of the submerged entry nozzle. **11**

2002 Development of Multi Mode EMS (MM EMS) process to address steel quality and machine performance issues on all-speed, all-width thick slab casters.

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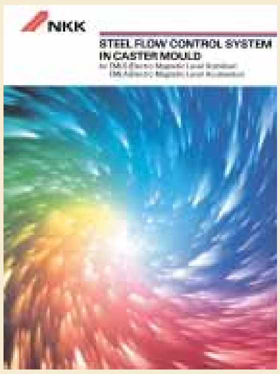
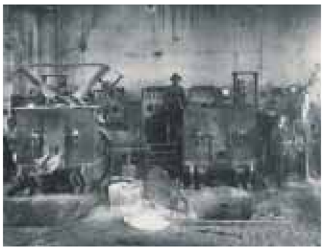


Danieli Group history



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1914
Danieli's origin dates back to 1914 when two brothers, Mario and Timo Danieli, founded the Angelini Steelworks in Brescia, Italy. This was one of the first Italian companies to use Electric Arc Furnaces in steelmaking. **1**

1929
Part of the Angelini Steelworks was transferred to Buttrio, Italy. In those days the Company manufactured tools for forging plants and auxiliary machines for rolling mills.

1955
Luigi Danieli took over the family business which, at that time, employed 50 people and started designing and manufacturing equipment for the steel industry. Mr. Danieli's idea was to manufacture more competitive equipment, simplify layouts and maximize the use of automation. One of the concepts developed, namely the "EAF - conticaster - rolling mill" production route, has characterized and contributed to the successful development of the minimill process which is widely adopted today.

1964
The first minimill was installed in Germany and the first continuous casting plant was installed in Italy with the Riva Group **2**. The success of the minimill concept spread to Spain, the USA and the Far East.

1977
The first large turnkey order was placed with Danieli for a complete steel mill in the former GDR **3**. Company turnover was 25 million Euro with 1,700 people employed.

1980
Mrs. Cecilia Danieli, who had managed the financial and administrative departments of the Group since 1977, was appointed Managing Director and Mr. Gianpietro Benedetti, who had been Group Sales Director since 1977, was also nominated Director of Engineering.

1981_1985
Numerous plants were supplied on a turnkey basis by Danieli in the USA, the Far East, the former Soviet Union and North Africa considerably increasing the Group's turnover **4**. The large-scale investments made in research enabled the company to achieve a leading position worldwide in plants for commercial long products.

1986_1990
The first direct casting-rolling plant for long products was built in Italy **5**. In the USA Danieli conquered 80% of the long product plant market. Morgårdshammar in Sweden

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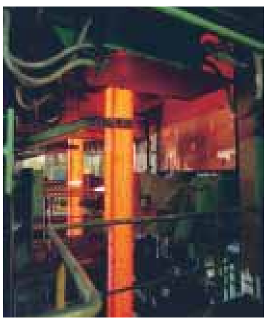
was acquired. The company, founded in 1856, was world leader in the supply of rolling mills for long products in special steels. Centro Met in Sweden was founded as a specialized team in steel melting and refining processes for quality steel production. The orders from major steel producers like Krupp, Cogne, Ovako, Teledyne, Uddeholm made Danieli an international leader in specialty steels. Futhermore an industrial-scale prototype of the Thin Slab Caster was created for research purposes.
Group turnover, which in 1980 was 67 M Euro, increased to 396 M Euro; employees reached 1,870 people.

1991_1995
Mrs. Cecilia Danieli was appointed Chairman of the Board and Mr. Gianpietro Benedetti was appointed President and CEO. A strategic decision was made to expand into the flat product sector which, at that time, was



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dominated by German, English and Japanese plant manufacturers. Danieli acquired Wean Industries and United Engineering in the USA, founded in 1929 and 1901 respectively which, between 1950 and 1980, designed and manufactured 60% of the plants for the production of flat products worldwide **6**. The value and importance of Danieli's technology in the flat product sector has been recognised since the beginning and this brought to a long series of significant orders like: the Thin Slab Caster revamp at Nucor Hickman; the Hot Strip Mill at North Star-BHP Steel;

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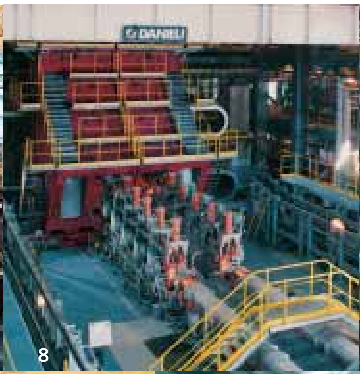
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the Thin Slab Caster and HSM at Algoma Steel, the first in the world to produce a wide range of quality steels, including peritectic; World leading companies Sund Birsta - finishing and tying services for long products, Sweden -and Rotelec - electromagnetic stirrers for casters, France - were acquired. The second unique "direct casing-rolling" plant in the world for quality steels at Republic Engineered Steels in the USA was commissioned **15**. Kia Steel, Korea, ordered an automatic conditioning plant for specialty engineering steels.

1996_2000

Cold Strip Mills were also supplied to Nucor Hickman, Usinor, Sidmar and Strip Processing Lines to Worthington Steel, US Steel, Galvak, Hoogovens, Sidmar, Stahlwerke Bremen **12, 13, 14**. Thin Slab Casters and Plate Mills were supplied to Nucor and to IPSCO, in the USA obtaining in 1999 the 30% market share. Danieli's world leadership for long products in commercial and special steels was consolidated with an international market share of 65%. It was furthermore decided that it would be strategically sound to continue manufacturing noble equipment in-house and, consequently, 130 M Euro were invested in a significant modernization of the mechanical workshops in Buttrio. In 1997 a major research project for the first endless casting and rolling for long products was given the go-ahead, the results of which could be seen in the year 2000.

In 1999 Danieli entered into a joint venture with Corus Technical Services to integrate its product lines with Blast Furnaces, converter meltshops and associated services. In the same year Danieli also acquired the patents of the "Arex" direct reduction process, an innovative technology that improves the efficiency of iron ore reduction process granting lower production and depreciation costs. Josef Fröhling, a German company specialized in narrow cold strip rolling mills and finishing plants for stainless steels and non-ferrous metals was acquiered. On June 17, 1999, at the age of 56, Mrs. Cecilia Danieli passed away; her contribution to the development of the company was invaluable. Danieli acquired Davy Distington, UK, a company specialized in engineering and design of slab and bloom casters. In 2000 Danieli had a sales revenue of over 930 M Euro, with some 3,200 employees in Italy, Sweden, Germany, USA, UK and France.

The most revolutionary endless casting-rolling minimill for specialty steel long products was started up at ABS, Italy **8, 10**. Thick slab caster orders were placed by Thyssen Krupp, and Sidmar (for the most technologically-advanced thick slab caster in Europe) **9**. An order for Blast Furnace revamping was awarded to Danieli Corus by Açominas, Brazil, following the ones from Riva Acciai and Corus UK. During this period Danieli completed its product range covering the whole steel production spectrum from iron ore to finished products.

2001_2004

Danieli increased its market share in China also with regard to flat products (e.g. Tangshan, Handan, Benxi, Tonghua, Anyang, Shaoguan) and started up several thin slab casting plants, setting the worldwide production record of 3 Mtpy with a 2-strand TSC at TISCO. Also the important thin slab casting and rolling plants of Ezz Flat Steel **7, 11** and Nisco were started up. Thanks to these successful start-ups Danieli definitively ranks among the front-runners in the supply of hot and cold rolling plants and processing lines for flat products. A second Casttgrind® plant for grinding of hot stainless steel slabs was supplied to Outokumpu Stainless. The most advanced conticasters for stainless steels were supplied and commissioned at Acciaierie Valbruna and NAS (Acerinox) with excellent performances in terms of surface and internal quality.

Significant orders for various technologically-advanced plants featuring Spooled bars-in-coil, endless rolling by billet welding, wire rod finishing at speed of 115 mps, the modernization and complete revamping of the VAS Donawitz rail mill in Austria and the startup of a complete minimill for special steels at Baosteel Shanghai No. 5, were acquired.

At Deacero, Mexico, a Danieli EAF with the performance of 42 heats per day set a new record. Important orders for thick slab casters from Baosteel and Arcelor confirmed Danieli technology leadership. Pelletizing and beneficiation plants supplied in Middle East opened new opportunities for the Company also in this field. Danieli entered the market of plants for seamless pipes and the newly formed Danieli Centro Tube was blessed by the acquisition of the order for the first hot and cold seamless pipe complex.

Danieli started its activity in 1914 and since then has manufactured:

101 Complete turnkey plants | 96 Blast furnace projects | 129 AC and DC Electric Arc Furnaces | 198 Secondary metallurgy stations | 1,414 Billet and bloom casting strands 1,541 Electromagnetic Stirrers for billets and blooms | 95 Thick and thin slab casting strands | 196 Electromagnetic Stirrers for slabs | 236 Hot and Cold strip mills

Scorecard

1 Aerial view of an 80,000-tpy steel complex for producing billets, blooms, forgings and heavy-drill rods.
2 400,000-tpy minimill for bars and sections.
3 700,000-tpy specialty steels producing complex.
4 1.2-Mtpy turnkey Thin Slab Casting and Rolling plant for the production of Ultra-Thin strip gauges.

23 Induction Edge Heaters for hot strip mills | 752 Strip processing lines
282 Specialty rolling and cluster mills | 342 Rolling mills for long products
64 Plant automation and process control systems | 1,050 Grinding machines
450 Drawing lines | 274 Extrusion and forging presses

5 185-t AC Danarc EAF equipped with Module technology.
6 Plate mill complex producing plates directly from medium/thin slabs provided by a 1-Mtpy Caster.
7 Danieli high-speed bar mill in a 500,000-tpy minimill complex.
8 6-stand finishing mill of the 1.35-Mtpy fTSR-flexible Thin Slab Rolling plant.

Strength and capabilities

Danieli Rotelec offers electromagnetic technology to fulfil the most demanding applications in terms of both quality and productivity.

Danieli Rotelec is the ideal supplier that brings unmatched capability to design and build a complete range of electromagnetic stirrers for continuous casting machines, for commercial and specialty steels, for long and flat products. It also brings 15+ years of expertise in the design and construction of induction edge heaters for hot strip mills.

Headquartered in Bagnolet/Paris, base of commercial/ development engineering, it has its own mechanical and electrical construction departments as well as manufacturing, assembling, testing and training facilities at Saint-Quentin-Fallavier/Lyon.

Danieli Rotelec is metallurgical know-how.
Danieli Rotelec is metallurgical know-how since its inception. The company finds its origin in 1968 after an idea from Irsid, the world-renowned research institute that served the French steel industry (now part of Arcelor, a 40-million ton-per-year group). It was the beginning of a long technical relationship that is still standing. In 30 years, its engineers commissioned close to 2,000 electromagnetic stirrers and induction edge heaters in 40 countries.

Danieli Rotelec is unique combination of concept and design.
All Rotelec stirrers and heaters are tailor-made. Each unit is conceived and designed at the company's technical department after discussions with the customers and the understanding of their metallurgical/productivity needs and goals.
All stirrers and heaters are built and tested at the Rotelec's own workshop. It is also where customers "get their feet wet" and receive hands-on training before their own equipment is packed and shipped to their steel plants. Each equipment is fully tested before shipping, including performance tests at maximum power.

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1-2 Assembly and functional test of single-head edge inductor for slab/transfer bar edge heating.

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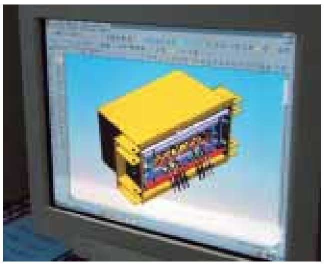
Danieli Rotelec is wide scope of services.
The company does not sell equipment and licenses only. It also provides extensive electrical, mechanical, process and maintenance training that usually takes place during the final tests at Rotelec's facilities on the running equipment, before delivery. It offers metallurgical guarantees, performance guarantees, on-site training and continued assistance after startup.

Research and Development.
Danieli Rotelec is a technical partner whose publications and presentations are internationally regarded for their right-to-the-point and stimulating topics. The company's R&D efforts cover such domains as mathematical modeling of liquid steel with or without the imposition of electromagnetic forces, pilot plant experiments on low-temperature melting alloys, and determination of liquid steel flow pattern in industrial caster molds.

Danieli Rotelec is versatility.
Its autonomous subsidiary status within the Danieli group entitles it to supply equipment regardless of machine builder.

3 External view of the Danieli Rotelec workshop at Saint-Quentin-Fallavier/ Lyon.
4-5-6 Mold stirrers for slab and billet casters, and single-head IEH pre-assembled and ready to be shipped.
7 3D rendering of a slab mold stirrer on a CAD station at the development engineering department.
8 Mathematical simulation of electromagnetic stirring in a billet/bloom caster mold.
9-10 Danieli Rotelec training activity.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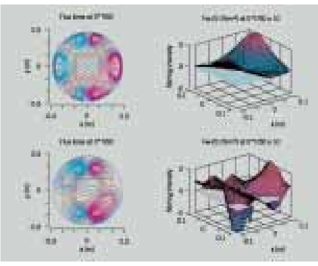
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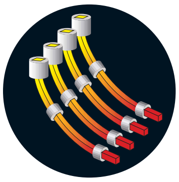
Production program

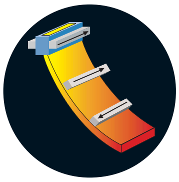
Danieli Rotelec designs and builds electromagnetic stirrers for billet, bloom and thick slab casters; it also designs and builds induction edge heaters for steel bars as they travel through hot strip mills.
Both technologies apply electromagnetic power that is either transformed into a force that moves liquid steel or into thermal energy that heats up solid steel. Danieli Rotelec engineers use Maxwell and Laplace fundamental equations to size the equipment that is required to generate the aim function.

