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EFFECT OF MOLD EMS DESIGN ON BILLET CASTING PRODUCTIVITY AND PRODUCT QUALITY

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Abstract—Increased casting productivity, especially with the introduction of high speed billet casting (HSBC), re-emphasized the importance of high performing mold electromagnetic stirring (M-EMS) in attaining the targets of productivity and product quality. To provide operating flexibility and to enhance metallurgical performance, adapting M-EMS design to the requirements of casting practice with either the open stream pouring or submerged entry nozzle (SEN) has become critical. In that context, it is especially important to assess the effects of EMS design parameters that control stirring velocity in the meniscus region and the rest of the mold. Such a control is the key to EMS compatibility with the continuous casting practice and its high metallurgical performance.

In this paper, we discuss different M-EMS designs with reference to their metallurgical performance. © 2000 Canadian Institute of Mining and Metallurgy. Published by Elsevier Science Ltd. All rights reserved.

Résumé—L'augmentation de la productivité de coulée, spécialement avec l'introduction de la coulée de billette à haute vitesse (HSBC), a de nouveau attiré l'attention sur l'importance de l'agitation électromagnétique à haute performance du moule (M-EMS) pour atteindre les cibles de productivité et de qualité de produit. Afin de fournir une flexibilité d'opération et pour améliorer la performance métallurgique, il est critique d'adapter la conception M-EMS aux exigences de la pratique de coulée avec soit le déversement à jet libre ou avec un ajutage d'entrée submergé (SEN). Dans ce contexte, il est spécialement important d'évaluer l'effet des paramètres de conception du EMS qui contrôlent la vitesse de mélange dans la région du ménisque et dans le reste du moule. Un tel contrôle est la clé de la compatibilité du EMS avec la pratique de coulée continue et de sa haute performance métallurgique.

Dans ce document, nous discutons de différents concepts de M-EMS avec référence à leur performance métallurgique. © 2000 Canadian Institute of Mining and Metallurgy. Published by Elsevier Science Ltd. All rights reserved.

INTRODUCTION

Productivity of continuous casting of billets and blooms has markedly increased in recent years. A notably dramatic progress in productivity of billet casting was achieved with the industry-wide implementation of high speed casting in the early 1990s. As a result, the caster throughput was increased by 40–100%, depending on billet size and steel grade [1]. This rapid progress in new casting technology became possible mainly due to developments in mold design, secondary cooling and other components of casting equipment. In addition to these developments, a series of technological measures were also implemented in order to sustain such a high casting speed without compromising the product quality. M. Wolf summarized many of these measures necessary to cast fast in the so-called "Technology Package" [2]. In-mold electromagnetic stirring, M-EMS, was a part of that package owing to the favorable effects it has on uniformity of early shell solidification and prevention of slag entrapment. M-EMS has also demonstrated a profound effect on the internal quality of the as-cast products, especially those of demanding steel grades. From this perspective, M-EMS role becomes central in achieving increased productivity and product quality, hence it facilitates uniformity of shell solidification and alleviates adverse effects of high speed casting. However, in order to maximize these metallurgical benefits, design and operating parameters of the stirring systems have to be compatible with the casting practices they are integrated with.

In this paper, we addressed these issues by considering the effects M-EMS design has on stirring intensity and its control, as well as overall metallurgical performance. In this context, single-coil and dual-coil M-EMS systems have been compared. The operating results obtained at a number of melt shops supplement that comparison.

EFFECT OF STIRRER DESIGN AND OPERATING PARAMETERS ON STIRRING INTENSITY

Stirring intensity is commonly characterized by velocity of the swirl motion induced by a stirrer in a pool of liquid metal. Quantitatively, the stirring velocity is chiefly determined by electromagnetic torque produced by the stirrer magnetic field, in accordance with the equation:

$$T = 0.25\pi\sigma\omega B^2 R^4 L \qquad (1)$$

where T is the magnetic torque applied to the melt, $\omega = 2\pi f$ is the angular frequency of the magnetic field, f is the frequency of the applied voltage, σ is the electrical conductivity of the melt, B is the magnetic flux density in the melt, R is the radius of the liquid metal pool and L is the length of stirrer iron core (i.e. the magnetic pole height).

As seen, the magnetic torque is determined by both magnetic (i.e. B^2f) and dimensional parameters (i.e. R^4L) of the stirrer. Therefore, these parameters will determine the input in kVA needed to produce required magnetic torque. The effect each of these parameters has on the stirrer characteristics and performance shall be considered in the context of their interaction rather than as an independent impact.

The magnetic component of the torque, i.e. magnetic flux density B, is defined by the ampere-turns of excitation and the separation distance between the magnetic poles referred to as the stirrer diameter:

$$B = K\mu_0 \frac{NI}{D} \tag{2}$$

where B is the magnetic flux density of the stirrer, K is a proportionality coefficient, μ_0 is the magnetic permeability of free space, N is the number of winding turns per pole, I is the supplied current and D is the stirrer diameter.

The above relationship is derived for a magnetic coil of infinite length and, therefore, it does not account for the magnetic flux losses caused by the magnetic field leakage at the ends of a finite length stirrer. These losses are negligible if $L \gg D$. However, for a common M-EMS design ratio of $L/D < 1.5$, length of the stirrer iron core affects the magnetic flux density axial distribution and its average value. Figure 1 shows that at a given kVA input and stirrer diameter, an increase of stirrer core length will cause the magnetic flux density to increase. This is due to a diminishing effect of the magnetic flux losses at the core ends. In spite of magnetic flux density growth, stirring velocity is decreasing, except that at the start of the core length increase, due to much faster rate of frequency reduction. The frequency reduction is necessary in order to maintain the current level while the stirrer impedance increases along with the stirrer core length.

As seen from Eq. (1), the magnetic torque is linearly proportional to both the frequency of current supplied to the stirrer and the length of its core. However, this proportionality becomes non-linear due to the escalating attenuation of magnetic flux with frequency increase in the presence of a copper-alloy mold. Thus, it is obvious that there is a frequency for any given mold at which the maximum magnetic torque is delivered to the melt. This frequency is termed optimal. Figure 2(a) shows the relationship between the variable component of magnetic torque equation, i.e. B^2f, and frequency for molds of different size. The optimal frequency and therefore the magnetic torque will decrease with mold size increase.

The electrical conductivity of the mold material also plays a significant role in the above relationship. As the attenuation of magnetic flux by the mold decreases with its electrical conductivity decrease, magnetic torque delivered to the melt may be notably increased mainly due to ability to utilize a higher optimal frequency. As shown in Fig. 2(b), mold fabricated from copper alloy with electrical conductivity of approximately 60% IACS is much more preferable for use with M-EMS than that with the electrical conductivity of 92–95% IACS.

STIRRER DESIGNS

Single-coil M-EMS

An M-EMS designer has to deal with two major challenges. The first is the limited space available for the stirrer within or outside of the mold housing, and the second is to position the stirrer in such a way to provide a desirable stirring intensity distribution between the meniscus region and the bulk of the mold.

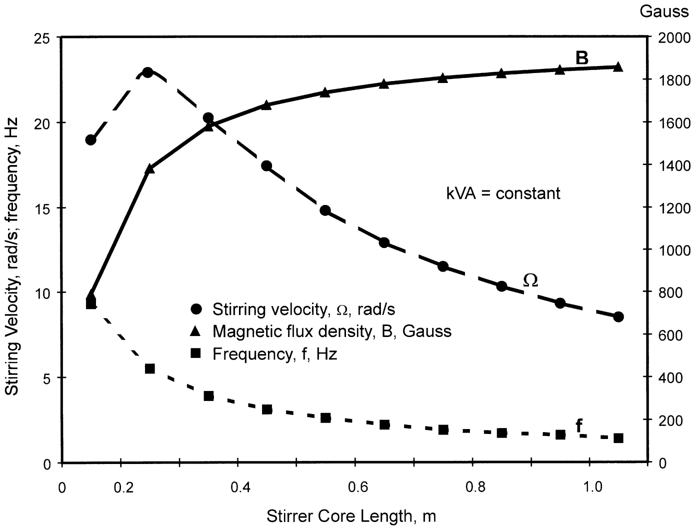

Fig. 1. The relationship between stirrer iron core length and magnetic flux density, current frequency, and stirring angular velocity.