Electromagnetic stirring for billet/bloom casters



Billet and bloom casters use rotative electromagnetic stirrers that generate the force required to move the liquid steel. Indeed, rotative stirrers can easily fit around billet/bloom product.
A rotative stirrer acts like the stator of an AC motor fed by a 3-phase electrical current. The stirrer surrounds the billet/bloom. The liquid steel becomes the rotor of the motor and is put in rotation around its axis in a plane perpendicular to the casting direction.
The movement propagates in 2 directions: above the stirrer by viscosity, below the stirrer by inertia. Billet/bloom rotative stirrers may be installed in the mold, along the strand, in the final stage of solidification, and any combination of it.
Current frequency is between 2 and 50 Hz depending on the application.

Electromagnetic stirring for slab casters



Linear, also called traveling, electromagnetic stirrers are used on slab casters as their large size would prevent the installation of rotative stirrers surrounding the cast product. Linear stirrers are fed with 2-phase AC current. They have to be understood as the stator of a motor that has been cut open and uncoiled along the width of the slab.
The result is a one-direction force in the slab that moves from one narrow face of the slab to the other. If the stirrer is installed in the strand, the induced movement generates circulating loops in the liquid steel, up and down, that are known as "butterfly" patterns. If the stirrer is installed in the mold, the force may be used to slow down or accelerate the liquid steel stream as it exits the submerged entry nozzle; it may also be used to put in rotation the liquid steel at the meniscus. Current frequency is between 0.5 and 6 Hz depending on the application.

Induction edge heaters for hot strip mills

Induction edge heaters act as electrical current transformers that generate fixed, transverse magnetic fields. In practice, the primary coils are disposed on a magnetic core that forms a C, with the hot band traveling in the gap. The primary coils are powered with single-phase AC current at medium frequency (300 Hz). The traveling steel bars act as the secondary coils; the eddy currents that are created heat up the steel. The originality of the Danieli-Rotelec-patented design lies in an articulation in the magnetic core that allows adjusting the gap, without magnetic losses, by independent movement of the upper and lower arms. As a result, high heating efficiency is maintained, even at large gaps, allowing to correctly reheat the bar heads and tails that are frequently deformed.

1 High-speed bloom caster for special steels at ABS Luna, Italy.
2 High-productivity two-strand slab caster for ULC, LC, MC and HC steels, including peritectic and microalloyed grades.
3 6-stand finishing mill in a 2.2-Mtpy slab casting and rolling plant.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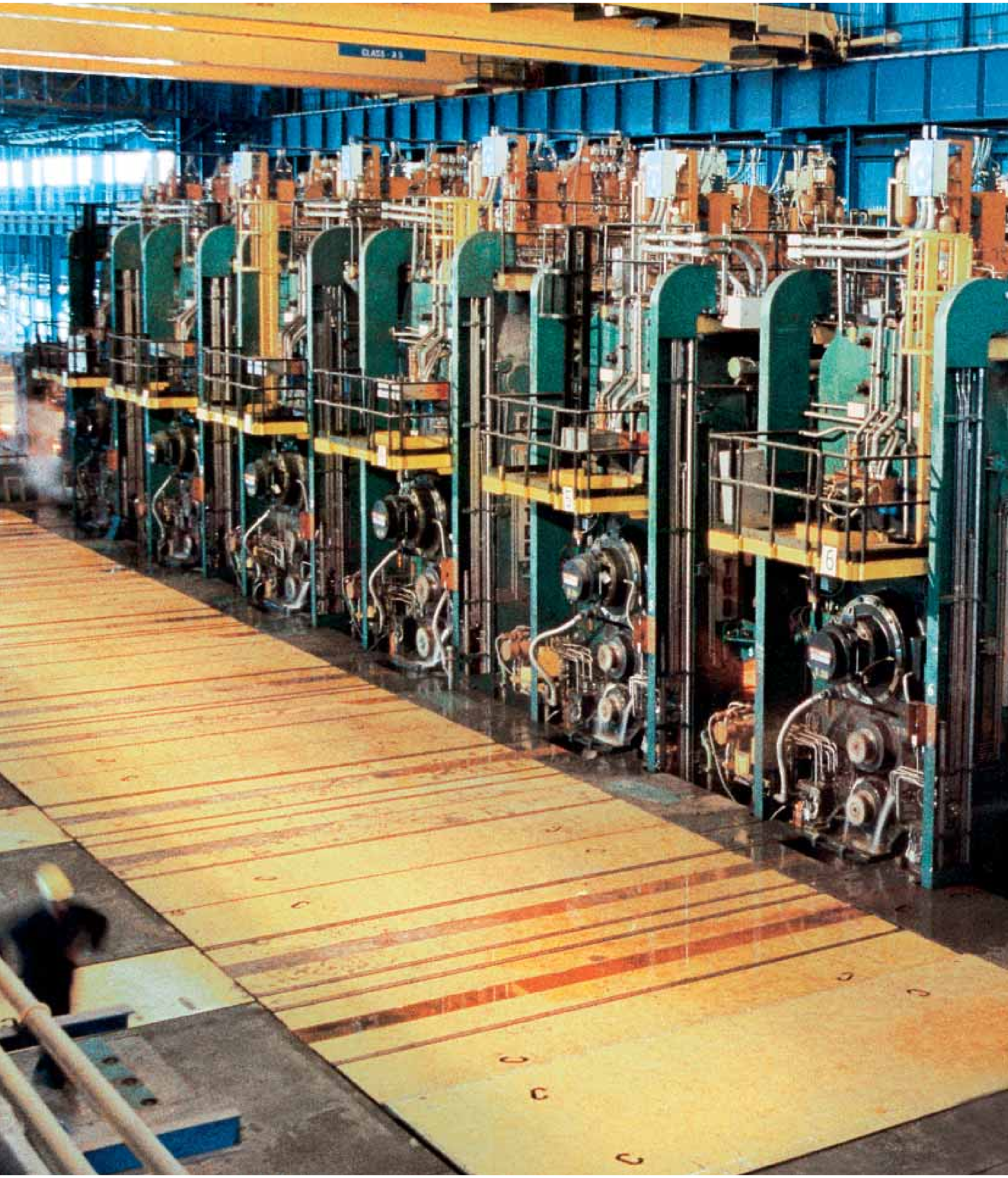
3

4-strand bloom conticaster for special and stainless steels and high and medium alloys, equipped with mould (internal) and final EMS.

Exit end of a two-strand slab caster equipped with INMO mould and Multi-Mode EMS.


DANIELI
DAVY DISTINGTON



Six-stand finishing mill in a 800,000-tpy hot strip mill for structural steels.

ELECTROMAGNETIC STIRRING FOR BILLET/BLOOM AND SLAB CASTERS

Danieli Rotelec designs and builds electromagnetic stirrers for billet, bloom and thick slab casters.
These technologies apply electromagnetic principles to generate forces that move the liquid steel. Control of the liquid steel movement improves product quality and caster productivity.

Principle
Liquid steel cannot be moved magnetically, since it is always above the Curie temperature and thus nonmagnetic. EMS does not mean magnetic but electromagnetic stirring. In other words, EMS uses electromagnetic forces like in an electrical asynchronous AC motor. One has to distinguish between rotational and linear stirrers (inductors, motors), the former applied to billet and bloom sections, the latter applied to slabs.

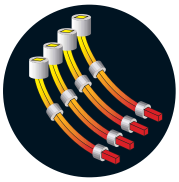
Faraday and Lorentz
The stirrer performance for both rotational and linear systems is given by the stirring force F, more precisely by the electromagnetic force density F (N/m^3), which depends on the relative velocity between liquid steel and magnetic field and on the magnetic induction B (Tesla or Gauss).
Faraday's law says that the magnetic field moving at speed V (m/sec) induces eddy currents J (A/m^2) that are perpendicular to V and B. Lorentz's law says that the eddy currents J combined with the magnetic induction B produce a volume force F that is perpendicular to J and B ('three-finger' rule) and thus parallel to V:
The velocity V of the magnetic field is given by the frequency f of the electrical power supply and Faraday and Lorentz laws become respectively

$J_z = \sigma V_x B_y$ and

$F_x = \sigma V_x B_y^2 \propto f B_y^2$

i.e., the volume force generated by a given stirrer in a given point of the steel is proportional to the power supply frequency and to the square of the magnetic induction in the same point inside the steel. To compute the total torque (in case of rotational stirring) or total thrust (in case of linear stirring) one obviously has to take the integral of F over the full volume of the liquid steel in the vicinity of the stirrer.
That means, the performance of a stirrer can not be characterized by the magnetic induction in only one point, although many people believe so.

EMS for billet/bloom casters



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The movement propagates in 2 directions: above the stirrer by viscosity, below the stirrer by inertia. Billet/bloom rotative stirrers may be installed in the mold, along the strand, in the final stage of solidification, and any combination of it. Current frequency is 50/60 Hz for strand and final stirrers of billets and < 10 Hz for all mold stirrers.

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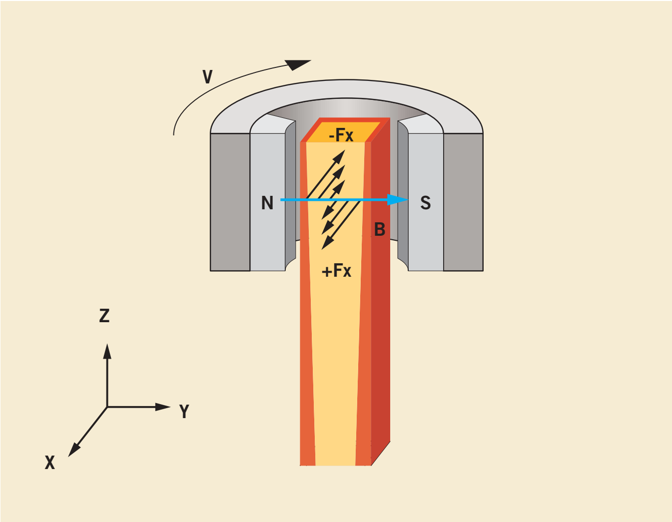
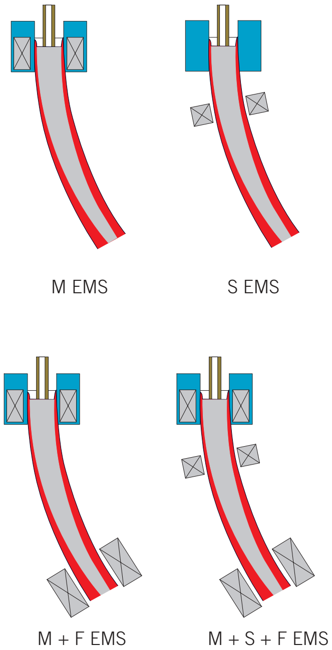


Strand EMS or Mold EMS?

In 1973, at Hagondange, the purpose of strand stirring was to improve internal quality of as-cast billets and blooms by eliminating mini-ingots, reducing center porosity and generating equiaxe structure. Less than 4 years later, driven by new metallurgical goals (surface quality improvement) and made possible by the availability of low-frequency current converters, the world's first industrial mold electromagnetic stirring application went on stream at ARBED-Eschweiler in Germany on a 4-strand square/round billet/bloom caster designed and built by Irsid/CEM.

In the decade that followed, both S-EMS (S for Strand) and M-EMS (M for Mold) co-existed, with M-EMS (Figure 2) progressively taking the lead as it was observed that M-EMS could improve not only surface quality (by washing the solidification front) but also internal quality. As a matter of fact, M-EMS could improve internal quality better than strand stirring! The reason for this second, unexpected result was puzzling, as in the early days many people believed that the enhancement of equiaxed zone observed with S-EMS was due to a mechanical effect of the stirrer that would break the tip of the dendrites. That opinion was wrong.
The explanation, that is now state-of-the-art, calls for a thermal effect, not a mechanical effect:

equiaxed structure can only develop if liquid steel is below liquidus temperature i.e., if superheat has been removed;
heat extraction from the liquid steel to the exterior is better in the mold than in the strand;
heat extraction is better when the liquid steel is in movement.
Stirring in the mold combines both mechanisms and is, therefore, a very strong steel superheat remover and equiaxed zone maker!



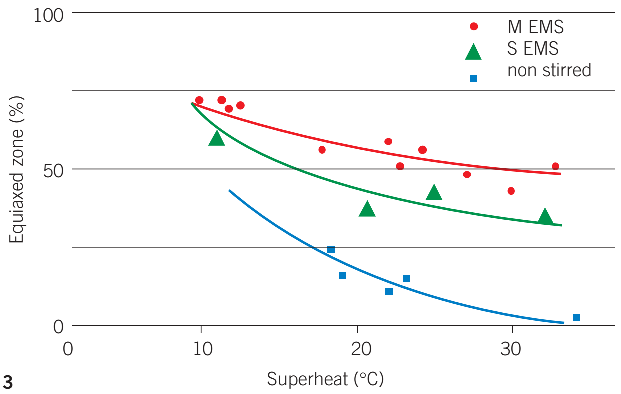
2

1 Schematic of EMS for billet/bloom casters.
2 Stirrers may be installed in the mold, along the strand or in the final solidification zone.

M-EMS and S-EMS comparison: metallurgical results on blooms and billets.

Type of stirrer	M-EMS	S-EMS
Surface / subsurface		
Pinholes	decrease ≈ 70%	no effects
Blow holes	decrease ≈ 70%	no effects
Slag entrapments	decrease ≈ 70%	no effects
Subsurface inclusions	decrease ≈ 70%	no effects
Surface cracks	eliminated under certain conditions	eliminated under certain conditions
Internal		
Equiaxe zone	40%	30%
White bands	no	yes
Internal cracks	eliminated under certain conditions	eliminated under certain conditions
Bridging	eliminated	eliminated
Porosity	index reduced by 2	index reduced by 1
Macro segregation	reduced by 40%	reduced by 20%

3-4
Mold EMS is better than strand EMS for equiaxed zone formation (240-mm size bloom AISI1548), both for centerline segregation (0.45% C rail grade, 240-mm square blooms).