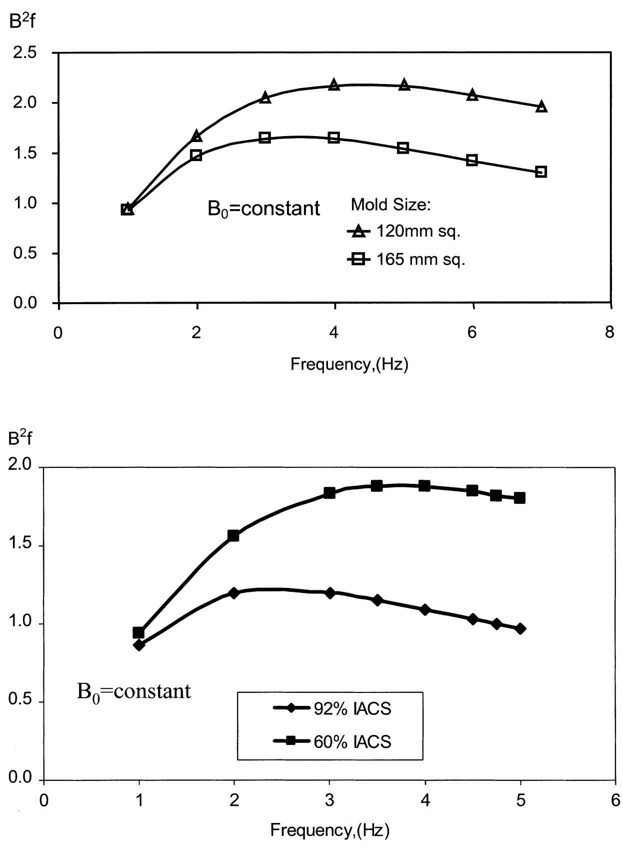

Fig. 2. Effect of the mold size (a) and electrical conductivity (b) on magnetic torque.

As it is well known, casting through a metering nozzle requires rather intensive stirring in the meniscus region in order to control pinholes, blowholes, and slag entrapment in the shell. As for the submerged pouring practice, stirring at the meniscus must be restricted to avoid disruption of mold lubrication, along with powder entrapment and SEN erosion. The requirements of these casting practices have led to a few modifications of M-EMS systems based on single induction coil, i.e. the so called single-coil stirrer.

A long-core stirrer, as shown in Fig. 3, is arranged within the mold housing and it extends to a relative proximity of the meniscus. The stirrer could also be positioned outside of the mold housing in the so called external arrangement. This type of a stirrer provides intensive stirring throughout the mold, including the meniscus region. However, with this stirring arrangement, stirring intensity at the meniscus will be almost as strong as that within the stirrer boundaries. It could as well exceed the level needed for effective control of pinholes and create excessive turbulence which might result in the occurrence of the surface defects such as bleeds and laps [3]. Some steel grades, especially those with a wide freezing range such as high carbon and free cutting steels, are more sensitive to meniscus overstirring [3, 4]. High casting speed through the metering nozzle may also exacerbate the problem due to a greater impact of the pouring stream on the meniscus [4]. Smaller section billets are apparently more sensitive to the effect of pouring stream on meniscus turbulence and formation of bleeds and laps. Should meniscus overstirring occur, the M-EMS stirring output has to be reduced, which in turn will diminish stirring effect on soundness of axial structure and segregation in those steels. Under such circumstances, the very reason for applying intensive stirring, to improve the internal quality of high carbon and alloy steel billets, will be compromised.

A short-core stirrer positioned in a lower portion of the mold housing is commonly used for the submerged pour casting to minimize the stirring action at the meniscus (Fig. 4). In spite of such an arrangement, with a standard length mold of approximately 0.8 m, these stirrers often operate at 60–80% of the nominal current input to avoid excessive SEN erosion and mold powder entrapment. In some

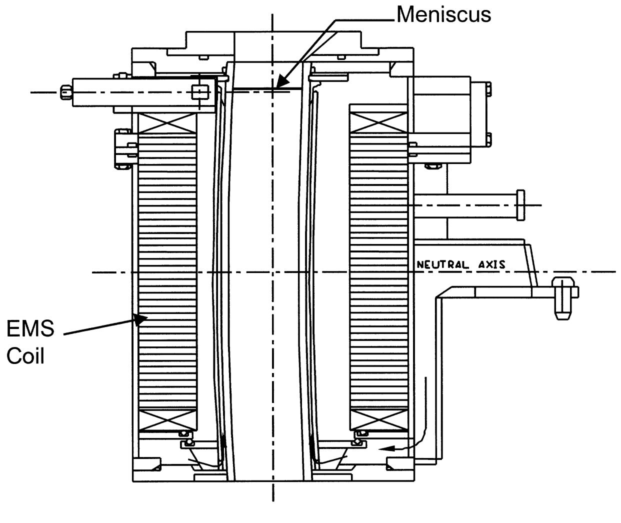

Fig. 3. Schematic of a long-core M-EMS arrangement in a mold housing.

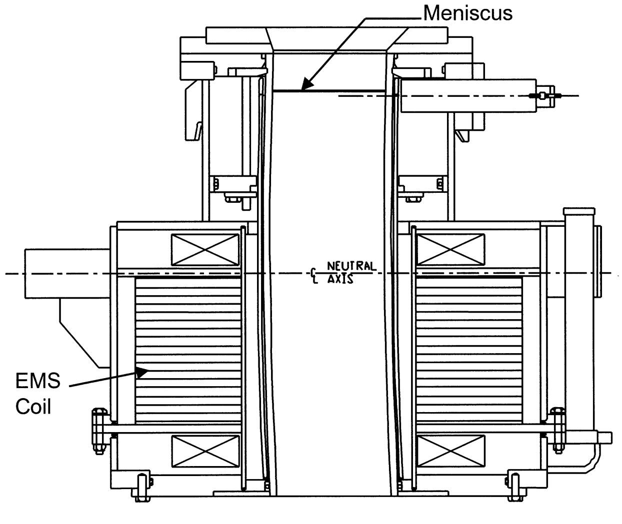

Fig. 4. Schematic of a short-core M-EMS arrangement in a mold housing.

instances, this type of M-EMS was entirely withdrawn from operation with the submerged pouring practice and replaced with strand-mounted EMS [5]. When a casting facility equipped with short-core EMS is used not only with a submerged pouring but with metering nozzle practice as well, the stirrer will fail to control pinholes effectively.

In an effort to satisfy the requirements of both casting practices regarding stirring intensity at the meniscus, an externally arranged movable stirrer is used in some installations (Fig. 5(a)). This stirrer, in its upper position provides stirring intensity sufficient for pinhole and subsurface inclusion control. In its low position, however, the movable stirrer is no different from its short-core stationary version. In order to further minimize stirring effect on the meniscus, for casting with the submerged pour, a stirrer arrangement can allow for its partial extension below the mold, as shown in Fig. 5(b).

Dual-coil M-EMS

Developed in the mid 1990s, the dual-coil M-EMS system [6] was designed to rectify the shortcomings of the single-coil M-EMS and provide independent control of stirring in the meniscus region and the rest of the mold. A schematic representation of a dual-coil M-EMS is shown in Fig. 6. As seen from that figure, the system comprises two sets of induction coils. One set is arranged around a low portion of the mold, similar to a short-core M-EMS, while another one is positioned in the meniscus region.

The M-EMS and the upper stirrer are energized from separate current sources which allow independent control of their respective magnetic fields, namely strength, rotational direction and frequency. Thus, the stirring intensity in the meniscus region can be adjusted to meet the casting requirements by increasing or reducing the current input to the upper stirrer or by reversing rotational direction of its magnetic field. Magnetic field of the upper stirring coils mainly impacts a rather limited portion of the stirring pool near the meniscus where its action modifies the stirring intensity by either enhancing or reducing it. Because of this dual function, the upper stirrer is termed the A.C.-Stirring Modifier, or AC-SM.

By reversing the rotational direction of the AC-SM magnetic field with respect to that of the main stirrer, the AC-SM becomes a magnetic brake. Dynamic equilibrium can be achieved at the meniscus since the magnetic torque of the brake opposes the momentum of stirring flow transported to the meniscus from the region of active stirring in the lower mold. As a result the rotative stirring motion at the meniscus comes to a virtual halt.

Although the braking torque action is limited to the meniscus region, it makes an impact on the whole stirring flow in the mold and results in a reduction of stirring velocity within the active stirring zone. The effect of the brake on stirring velocity in the mold is shown in the example with a pool of mercury (Fig. 7(a)). However, the stirring velocity reduction in the mold can be compensated by increasing the power on the main EMS which otherwise could not be achieved without the brake (as shown in Fig. 7(a) for the current input of 400 A). The impact of the brake on the main stirring flow can also be reduced by practicing a partial braking (e.g. 80% of the full braking action) which can be recommended in some instances for successful operation with the submerged pouring.