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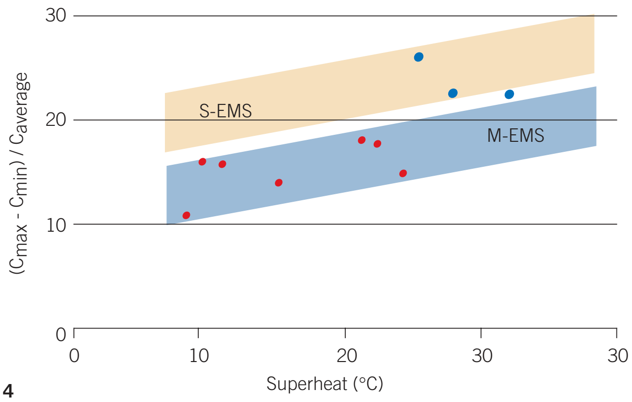

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Mold EMS for surface and internal quality

Currently, M-EMS, in spite of its higher cost, has replaced S-EMS because of the following specific advantages:

Improved surface and subsurface quality, an objective that is not achievable with strand stirring that comes after the fact (Figure 6, 7).

More uniform shell thickness, which may result in significant gains in casting speed and breakout frequency (Figure 5).

More equiaxed zone than with S-EMS due to the earlier elimination/dissipation of the steel superheat. As a result, center segregation and porosity are also better than with S-EMS (Figure 9).

Large elimination of negative segregation, the white-band defect typical of S-EMS, although in the latter case, white band can be improved with alternate stirring (a stirring mode that consists of reversing stirring direction periodically). Figure 8.

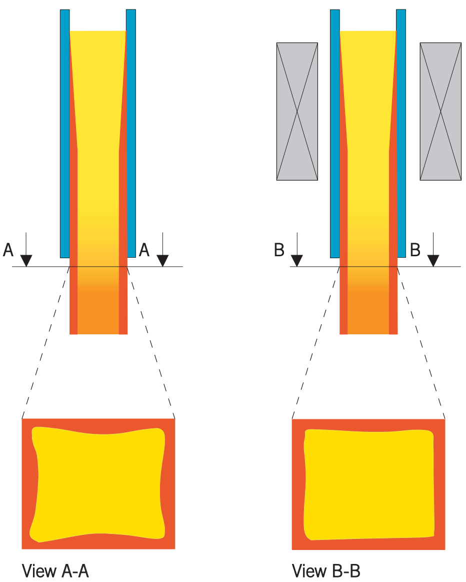
Significant reduction of centerline porosity.

Reduced centerline segregation.

If used in conjunction with F-EMS (an additional stirrer appropriately positioned in the Final mushy zone), the M+F EMS configuration will further minimize internal segregation and centerline porosity in specific high-carbon and high-alloy steel applications (Figure 10, 11).

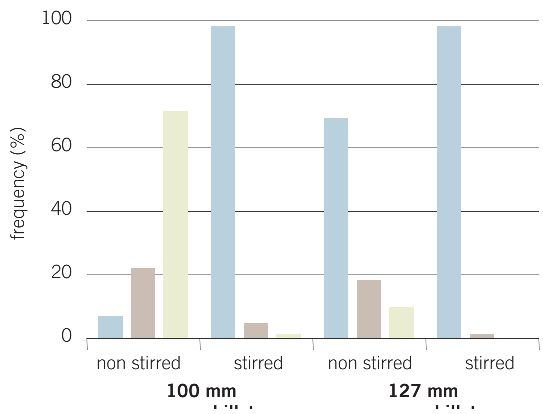
Nowadays, S-EMS is little used, except for some special cases and in multi-stage stirring combinations. M-EMS has replaced S-EMS for all billet and bloom sections and this up to the 400 mm x 600 mm section of BHP Newcastle.

5



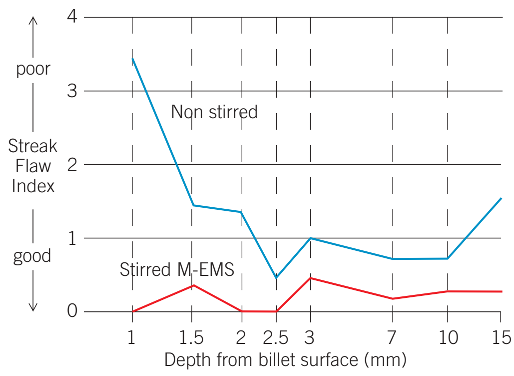
5 Mold EMS makes shell thickness more uniform allowing higher casting speeds without breakouts.

6



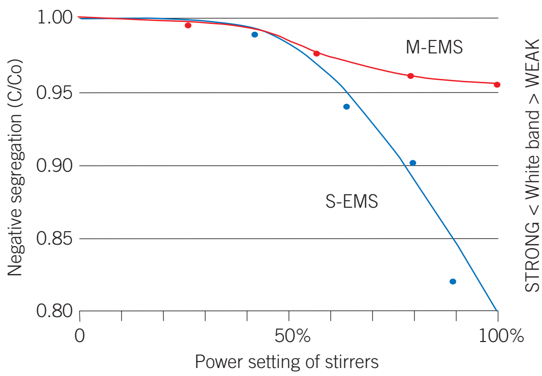
6 Mold EMS improves billet/bloom surface quality significantly (DIN 2275 grades):
0-2 defects / m², no conditioning;
2-20 defects / m², local manual conditioning;
over 20 defects / m², grinding of the entire surface.

7



7 Subsurface cleanliness for a 300x400 mm high carbon steel bloom.

8



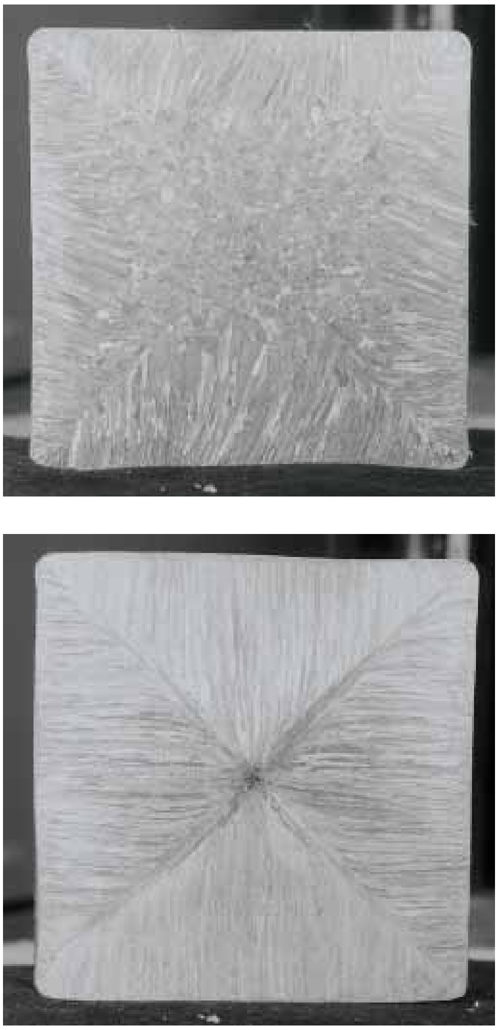
8 Mold EMS is better than Strand EMS for white bands (negative segregation).

9 **Mold EMS increases equiaxed zone significantly (up); 160-mm square blooms, AISI 409Nb grade.**

10 **Final EMS in combination with Mold EMS further reduces center segregation on high-carbon grades (from 1.12 to 1.08).**

11 **F-EMS needs:**
A) Efficient mould stirrer
B) Sufficient power and length of final stirrer
C) Fixed conditions of casting speed and cooling pattern: position P of final stirrer fixed –> L1 metallurgical length and casting speed fixed.

9



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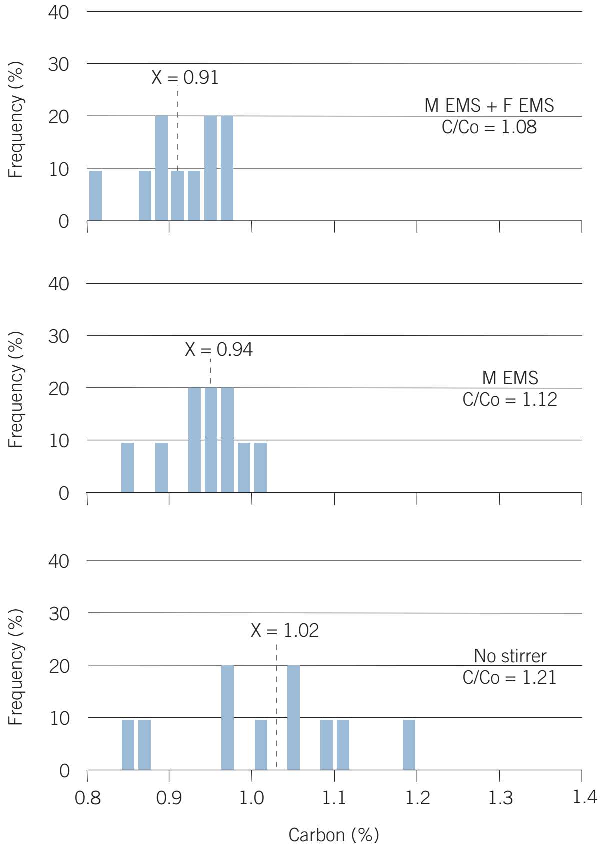

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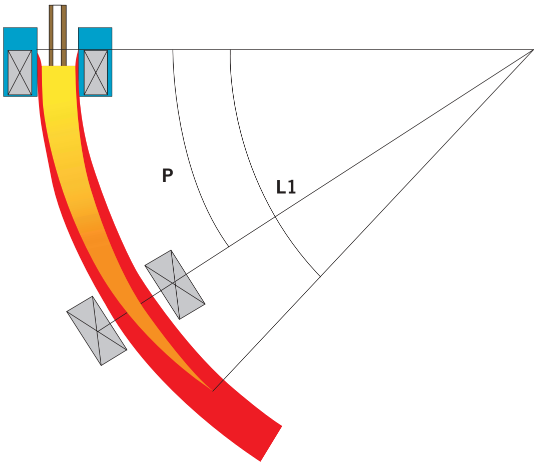


SEN erosion and mold powder entrainment dependent on SEN depth

Until the late 1990s, views against M-EMS were expressed in the literature emphasizing powder/slag entrapment and SEN refractory wear as dangerous drawbacks. The point was that a larger equiaxed zone requires a higher stirring intensity and that, beyond a threshold intensity, excessive steel/slag movements entrain mold powder, generate inclusions (figure 13) and increase SEN wear. Note that the SEN wear (figure 14) was not at the slag line but inside the bore and at the tip of the SEN.

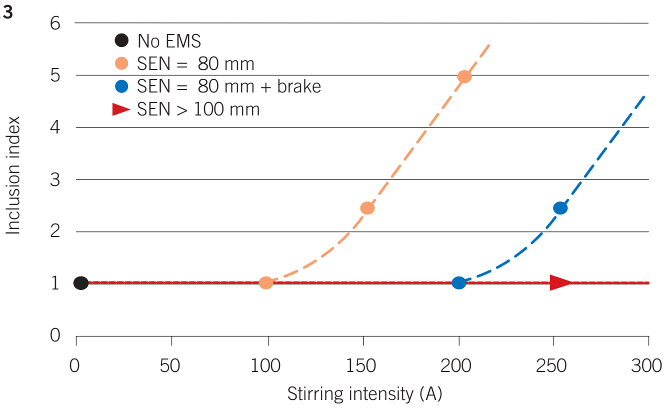
As an immediate result of these observations, several alternate EMS configurations were proposed in the market place as apparent "fancy" countermeasures (the Sub-mould, Combi and Dual designs).

A scientific, rational explanation of these observations and developments took much effort and long time (intensive experiments with Wood metal, comparative trials on an industrial billet caster, extensive steel cleanliness evaluations, sulfur prints, blue brittle tests) and led to thorough understanding of the mechanisms of M-EMS that was presented for the first time at the Madrid Conference in 1998.

Not only was it confirmed that improvement of internal quality on long products is best with M-EMS stirrer close to the meniscus, also it was demonstrated that powder/slag entrapment and SEN wear do not require "fancy" Mold-EMS countermeasures. They simply require stable mold level conditions i.e., a sufficient SEN immersion depth (and the use of mold level sensors that are not affected/fooled by mold powder slag thickness)!

12 SEN-Submerged Entry Nozzle wear that was believed to be due to M-EMS was in fact due to insufficient SEN immersion depth.

13



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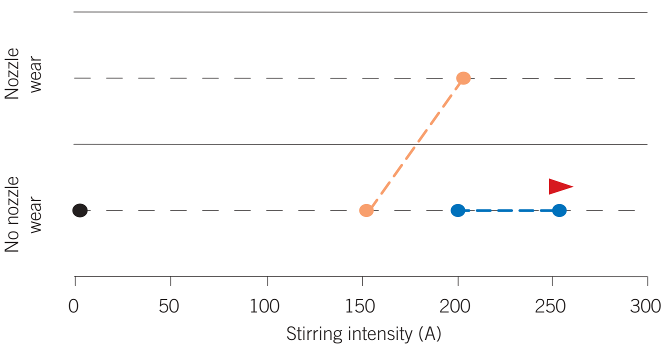


13-14 High stirring intensities above a certain threshold can generate powder inclusions, slag entrapment, and increased SEN refractory wear. That, however, depends on SEN immersion depth and can be prevented if the immersion of the SEN is deep enough: 130 mm vs. 80 mm in this example of a 150 mm square billet machine.