As stirring conditions in the meniscus region of the oil lubricated mold are totally opposite to those with the submerged pouring and often require a further increase of stirring intensity for effective pinhole control, the AC-SM operates to assist to the main stirrer. The overall stirring velocity in the mold will be increased as a result of this action with an especially marked increase of velocity in the meniscus region. A profile of stirring velocity distribution within a column of mercury is shown in Fig. 7(b).

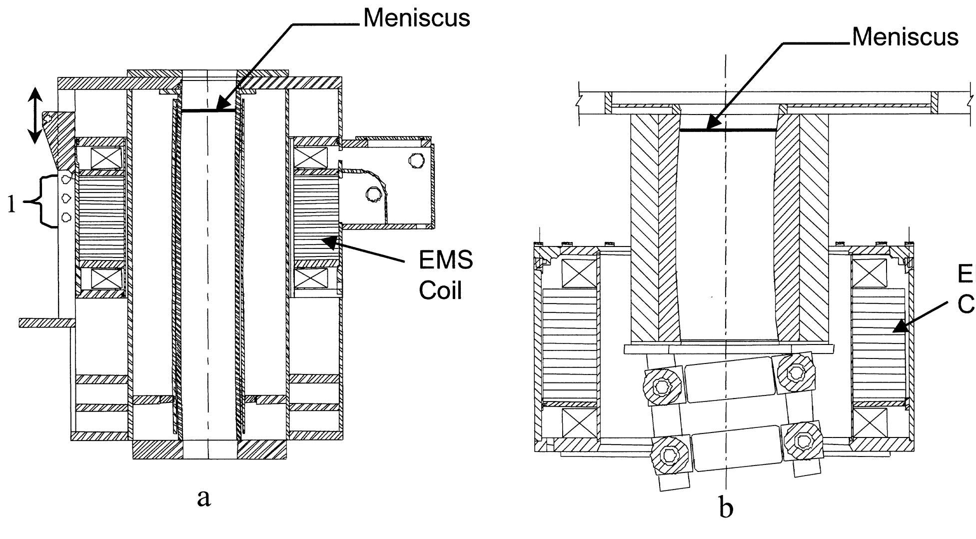

Fig. 5. Schematic of an external arrangement of a short-core M-EMS. (a) Movable M-EMS—the holes for stirrer positioning are indicated by the sign 1. (b) M-EMS with a partial extension below the mold.

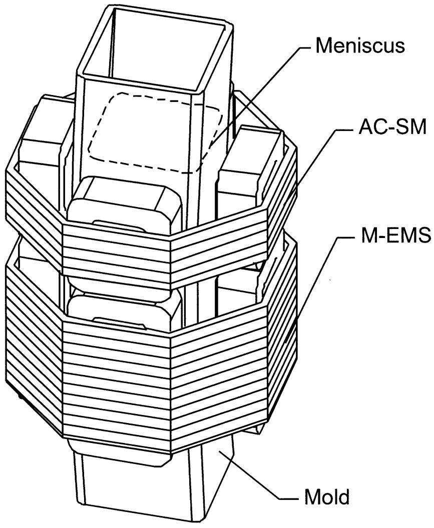

Fig. 6. Schematic of a dual-coil M-EMS system.

MENISCUS STABILITY

Control of stirring velocity at the meniscus and its vicinity requires accurate proportioning of the brake magnetic torque with respect to the angular momentum of stirring flow. At certain conditions, the interaction between these two dynamic forces could lead to turbulence developed in the mold corners which affects the whole meniscus area. This turbulence arises due to vertical flows resulting from the angular momentum gradient in the axial direction [7]. The vertical flows therefore are inherent to the rotary type EMS.

Excessive meniscus turbulence, causing instability could produce an adverse impact on the casting process and product quality [8–11]. Deterioration of billet internal quality in particular was attributed to meniscus turbulence initiated by braking action. Confronted by this experience, Danieli Rotelec concluded that "the magnetic brake cannot be recommended" [9, 11]. The experience gained by JME with design and commissioning of a number of dual-coil stirring systems proves that meniscus turbulence and instability can be controlled. Hence, the stirring system design by Rotelec was obviously the major contributing factor to the problem.