15

EMS Configuration	Steel Grades and Sections	Domain of Improvement	Primary Mechanism
Mold EMS (at meniscus level)	- All sections - All grades	1) Surface/subsurface cleanliness 2) Surface/subsurface integrity	Mechanically move inclusions, blowholes and pinholes away from surface thru: - Cleaning waves at the meniscus - Washing of the solidification front - Centrifugation of steel vs. inclusions
		3) Segregation 4) Porosity 5) Intercolumnar cracking 6) Grain/structure refinement	- Mix hot and cold steel - Promote early superheat removal - Promote wide/fine equiaxed zone - Reduce mini-heterogeneities - Chip/break large porosities - Eliminate long dendrite structure - Increase number of crystal nuclei and germs
		7) Shell thickness uniformity Breakouts frequency	- Reduce thermal unevenness between mid faces and corners - Move large inclusions away from first solidification shell
Strand EMS (below the mold; before the mushy zone)		- No surface quality improvement (items 1, 2, 7) - Limited internal quality improvement (items 3 thru 6)	- Not recommended unless used for large section in conjunction with a Mold EMS unit
Mold EMS + Strand EMS (between the mold and the mushy zone)	- Large sections e.g. 300x300 mm - All grades	- Consolidate/reinforce all above improvements (items 1 thru 7) - Specific focus on centerline porosity and segregation	- Additional mixing of hot and cold steel - Prevent dendrites to form again in the long liquid pool
Mold EMS + Final EMS (in the mushy zone)	- High carbon - High alloy with wide liquidus/solidus interval - All sections	- Consolidate/reinforce all above improvements (items 1 thru 7) - Specific focus on center segregation	- Additional mixing of high- and low-segregated domains within the mushy zone - Prevent segregation to propagate in mushy zone; destroy V-segregation channels

Table 15 lists internal and surface defects frequently observed on billets and blooms, for carbon and alloy steels. Typical EMS countermeasures are also listed. The comparison should help steelmakers determine what configuration is most appropriate to maximize the quality of their product.

The two predominant, successful EMS applications for billet and bloom casting are (1) M-EMS for low and medium carbon grades, and (2) M+F EMS for high carbon and high alloy grades.

S-EMS is only applied in some special conditions (large sections, in combination with Mold EMS).

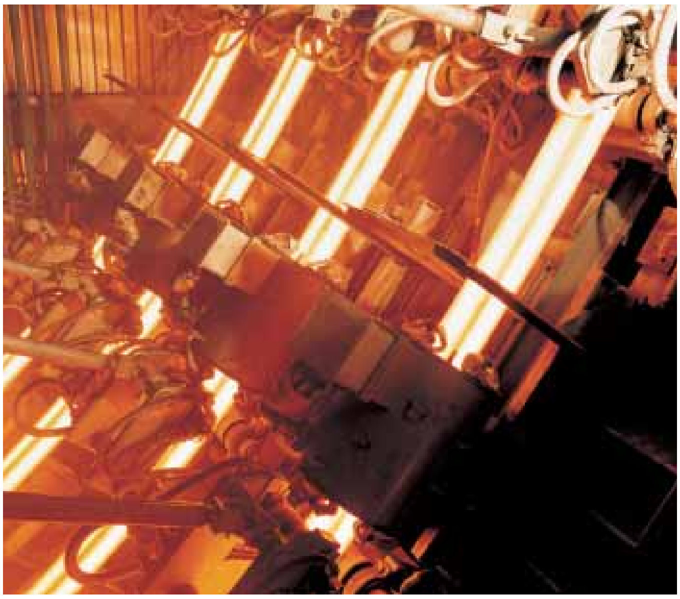
Benefits and incentives
Today, there is practically no quality-oriented billet/bloom caster in the world that does not have electromagnetic stirring. Simply said, it is a must.

Besides the very specific metallurgical benefits that were listed above (improved surface/subsurface quality, more uniform shell thickness, more equiaxed zone, less center segregation/porosity, less white band), other incentives include:

Extension of the product mix to high-quality specialty steel grades,

Maximization of caster productivity

And increase of prime billet/bloom application ratio up to 100%.



15 Carbon and Alloy Steels - Internal/ Surface Defects on Billets and Blooms and EMS Countermeasures.

Interface with Plant

20


21


Mold/EMS mechanical interface
Among the various technological options offered by Danieli Rotelec, are the internal/external installations to the mold, the immersed or hollow copper conductor constructions, and the separate or shared cooling system with the mold. Regarding this last item, it is important to mention that only the Danieli Rotelec coil technology of immersed windings is able to operate with normal, industrial mold water quality. Internal vs. external installation of the stirrers affects investment, operating costs and equipment reliability. Internal stirrers (one per mold) are closer to the strand; hence electrical consumption is less for a same stirring force (typically 20% less). External stirrers (one per strand) are further away from the strand but do not require electrical/water connections/ disconnections at each mold change; hence, less risk of polluting the water cooling system or damaging the electrical connectors. Internal stirrers are well suited for machines that cast wide ranges of sections or stirring performance would be very erratic. External stirrers may not be suited for installation on existing machines where only limited space may be available between strands. Other considerations are of importance. To name a few, external stirrers require the entire body of the mold assembly to be made of non-magnetic stainless steel while internal stirrers only require changes of the cooling chamber plates; also, depending on the type of construction that is adopted, the stirrer weight must be compatible with the mold oscillation system.
Water flow rates that are necessary to cool the stirrers depend on the electrical power

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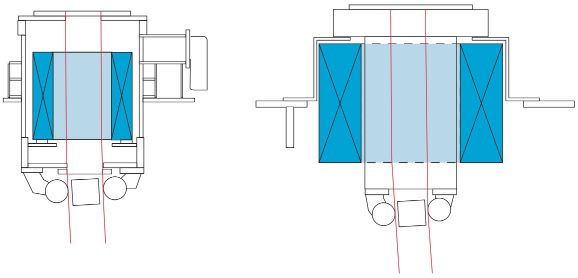

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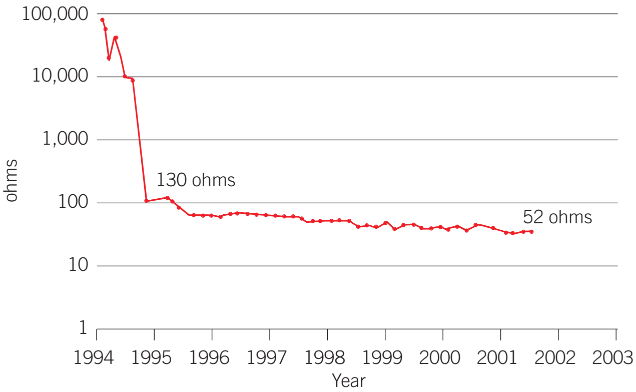

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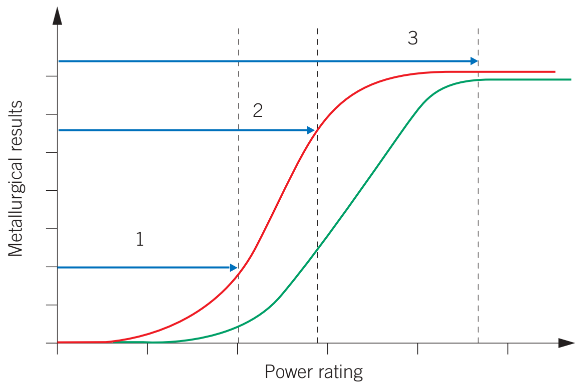


19


16 Molds stirrers are installed in the mold cooling chamber (left) or around the mold (right); 500/1,200-mm diameter, 200/1,500 kg, 80/500 kVA,200/1,000 A, < 10Hz.
17 Internal mold stirrers are cooled by mold water; electrical insulation is maintained for several years.
18 Justification of apparent, confusing, over-rating of electromagnetic stirrers: different steel grades respond differently to EMS settings (red and green curves) and need different power settings to reach aim results.
19 Equiaxed zone increase depends on power setting but is not linear.

22

20 **Small internal stirrer located inside mold assembly.**
21 **Big external stirrer surrounding the mold assembly.**
22 **Size comparison of strand (right) and final (left) stirrer designed for the same section size.**

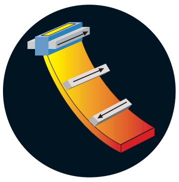
that is installed. Water quality is typically mold water quality, free of any solid particles, in particularly of ferro-magnetic particles that could damage the coils. Water flow meters and water temperature measurements are part of each stirrer protection system: electrical supply is automatically switched off when water failure is detected.

Power supply and utilities
It is the philosophy of Danieli Rotelec to maintain independence between each strand of the machine; hence, each strand stirrer is powered by its own electrical supply with its own transformer and PLC. Power supply is 3-phase, low- frequency and uses VVVF (variable voltage, variable frequency) transistor inverters with digital bus interface for current and frequency control.

Final stirrers
Final stirrers are always large and long as they need high stirring force to stir the mushy zone with small diameter and high viscosity. Their position(s) along the machine is (are) determined after thorough analysis of the casting conditions and metallurgical goals (casting speed, cooling rate, section size, grades) that need to be standardized to minimize the number of positions to be contemplated along the machine. Guiding rolls need to be placed before and after the stirrer to prevent damage to the coils. Water cooling and water flush are necessary.

Installation, commissioning and acceptance
Inspection and testing of the entire EMS equipment (electrical/ mechanical materials, components and sub-units) are integrated in the Danieli Rotelec manufacturing process. More specifically, complete functional and performance testing of the entire equipment is done at Danieli Rotelec workshop before shipment. This includes verification and calibration of electronics, controls and securities, complete electrical and thermal measurement, and establishment of stirrer's performance curves (magnetic torque vs. current and frequency. After assembling and testing, stirrers and power cabinets/ supplies are operated at full power for a minimum of 4 hours.
As a result, after installation on the caster, cold commissioning in presence of Danieli Rotelec supervisors, with control and adjustment of the operating parameters is very simple. Torque measurements are repeated (without steel in the mold) and coil current intensity/frequency setting recommendations are made in function of steel grades, sections and casting conditions; these settings are given as tables that can easily be integrated in the caster control computers. Experience shows that these recommendations are rapidly adopted by the customers after start-up, without modifications, allowing quick hot commissioning and acceptance.

EMS for thick slab casters



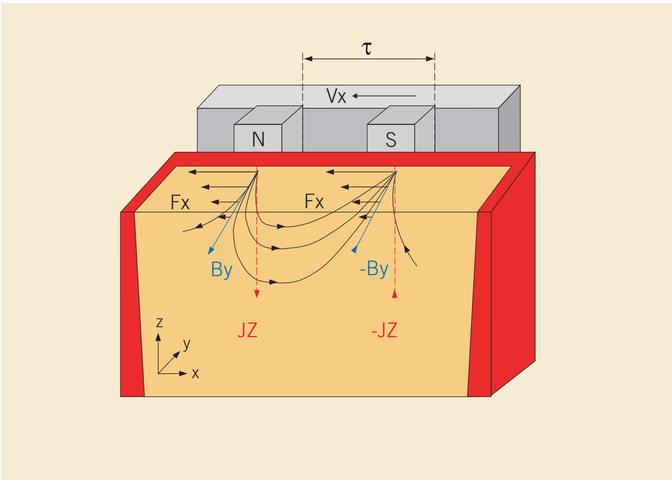
Linear -also called traveling field- electromagnetic stirrers are used on slab casters as the slab width would prevent the installation of rotative stirrers surrounding the cast product. Linear stirrers are fed with 2-phase AC current. They have to be understood as the stator of a motor that has been cut open and uncoiled along the width of the slab.
The result is a one-direction force in the slab that moves from one narrow face of the slab to the other. If the stirrer is installed in the strand, the induced movement generates circulating loops in the liquid steel, up and down, that are known as "butterfly" patterns. If the stirrer is installed in the mold, the force may be used to slow down or accelerate the liquid steel stream as it exits the submerged entry nozzle; it may also be used to put in rotation the liquid steel up to the meniscus.
Current frequency is between 0.5 and 6 Hz depending on the application.

Strand EMS or Mold EMS?

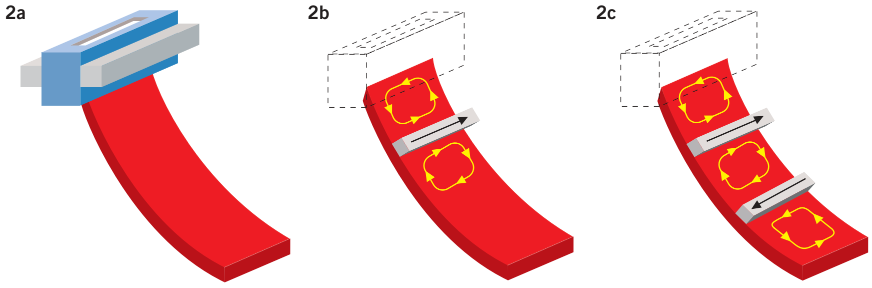
Backed by the experience gained with electromagnetic stirring for billet and bloom casters, Danieli Rotelec started as early as 1973 to develop strand- and subsequently mold- stirrers for thick slab continuous casting machines.

Strand stirrers
Strand stirrers address superheat removal, hence internal solidification structure, e.g., equiaxed zone, segregation and centerline porosity.
Historically, the first application of strand stirring on thick slab casters was for plate and tube grades with the goal of improving center segregation and porosity.
This function has now been replaced by soft reduction.
Nowadays, strand stirring is mostly used for ferritic stainless steels and high-silicon steels where the increase in equiaxed zone is known to reduce ridging and roping (a defect caused by solidification dendrites that "print out" on the coil surface after cold rolling) and sheet flatness (for example for electrical transformers).

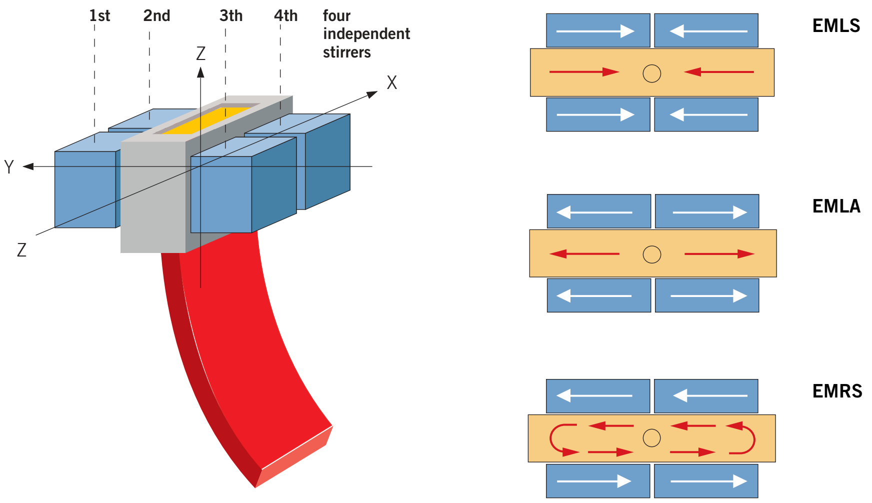
Mold stirrers
Mold stirrers address surface and subsurface slab/coil quality, e.g., slivers, longitudinal cracks, and inclusion content.
Their primary application is for low, extra-low and ultra-low carbon steels. Examples of goals are to maximize surface quality of coils for automotive applications, enhance internal cleanliness of D&I product for beverage cans, and eliminate longitudinal cracks on peritectic grades. In some instances, mold stirring also significantly improves casting operations, i.e., productivity (higher casting speed, less breakout alarms), yield (more direct prime slabs, higher slab application ratio) and energy consumption (higher direct hot rolling fraction).

1


1 Principle of linear stirrer with magnetic field B_y (Gauss) traveling at velocity v (m/sec) in x-direction inducing eddy currents J (A/m^2) in z-direction and generating volume forces F (N/m^3) in x-direction inside the liquid steel that decrease with increasing distance from the stirrer.

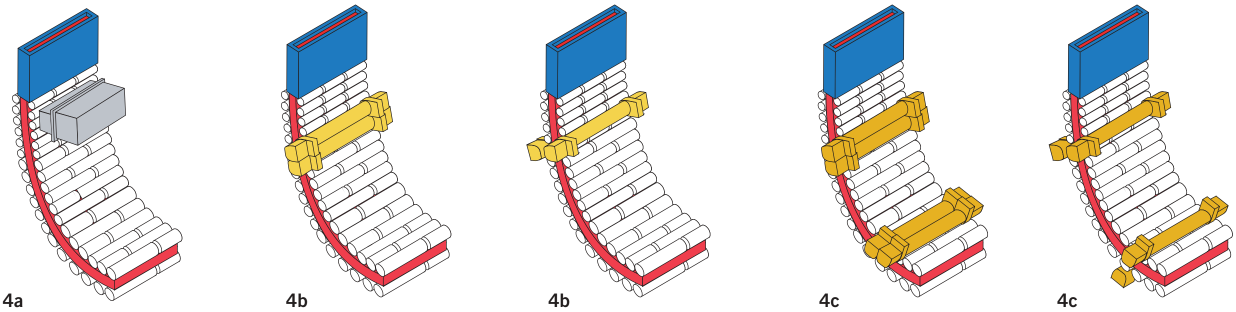


2 Different configuration of slab stirring:
a) M-EMS
b) Single stage S-EMS
c) Double stage S-EMS
Butterfly and triple-zero loops are generated by single-stage or double-stage stirring, respectively.



3 Four independent stirrers positioned at mid-height in a slab caster mold can slow-down, accelerate or put liquid steel in rotation (mold top view, MM-EMS process): EMLS, slowing-down function, magnetic field traveling inward; EMLA, accelerating function, magnetic field traveling outward. EMRS, rotative stirring, magnetic field traveling opposite.

Strand EMS for Internal Quality



4a 4b 4b 4c 4c

As a rule of thumb, the higher the stirrer in the machine, the better the heat removal and the larger the equiaxed zone, provided that the upper loop does not disturb the mold flow pattern that, as will be shown later, is key for steel surface quality.

Danieli Rotelec designs and builds two types of strand stirrers:

The box-type strand stirrer that is a good solution in the top of the caster where roll diameters are small, and the distance between stirrer and slab can be short (beyond 250 mm, very high electrical power is needed making this configuration expensive and space-demanding).

The In-Roll stirrers that are installed inside slab supporting rolls. They typically have a > 240-mm diameter. Machine builders now can design segments that accommodate such rolls even if the neighbor rolls do not have the same diameter. In-Roll stirrers are always used in pair to maximize stirring forces. If installed side-by-side, their function is equivalent to that of the box-type with the advantage that they can also be used in the lower part of the caster where roll diameter is larger. Front-to-front (one on each side of the strand) is the second possible configuration.

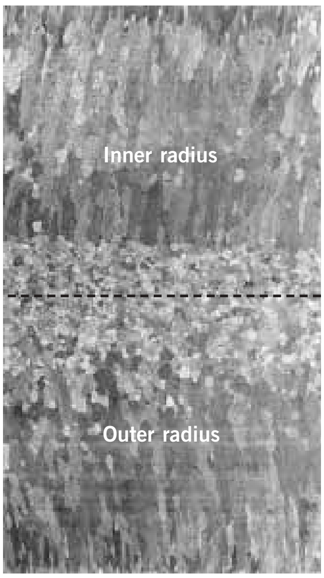
Strand stirrers can be installed in single or double-stage configuration. In-Roll stirrers are particularly suitable for double-stage stirring because of their easy positioning at different locations along the strand.

The macrograph on Figure 5 refers to stainless steel with 35 °C superheat and single-stage strand stirring. The typical asymmetrical equiaxed structure due to sedimentation of the solidification crystals to the outer radius of the strand is very apparent.

The Figure 6 shows that double-stage stirring can eliminate that asymmetrical distribution of the equiaxed zone. The Figure shows that double-stage stirring also makes equiaxed zone larger and more consistent than just single-stage stirring.

4 a) Box-type EMS for slab caster strands; b) In-Roll stirrers can be installed side-by-side or front-to-front c) In-Roll stirrers are suitable for single-stage or double-stage stirring.

5



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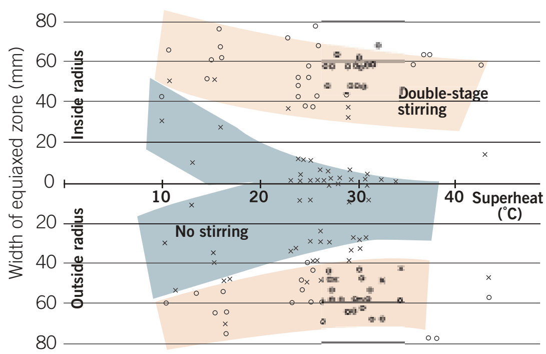


5 Macrograph of a stainless steel slab with 35 °C superheat and single-stage strand stirring.

6 Equiaxed zone versus superheat with In-Roll EMS (in beige) and without (in blue). Double-stage stirring eliminates the asymmetrical distribution of the equiaxed zone. Slab size: 1500-1800 mm x 250 mm; C content: 0.1-0.2 %; casting speed: 0.6-0.7 mpm.

Mold EMS for Surface Quality

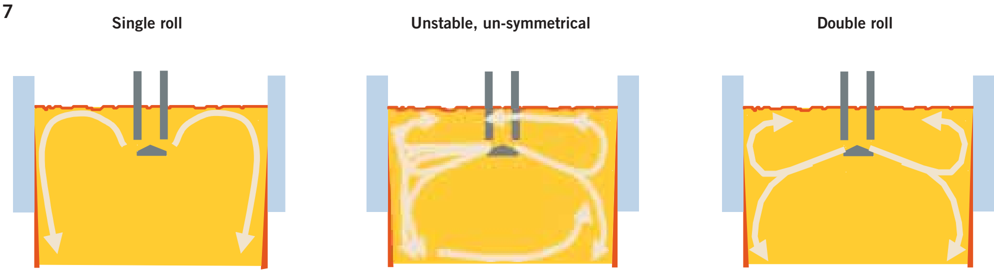
In 2000, Danieli Rotelec and NKK (now JFE) entered into an agreement to exchange their slab continuous casting know-how and jointly market the NKK EMLS/EMLA technology that can Slow down or Accelerate the steel as it exits the submerged entry ports.

The technology uses four Danieli Rotelec stirrers that are installed at mid-height in the mold (behind the back-up plates, two by two, on each side of the submerged entry nozzle) and extend over the entire width of the mold.
The technology is very versatile as, with proper electrical control, the direction of the four traveling fields can be selected so that forces can be generated inwards to slow down (EMLS), outwards to accelerate (EMLA) the liquid steel and also to put the steel in rotation in a horizontal plane at the meniscus (EMRS). (Figure 3).
Note that the left/right configuration of the four stirrers on each side of the SEN allows, if appropriate sensors are available, asymmetrical adjustment of the electromagnetic forces to compensate for biased/clogged SEN flow.

Mold EMS - Liquid steel flow pattern concept
The question of selecting the most appropriate electromagnetic stirrer to install on a mold remained puzzling until 2000 when the results of actual steel meniscus velocity measurements on two industrial casters were successively presented at the Nashville (1995) and Pittsburgh (2000) conferences.

It became clear that steel flow pattern in the mold is not just of any kind. It can be naturally single-roll, double-roll or unstable. The kind of flow that establishes itself depends on slab width, casting speed, argon flow rate and SEN depth/design (Figure 7).

7



Single roll is favoured by
- high argon
- large slab
- slow speed
- shallow SEN
- flat-up port angle.

Unstable flow can be anywhere (depending on the four parameters) and can be "permanently" unstable.

Double roll is favoured by:
- low argon
- narrow slab
- high speed
- deep SEN
- steep port angle.

7 The flow pattern in the mould of a slab caster depends on 4 parameters: argon flow, slab width, casting speed, SEN geometry and position.

It changes all the time during casting because of the changing casting parameters (e.g., slab width because of product mix, casting speed because of sequence casting, SEN immersion depth because of refractory erosion, argon flow rate because there are not necessarily standard operating practices on this item). However, both single-roll and unstable flows are causes of defect, and there is one preferred flow pattern: a not-too-weak, not-too-strong double-roll. Hence the dilemma: steel flow pattern controls slab/coil quality, but caster operators cannot control the flow. It became obvious, therefore, that the steel industry needed a technology that can steer the steel in the mold and drive it to follow the preferred flow pattern.

8 **Surface defects on cold rolled coils as function of meniscus velocity.**
9 **Blowholes count on broad and narrow slab faces with or without the use of EMRS.**

Mold EMS - EMLS/EMLA mode for high-speed casters
EMLS/EMLA is a technology specifically designed for high-speed (> 1.8 m/min) slab casters typically operating in the double-roll flow domain. Initially installed in the late '80s on the NKK Fukuyama No.5 slab caster, the technology was subsequently implemented in 1993 on the Fukuyama No.6 caster also. The early 2000s witnessed a boom in the development of the technology, with 4 units installed at POSCO: machines 3-3 and 2-1 at POSCO Pohang (commissioned in March 2002 and June 2005, respectively), machines 1-3 and 2-4 at POSCO Gwangyang (in June 2003 and August 2005, respectively). The purpose is to control meniscus steel velocity within an optimized operational window, independently of throughput and slab size. Indeed, operation/quality data shows that surface defects on cold rolled coils are minimum at this optimized meniscus flow velocity, alternately for that not-too-strong, not-too-weak double-roll flow pattern that was mentioned above.

At slow meniscus steel-flow velocity (i.e., low casting speed 1.0 m/min), alumina-based inclusions are formed because of weak heat transfer to the meniscus and long solidification hooks. Acceleration of the steel flow (EMLA) will bring more heat to the meniscus and save the situation.

At medium meniscus flow velocity (casting speed 1.5 m/min), the optimum of the operational window is attained, and inclusion content is minimum.

At high meniscus flow velocity (casting speed 2.0 m/min), large mold powder-based inclusions up to 300 microns are formed because of excessive meniscus flow velocity, mold level fluctuations and mold powder shearing. If at high casting speed, the EMLS slow down function is actuated, the powder-based inclusions disappear (Figure 8).

Mold EMS - EMRS for specific applications
The specific objective of the rotative function is to enhance circulation of the liquid steel at the solidification front with the goal of reducing/eliminating argon pinholes and CO-based blowholes as in pseudo-rimming steels for example (Figure 9).
Backed by more than 30 years of experience in the conception and manufacturing of electromagnetic stirrers, the Danieli Rotelec stirrers are strong and do not need to be installed close to the meniscus to generate the required rotative movement of the steel. The Danieli Rotelec solution maintains mold construction that is balanced, stiff and self-standing: no design complications such as thinner mold copper, reduced conductivity, shortened bolt pitch or asymmetrical structure.

MM EMS - A new Multi-Mode EMS concept for all-speeds, all-widths casters
Multi-mode EMS is a third generation of process control that was presented for the first time at the Birmingham conference in October 2002. Multi-Mode EMS combines, on one same caster, three electromagnetic stirring functions, namely slowing down, accelerating and rotating, and its control applies the most recent developments and knowledge on steel defect analysis/causes, fluid flow mechanics and MHD calculations. Its three functions are used in three operating modes:

The EMLS/EMLA operating mode that is used for high-speed casting.

The rotative EMRS operating mode that is used on specific grades.

The permanent operating EMLA accelerating mode that is used to transform defect-prone unstable and single-roll steel flow patterns into the preferred stable and optimized double-roll flow pattern. This is every caster operator's dream comes true: being able to create identical meniscus steel velocities and steel flow patterns regardless of changes in casting speed, slab width, argon flow rate, SEN immersion depth or design (Figure 10).

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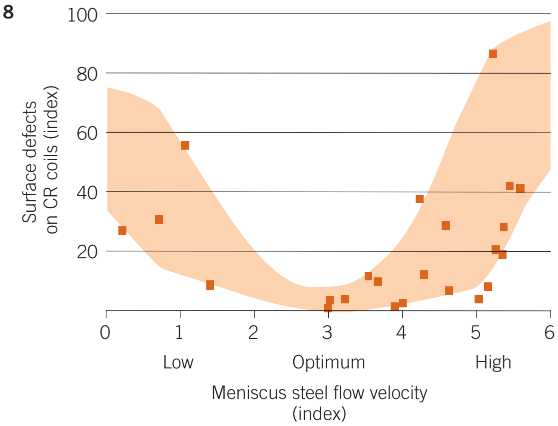

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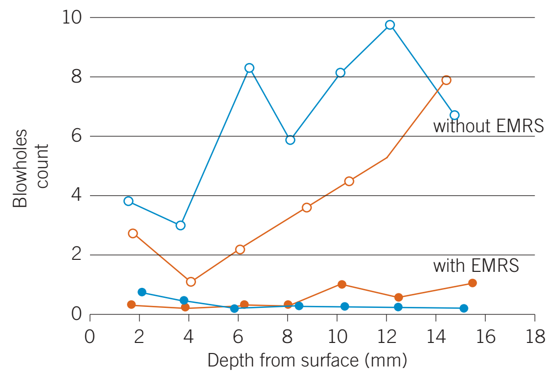

MM EMS - Process Control
The rotative EMRS mode is an on/off function. For specific applications (for example elimination of blowholes on pseudo-rimming steels), EMRS is switched on at full current intensity without any adjustment made in function of the casting conditions. With EMLS/EMLA we enter into a second generation of sophisticated flow control that

10 EMLA progressively transforms single-roll flow patterns into unstable and eventually double-roll flow patterns (mathematical simulation on one half mold).

11 2D simulation showing how increasing argon flow rate can transform a double-roll flow pattern into an unstable and eventually a single-roll flow pattern.

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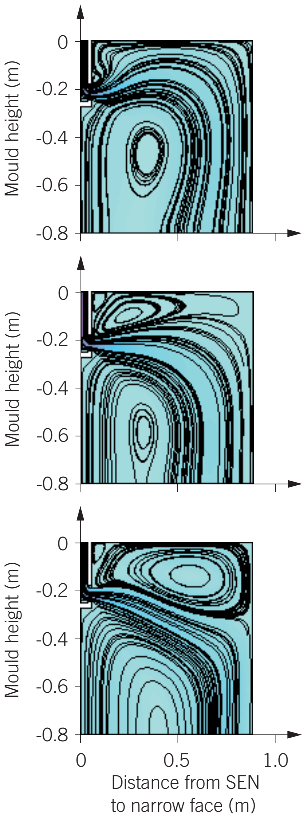
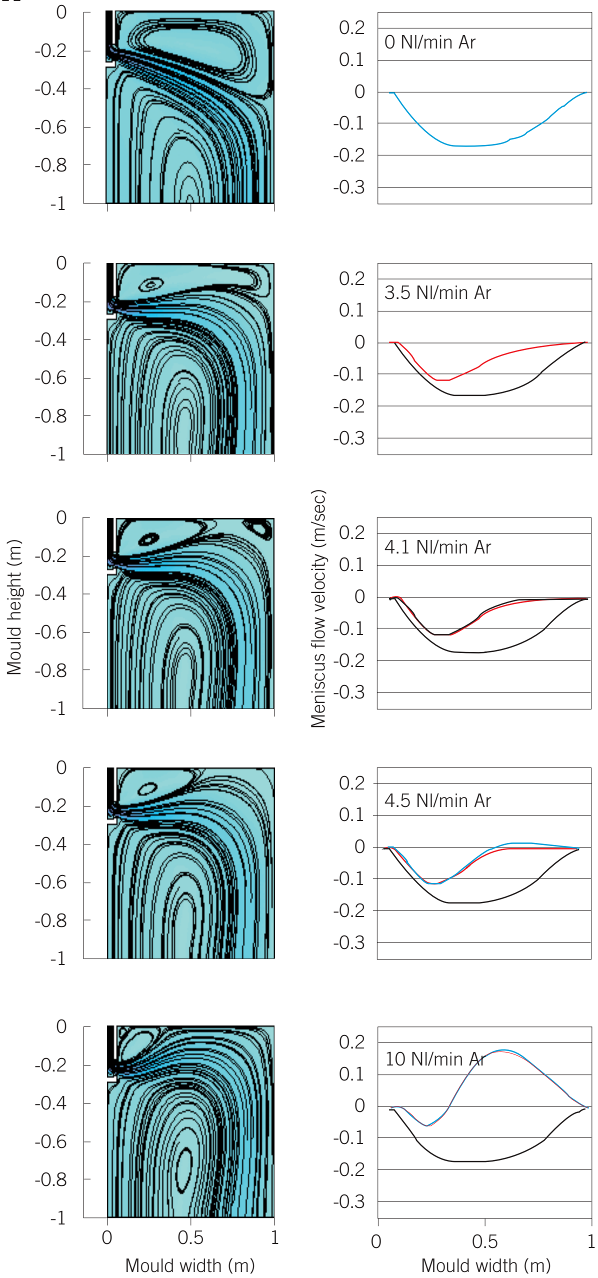


can no more be operated manually. The decision to slow down or accelerate, and at what intensity, is made in real time by a predictive computer model in function of slab size, casting speed, SEN geometry/depth and argon flow rate. It is the so-called F-value process control operation introduced by NKK (now JFE) in the early '90s.
The industrial application of MM-EMS requires automatic process control similar to that of the EMLS/EMLA operation. As there are, currently, no on-line steel velocity sensors that are compatible with EMS under industrial caster operation, a feed-back regulation mechanism is not possible yet. Hence, models have been developed that can (1) predict the "natural" steel flow pattern that results from the actual casting conditions: this is a fluid mechanics problem, and (2) predict the "electromagnetically-forced" steel flow pattern that results from the application of EMS forces: this is a MHD problem. Those models have been presented for the first time at the EPM conference in Lyon in October 2003. They were verified with data from four casters: LTV Indiana Harbor No. 2, JFE Fukuyama No. 5, POSCO Pohang No. 3-3 and POSCO Gwangyang No. 1-3 (nail board and refractory paddle measurements).

Figure 11 shows that the fluid flow model reacts well to changing argon flow rates with five simulations presented at 0.0, 3.5, 4.1, 4.5 and 10.0 l/min argon. Slab width is 2,000 mm, cast at 1.0 m/min, 20° downward rectangular-port SEN and 180-mm immersion depth.
For each simulation, steel flow trajectory is displayed on the left-hand side of the figure (half of mold width). Corresponding meniscus horizontal flow velocities are on the right-hand side. Double-roll flow (DR) that is characterized by negative meniscus flow velocities (from the narrow slab face to the SEN) is obtained without argon. Single-roll flow (SR) that is characterized by positive meniscus flow velocities (from the SEN to the narrow faces) is obtained at 10 Nl/min argon. Unstable flow (U) appears around 4 Nl/min argon: the progressive breaking/fracture of the upper loop of the flow and the simultaneous transition from double to single-roll flow are well apparent.

11



Mold or Strand EMS, What for What?

Tables 1 and 2 are decision-making trees that should help steelmakers determine what type of stirrers they may need.

1 - Internal defects on slabs/coils and strand EMS countermeasure (Carbon and stainless steels).

Strand EMS Countermeasures	Steel Grades	Typical Associated Defects	Superheat	Primary mechanism
Single-Stage EMS Box-type (behind the rolls) or In-Roll type one pair	Stainless Steels Ferritic Stainless Steels Austenitic	- Dendritic solidification structure - Segregation - Ridging/roping - Intergranular precipitation of non-dissolved components that create large undeformable inclusions	< 25° C	- Mix hot and cold steel - Promote early superheat removal - Promote wide/fine equiaxed zone - Reduce mini-heterogeneities - Chip/break large porosities - Eliminate long dendrite structure - Increase number of crystal nuclei and germs
	Silicon steels	- Dendritic solidification structure		
	Medium to high carbon steels for plates and tubes	- Centerline segregation - Centerline porosity - Crack susceptibility		
Double-Stage EMS In-Roll type two pairs	Same as above	Same as above	> 35° C	Same as above

2 - Surface/subsurface defects on slabs and coils, and Mold EMS countermeasures (Carbon steels).

Flow Pattern	Associated Negatives	Examples of Induced Steel Defects	Solution
Too fast Double-Roll	- Excessive narrow-face wave height - Excessive meniscus velocities - Excessive mold level fluctuations - Slag thinning near the narrow faces - Mold powder shearing	- Mold powder-based defects (slivers, pipe) - Loss of lubrication - Breakout events - Breakout alarms	EMLS (slowing down mode)
Optimum Double-Roll		- Minimum defects	
Weak Double-Roll	- Reduced heat transfer to meniscus - Reduced mold powder melting rate - Slow meniscus velocities	- Alumina-based defects - Cold/frozen meniscus - Slag spots - Sticking alarms	EMLA (accelerating mode)
Permanent Unstable and Transitioning Double/Single	- Steel flow reversion - Abrupt/local meniscus velocity increase - Flux entrainment - Flux vortexing	- Slab casting abnormalities - Downgraded slabs - Various unexplained defects	EMLA (accelerating mode)
Single-Roll	- Slag thinning near the SEN - Un-opposed, full-momentum flow of steel to the narrow faces - Un-opposed drive of argon bubbles and inclusions to the slab edges	- Mid broad-face longitudinal cracks - Alumina-based inclusions - Argon bubbles and inclusions accumulation in a 30-cm band along the slab edges	EMLA (accelerating mode)
Biased Right/Left Flow	- Asymmetrical/unbalanced flow - Mold level fluctuations - Non-uniform molten slag layer	- One-side accumulation of bubbles/inclusions	Asymmetrical Forces (individual right/left control)
Sluggish Flow at the meniscus	- Non-uniform steel velocities and temperature gradients along mold perimeter - Non-uniform solidification shell thickness - Weak heat convection to the mold faces	- Subsurface alumina and calcium aluminate inclusions - Argon-based pinholes in fully-killed steels - CO-based blowholes in pseudo-rimming steels - Longitudinal cracks on peritectic grades	EMRS (rotative mode)

Benefits and Incentives
Table 3 lists typical benefit areas of the Multi-Mode EMS system. Customer satisfaction (less claims and better coil quality ratings), better yield (less slab downgrading abnormalities, more prime slabs, less alumina/powder defects, less conditioning) and casting operation improvement (higher productivity, casting speed increase without defect increase, better copper/strand lubrication) are some of the incentives that are claimed for this technology.

3 - Benefit areas of Multi Mode EMS.

Molten slag layer thickness (constant over entire mold width)
Mold flow pattern (same, regardless of casting conditions)
Slivers (mold powder and alumina-based)
Subsurface cleanliness
Inclusion index
Blowholes and pinholes
First, last and transitioning slabs
Breakout alarms
Mold level control performance
Frozen meniscus
Maximum casting speed
Average casting speed
Caster productivity
Steelmaking rejection on cold-rolled product
Customer satisfaction (claims)
Slab application ratio

Design and installation

S-EMS Interface with caster - Mechanical interface
Danieli Rotelec has extensive collaborative experience with the world's main machine builders regarding implementation of S-EMS for new or revamped slab casters.
Basically, the installation of In-Roll stirrers on an existing caster requires much less mechanical modifications of the involved segment(s) than a box-type stirrer, especially if the normal rolls have a diameter close to the In-Roll stirrers.
The implementation of stirring rolls in a segment (typically in segment No. 1 (Figure 12), sometimes in segment No. 0) is just like for normal rolls.
The solution is very flexible, as roll positions may be diverse along the machine; the positions may be relatively easily modified after startup provided options have been provisioned for at the engineering stage.

In contrast, box-type stirrers require heavier mechanical adaptations/alterations to the design of the machine environment:
- Special segment design for insertion of the stirrer close to slab surface, while minimizing roll and segment bending.
- Part of the segment made of non-magnetic stainless steel.
- Rolls in front of the stirrer made of heat-resisting, non-magnetic stainless steel (same material as the sleeves of the In-Roll stirrers).
- Insulated bearings for the rolls located in the magnetic field.
- Optional stirrer-withdrawal device for quick segment change.

S-EMS - Single-line diagram
Electrical power supply of the stirrers consists of the following devices (Figure 13):
- One medium-voltage panel (usually supplied by the End User).
- One power transformer for voltage adaptation.
- One power-supply cubicle, including a diode rectifier and an IGBT inverter controlled by Pulse Width Modulation.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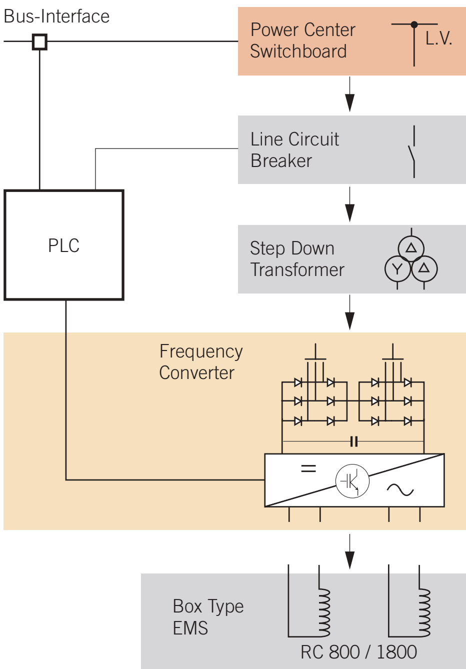

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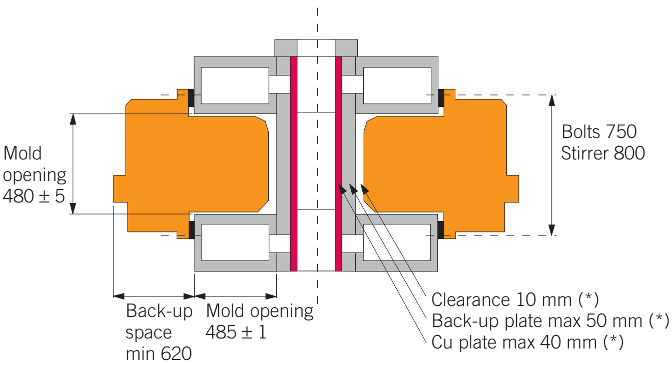

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- Two connecting boxes. to switch from normal power cables to heat resisting ones.

Because of the longer stirrer-to-slab distance, box-type stirrers demand, of course, more electrical power than In-Roll stirrers.

S-EMS Interface with Plant - Utilities
Strand EMS equipment needs the following utilities:
- Electrical power supply from the medium voltage mains.
- Electrical auxiliary power supply.
- Mold-water quality cooling water for In-Roll stirrers, de-ionized cooling water for box-type stirrer. Danieli Rotelec may alternately supply a water cooling and de-ionizing unit, for which primary industrial water will be required.
- Industrial cooling water for high-power inverter of box-type stirrer.
- Dry air or nitrogen to pressurize box-type stirrer.

MM EMS Interface with Caster - Mold mechanical interface
Danieli Rotelec has extensive collaborative experience with the world's main machine builders regarding implementation of MM-EMS equipment in slab caster molds. A typical mold mechanical interface is shown in Figure 14.

MM-EMS does not require any special mold design. Copper type and thickness are standard, and the stirrers only need a cavity to be inserted in, behind the backup plates, between the two water boxes. In contrast to other electromagnetic mould equipment, MM-EMS molds remain balanced, stiff and self-standing.

Backup plate thickness also remains standard.
Typical dimensions are:
- 40-mm thick copper plate and 50-mm thick back-up plate (or 30/80 mm, respectively).
- In conjunction with 81-%

IACS mold copper and 15-mm stirrer to back-up plate air gap.

Neighboring steel parts exposed to the magnetic field must be made of non-magnetic material, typically austenitic stainless steel, to minimize magnetic losses:

The back-up plates.

The mold cover (totally or partly according to its design).

And some mechanical components in the mold width change system.

MM EMS Interface with Caster - Electrical coupling

Electrical coupling between power supply and stirrers can be accomplished two ways:

1. With the Danieli Rotelec-patented QCS (for Quick Coupling System) that also allows quick mold change. It consists of (i) an upper part (including male connectors) that is assembled onto the mold and oscillates with it, (ii) and a lower part (including female connectors) that is moved up and down, by (iii) a hydraulically-actuated carriage fixed on the machine structure. QCS requires a simple mechanical interface to be agreed on with the machine builder.
2. With connection boards mounted on the mold frame or the machine structure nearby, for manual connecting and disconnecting.

MM EMS Interface with caster - Influence of magnetic fields on neighboring sensors

The anti-breakout thermocouples are affected by the low-frequency AC field, and a noise filtering system is included in the supply that eliminates interferences.

The NKK/JFE-NIRECO mold level sensor is not affected by the magnetic field.

Other mould width and mould level sensors may or may not be affected by the magnetic field. Countermeasures are specific to casters and must be addressed by each End User, individually.

MM EMS Single-line diagram

The electrical power supply of the stirrers consists of the following devices:

One or two medium-voltage panels (usually supplied by the End User).

One or two power transformers for voltage adaptation.

Two power-supply cubicles (left and right sides), each including a diode rectifier and an IGBT inverter controlled by Pulse Width Modulation.

Two inversor-switch cubicles to switch between EMLS/EMLA and EMRS.

Two connecting boxes to switch from normal power cables to heat resisting ones.

Two coupling devices.

Two double stirrers (inner and outer sides).

MM EMS Interface with Plant - Utilities

MM EMS equipment needs the following utilities (Figure 15):

Electrical power supply from the medium voltage mains.

Electrical auxiliary power supply.

De-ionized cooling water for stirrers. Rotelec may alternately supply a water cooling and de-ionizing unit, for which primary industrial water will be required.

Industrial cooling water for inverters.

Dry air or nitrogen to pressurize stirrers.

For optional Quick Coupling System: (i) hydraulic oil and pressurized air for actuators, (ii) clean air for anti-steam and anti-dust pressurizing.

M-EMS Data interface - System configuration

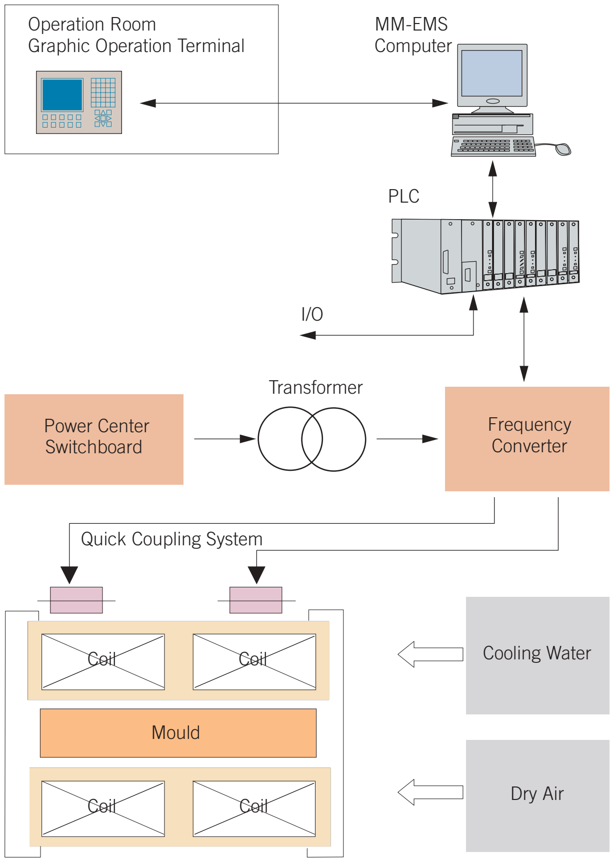
Automatic process control is performed by a Process Computer interfaced with both the End User's caster PLC and HMI, and a dedicated EMS-PLC.

The End User's level II or the caster PLC sends the following data to the Process Computer:

Heat No.

Steel grade.

Operating mode.



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Nozzle geometry.

Nozzle immersion depth.

Slab thickness.

Slab width.

Casting speed.

Argon flow rate.

Based on those actual data, the Process Computer determines what stirring function (EMLS, EMLA or EMRS) must be applied to optimize the in-mold molten steel flow and the related stirrer settings (such as traveling magnetic field direction, coil current and frequency), and sends them to the EMS-PLC. The settings are recalculated every 5 seconds, allowing an automatic adaptation of the MM-EMS to changing casting conditions. In turn, all the necessary feed-backs (measured values, equipment status, alarms and faults) are transmitted to the End User's control system.

12 In-Roll EMS arrangement in a slab caster.

13 Schematic of a electrical power supply for a box-type stirrer.

14 Section view of a typical mold mechanical interface: Back-up plates and mold assembly in non magnetic stainless steel; Note: other arrangement possible depending on space and goals.

15 Block diagram of MM-EMS equipment.

INDUCTION EDGE HEATERS FOR HOT STRIP MILLS

Danieli Rotelec designs and builds induction edge heaters for steel bars as they travel through hot strip mills.
This technology applies electromagnetic principles to generate eddy currents on the bar edges that compensate the heat losses. Reheating of the bar edges before the finishing mill reduces coil edge trimming and improves strip thickness control. Work roll wear may also be significantly diminished.

Induction Edge Heaters for hot strip mills (IEH)

Induction edge heaters act as electrical current transformers that generate eddy current in the bars. In practice, the primary coils are disposed on a magnetic core that forms a C, with the hot band traveling in the gap. The primary coils are powered with single-phase AC current at medium frequency (300 Hz). The traveling steel bars act as the secondary coils; the eddy currents that are created heat up the steel. The originality of the Danieli-Rotelec-patented design lies in an articulation in the magnetic core that allows adjusting the gap, without magnetic losses, by independent movement of the upper and lower arms. As a result, high heating efficiency is maintained, even at large gaps, allowing to correctly reheat the bar heads and tails that are frequently deformed.

C-Type inductor systems with adjustable arm gap enhance heating efficiency, improve metallurgical results and reduce trimming on full bar length for added-value coils.

Principle and historical development

The principle of induction heating is shown on Figure 1. Coils on a magnetic core and powered with AC current generate a magnetic flux that crosses a traveling steel bar. The magnetic flux induces eddy currents that circulate in horizontal loops in the volume/thickness of the bar.
By positioning the poles of the magnetic core toward the edges of the bar, the section of metal through which the eddy currents circulate is reduced, and consequently current density and heating effect (Joule's Law) at the edges of the bar are increased.
Such heating is applied to transfer bars before they enter the finishing stands of the hot strip mills.
Initially developed in Japan using U-type inductors, edge heating now exclusively uses C-type inductors (Figures 1 and 2): in the C-type configuration, heating efficiency is considerably increased as magnetic flux crosses the bar only once vs. twice in the U-type.
In 1989, in cooperation with IRSID, Danieli Rotelec developed and patented a C-type inductor with adjustable gap. It was simultaneously installed at Sollac-Fos (today Arcelor), France and NKK/Keihin (today JFE) and rapidly became a success.

Why heating?

During hot rolling, the temperature of the transfer bar gradually decreases; the edges

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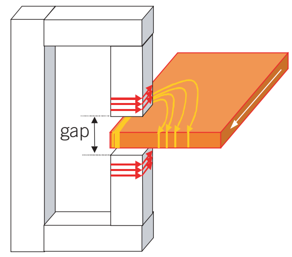

C-type inductor

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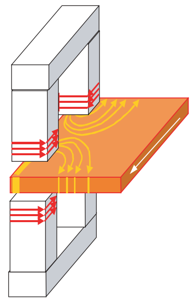

U-type inductor

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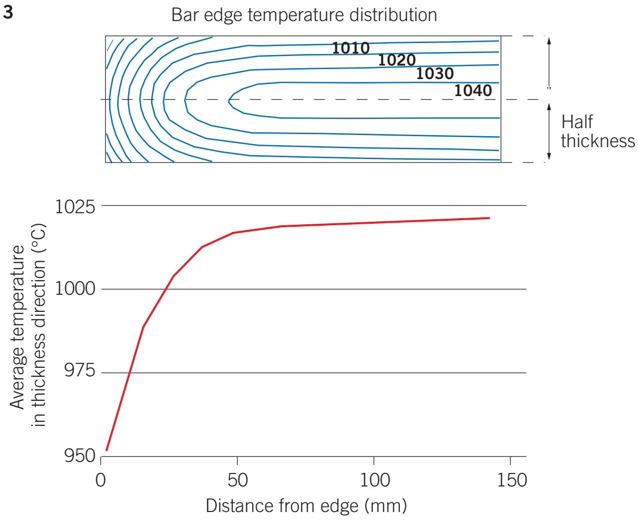

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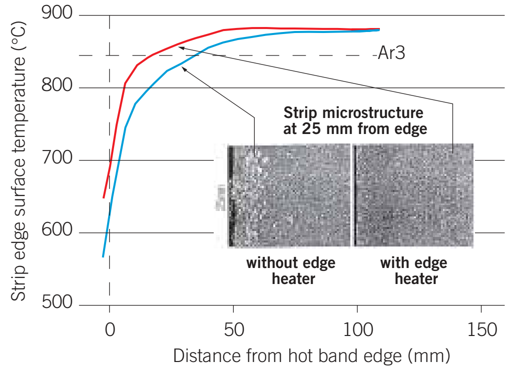
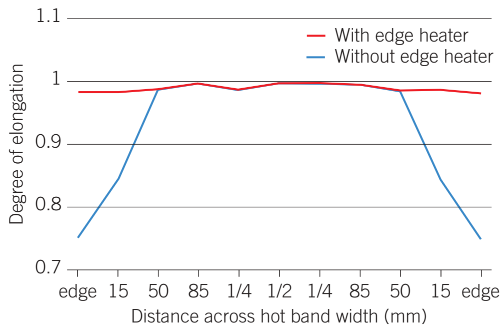


1-2 Bar Edge Heating with transverse flux: U-type and C-type inductors.
3 Computer-simulated temperature distribution through bar thickness. Temperature drop at bar edges must be compensated by edge heating. Calculations determine amount and profile of the drops as a function of the bar rolling history, typically 100°C on 50mm.
4 Effect of edge heating on hot band temperature and grain structure. Hot band thickness 2 mm, rolling temperature AR3 + 20°C, samples taken 25 mm from edge. Edge heating reduces the 30-mm coarse grain band to 14 mm thus saving 16 mm trimming.
5 Bar Edge Heating: improvement of elongation on low carbon steels.
6 Bar Edge Heating: reduction of rolled-in scale on ferritic stainless steel.

5



Almost constant quality/properties are obtained over the entire width of the reheated bars, whereas considerable deterioration is observed on the non-heated hot bands in a 50-mm band along the edges.

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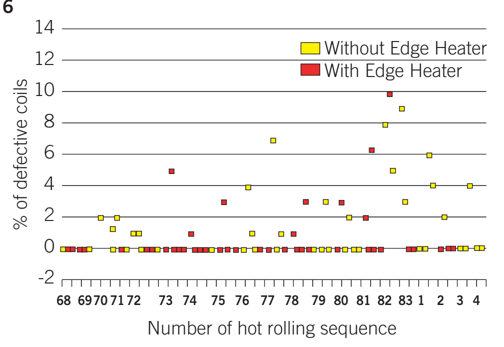

The x-axis represents the number of hot rolling sequences; the y-axis represents the percentage of defective coils in each sequence. Edge heating reduces defect ratio by a factor of three.

cool down faster than the middle of the bar due to the larger surface that is exposed to radiant cooling (Figure 3).
On low carbon steels, cold edges reduce the mechanical properties of the steel because of austenite transformation, rapid re-crystallization and formation of brittle/coarse ferrite grains.
On stainless steels, temperature drop at the bar edges (hence lower ductility of the steel) combines with the necessary higher rolling pressure and causes rolled-in scale, surface defects and cracks.

Benefits from heated edges

The purpose of edge heating is to compensate the temperature drop in the edges of the transfer bar (Figure 3) typically resulting in the following benefits:

Improve elongation on low carbon steels (Figure 5);

Reduce rolled-in scale on ferritic stainless steels (Figure 6);

Significantly reduce coil edge trimming (Figure 4).

Enhanced results with the Danieli Rotelec system

In addition to the intrinsic benefits of edge heating listed above, the Danieli Rotelec C-type technology brings additional specific advantages regarding bar heating and bar quality:

Full-bar length heating including head and tail.

Consistent temperature profile control.

Power regulation.

Warp detection above and below mill pass line and optimized gap adjustment.

Process automation.

Prevent bar hits and damage to equipment.

The C-Type Danieli Rotelec system

Each C-type inductor consists of a battery of capacitors, two coils, two magnetic poles and one articulated magnetic core with upper and lower arms.
The coils are powered with medium-frequency current.
The upper- and lower- arm positions are independently adjusted in function of bar thickness and actual shape of the bar as detected by infra red cameras.
One or two inductors may be necessary on each side of the bar. They are installed on cars that can move in- and outwards according to bar width.
The number of inductors depends not only on the power required but also on the space available for installation in an existing mill.

Temperature control
The temperature rise (ΔT) that has to be generated in the edges is controlled by the electrical power that is supplied to the inductor. Constant electrical power, constant speed of the bar and constant pole gap mean constant temperature rise along the bar length.
In the bar thickness, the temperature rise is almost constant because of the transverse flux configuration and the fact that the thermal energy generated by the induction is almost constant through the bar thickness.
Across bar width, however, heating must be the inverse of the temperature drop profile in the bar (Figure 3).
The heating profile can be made steeper or flatter by moving the inductor poles outward or inward with respect to the bar edges (Figure 7).

Power requirement and power rating
The thermal power to be injected in the bar depends on the specific heat of the steel and three process variables namely the temperature drop that has to be compensated (or the temperature rise that has to be generated), the bar thickness and the bar traveling speed.
Coil design determines the maximum electrical current that can be supplied to an inductor.
In turn, the maximum heat that can be generated in a bar will depend on the efficiency of the system and the gap between the two poles of the inductor: the larger the gap, the smaller the maximum thermal power P_{TH} that can be generated by the inductors (Figure 8).
Typical data are:
Temperature rise aim: 100 °C.
Bar thickness: 32.5 mm.
Bar speed: 1.5 m/sec.
Thermal power to be generated in the bar: 700 kW/edge.
150-mm electrical gap between inductor poles.
Inductor efficiency: 70%
Electrical power to be supplied to the inductor: 1,000 kW/edge.
Medium-frequency power supply: 2,300 kW for the 2 edges.

Adjustable vs. Fixed Arm Gap Heater
The gap adjustment, made possible with the Danieli Rotelec upper/lower arms independent positioning system, results in very important advantages:
Increase of the maximum available heating power P_{TH}
Reduction of the number of inductors necessary, i.e., very often there is the possibility of

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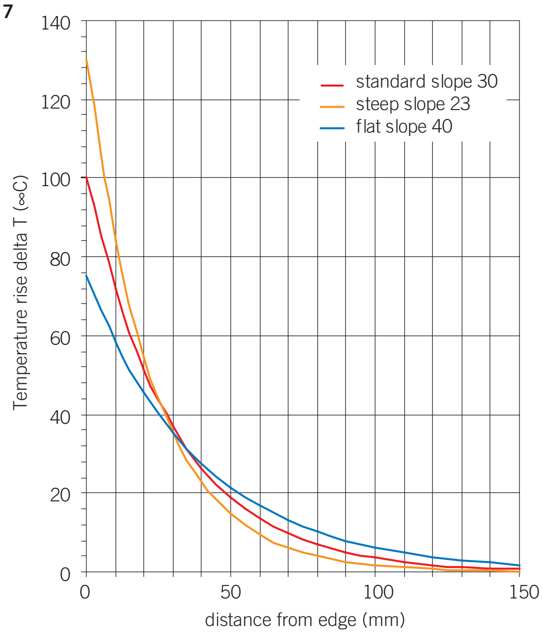

Computation data:
Specific heat 0.157 kcal/kg°C
Specific weight 7:55 kg/cm^3

Required thermal power P_{TH} = 538 kW at DeltaT=100 °C, speed 1.25 m/s, thickness 30 mm

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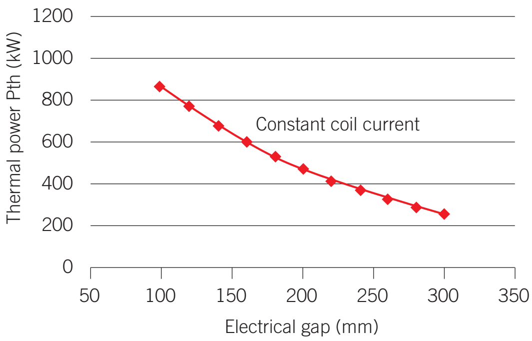
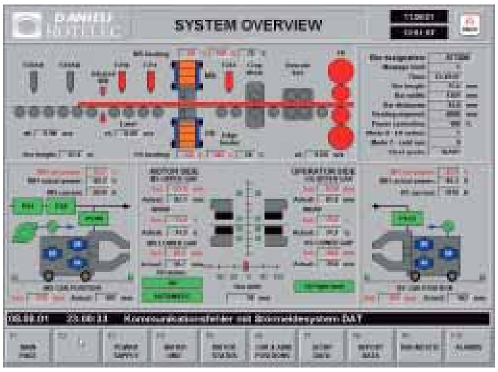


7 Example of heating temperature profile. ΔT decreases exponentially with increasing distance from bar edge. The slope of the decrease can be made steeper or flatter by moving the inductor poles outward or inward with respect to the edge.

In this example, ΔT=100°C is obtained in a 30-mm thick bar running at 1.25 m/s through the inductor, for a thermal power P_{TH} = 538 kW generated by the inductor.

8 Maximum available heating power versus pole gap. The x-axis is called “electrical” gap, as the values refer to the real distance between the magnetic core of the poles, not to the apparent distance between thermal screens.



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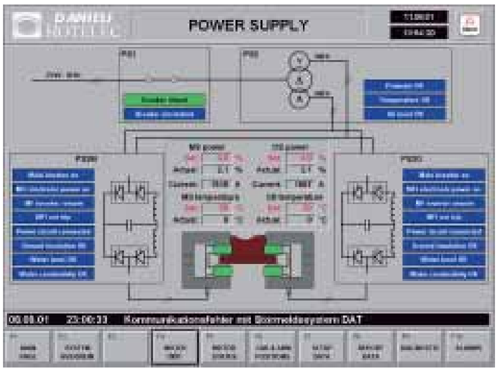

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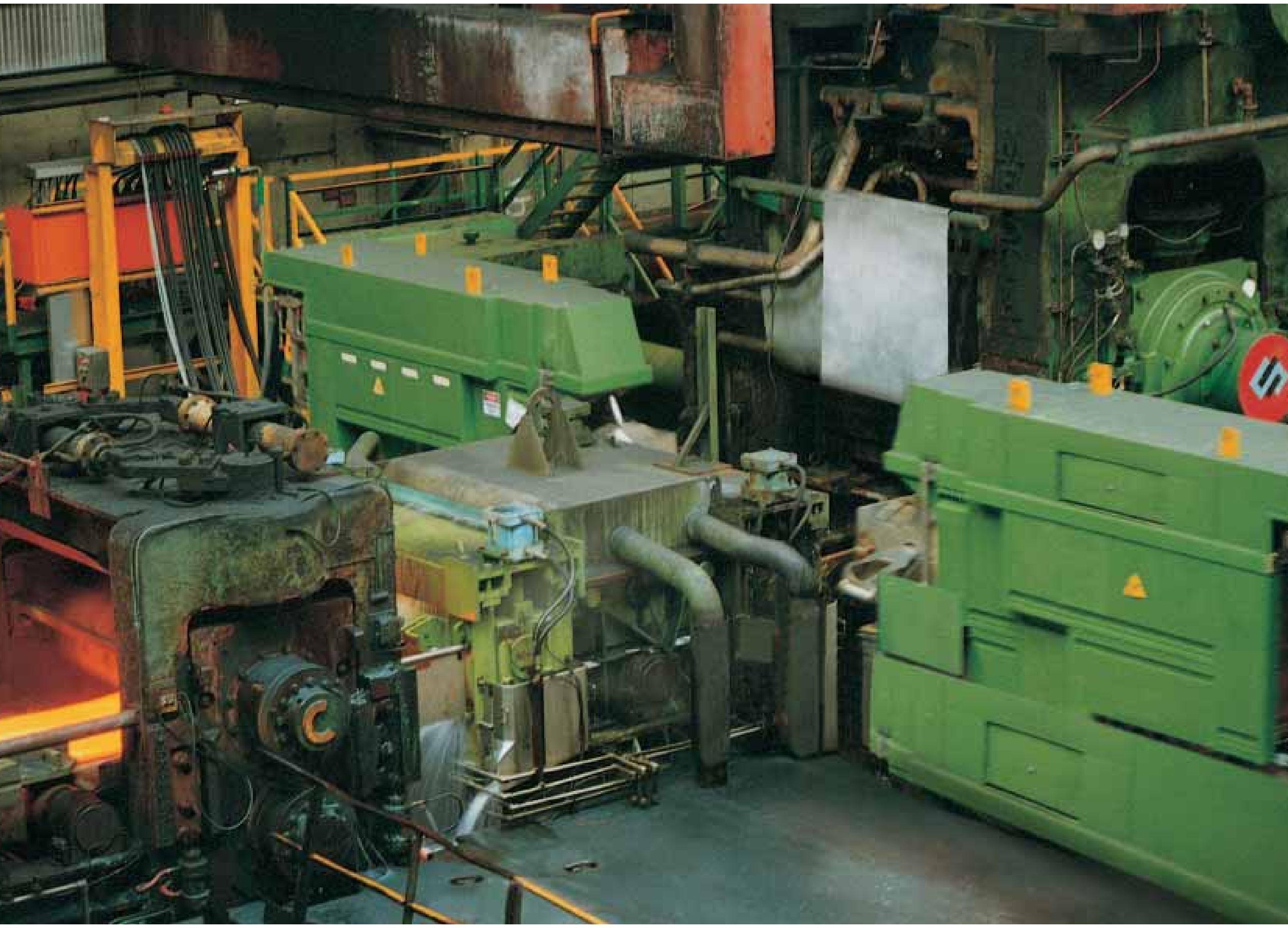
9-10 **Overall system control and power supply control HMI display for Induction Edgen Heater.**

11 **Bar Induction Edge Heater installed between descaler and F1 stand.**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12 Benefits of gap adjustment: three examples of maximum available heating power versus pole gap.

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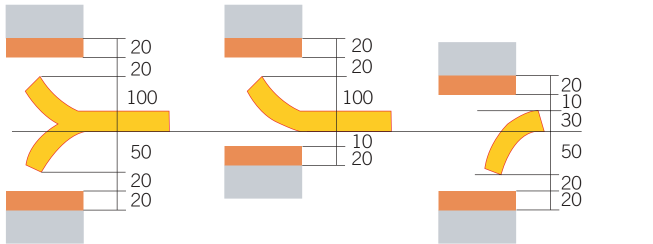

Fixed gap	Adjustable gap Bar head	Adjustable gap Bar tail
Gap setting 230 mm for up/down warp +100/-50 mm Heating power < 390 kW	Gap setting 170 mm for up warp +100 mm Heating power < 565 kW	Gap setting 150 mm for down warp -50 mm Heating power < 640 kW

13

Exclusive features	Benefits
- C-type adjustable gap (patent) - Multi-conductor Roebel-type coil (patent) - Ceramic thermal screen (patent)	High efficiency Long life
- Quick gap opening	Safety in emergency situation
- Independent positioning of upper/lower arms - Optical warp detector	High power availability for head and tail heating
- Real time generation of actual edge T° rise	Hot band quality control versus bar length

using one single-inductor per edge vs. one double-inductor.

Higher heating capacity available for bar heads and tails

Better heating efficiency along the entire bar length, hence electrical power savings

This is explained in Figure 12.

The example refers to a 30-mm thick bar traveling at 1.25 m/s with upward/downward warps of 100 mm and 50 mm, respectively. Aim temperature rise is 100 °C at the edges; required thermal power is 538 kW in each bar edge.

With a fixed arm gap machine (Figure 12 left), the gap must be set at an excessive 230 mm to accept the +100/-50 mm bar warps (150 mm total warp plus two 20 mm clearances plus two 20 mm heat shield = 230 mm).

It can be calculated that in these conditions, the power generated in the bar with one inductor will be 390 kW only.

In contrast, with independent/adjustable upper and lower arms (Figure 12 center and right), gap settings of 170 mm and 150 mm respectively, are sufficient to accept the same +100/-50 mm bar warps as above. As the smaller the gap, the larger the thermal power in the bar, the available power is 565 kW and 640 kW, respectively; this is more than the 538 kW required.

Interface with Hot Strip Mill - Installation on the roller table

From a practical point of view, the best location for the induction edge heater is on the roller table, before the crop shear.

However when the installation is on an existing mill, other positions may have to be considered such as between descaler and F1 (Figure 11) or between crop shear and descaler.

Interface with Mill Computer and Logic Controllers - Process automation

The edge heater PLC/PC system operates and controls the entire installation fully automatically.

The system also generates detailed bar heating reports for automatic display and archiving.

Heating temperature setting data, bar data (number/width/thickness/length), heating mode data (cold run, constant ΔT heating, variation of ΔT along length, power correction) and other mill data (date, time, steel grade) are given by the mill computer.

Bar speed and position are given by the mill PLC.

The operator can switch from automatic to semi-automatic operation and choose the heating value ΔT manually also.

Quality control

Comparison between aim and actual bar-edge ΔTs is most important information for quality control of the hot coils.

As surface temperature measurements are not very reliable and do not permit accuracy better than ± 15%, Danieli Rotelec developed a sophisticated system that combines performance test measurements under steady-state conditions with real-time measurements under operating conditions, and real-time computation that determines the actual temperature rise ΔT, with a high reproducibility. Such information is made available via HMI screen to the HSM operator for process control, to the HSM computer for quality control, and may be archived in the edge heater PC history logs for subsequent checking.

Conclusion

C-type edge heaters were developed in the late 1980s by Danieli Rotelec and Irsid and are now very sophisticated machines thanks to several exclusive, proprietary features such as (table Figure 13):

Compact design, hence compact integration into existing hot strip mills.

Quick gap opening mechanism for safe operation in emergency situations.

Independent positioning of the upper and lower inductor arms for high electrical efficiency.

Optical warp detector for high power availability for head and tail heating.

Real time generation of actual edge temperature rise for effective hot band quality control along bar length.

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