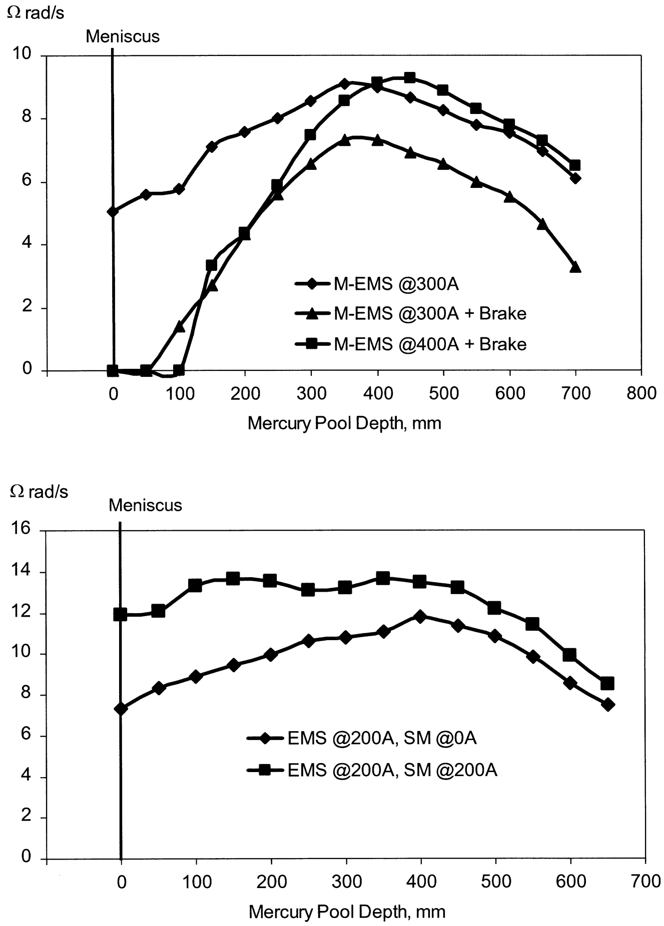

Fig. 7. Effect of the AC-SM on stirring velocity in the mold. (a) The AC-SM brakes the stirring motion at the meniscus of a mercury pool (110 × 110 mm section). (b) The AC-SM assists the M-EMS, stirring effect on mercury.

The results of tests carried out with large columns of mercury and Wood's metal stirred by the industrial dual-coil systems clearly demonstrated that intensity of vertical fluid flows in the mold corners can be controlled and satisfactory stability of the meniscus can be achieved. The videotaped meniscus appearances of Wood's metal in a 125 mm sq. mold are shown in Fig. 8. As seen, a full-swirl motion at the meniscus induced by the main EMS (Fig. 8(a)) was brought to complete stop by the magnetic brake (Fig. 8(b)).

Meniscus quiescence and absence of corner turbulence is clearly observed on the photograph. The results of experiments with Wood's metal and mercury have been confirmed by operating experience of industrial users [12].

METALLURGICAL RESULTS

As was noted, M-EMS contributes significantly to the increase of caster productivity and as-cast product quality. The effect of M-EMS manifests itself through the following.

1. Improvements in shell thickness uniformity and billet internal quality (i.e. axial soundness and segregation) which provide conditions for a casting speed increase.
2. Reduction of billet surface defects which results in an improvement of good steel yield. In the case of a dual-coil M-EMS application with submerged pouring practice, the following additional benefits are derived due to flexible control of stirring intensity in the meniscus region.
3. Prevention of stirring effect on SEN erosion, which results in increased casting sequence time and caster utilization.
4. Capability of maintaining intensive stirring action within the bulk of the mold which brings about further improvements in the billet internal quality.

With metering nozzle practice, dual-coil M-EMS provides capability to control surface porosity defects without possible meniscus overstirring.

The rate of shell growth, and especially shell thickness uniformity, becomes of paramount importance in attaining a substantial casting speed increase. It is well known that the shell thickness in billets cast without M-EMS is substantially reduced near the mold corners in comparison to the thickness in the area of mold mid-face. M-EMS promotes chill zone growth and its uniformity. The results of a study on this subject matter are shown in Fig. 9 [13]. The chill zone delineated on the sulfur prints was measured in its thickest (at the mold mid-face) and the thinnest points (near the mold corners) in stirred and unstirred billets of low, medium and high carbon steel. As seen, both thickness and uniformity of the chill zone in all three steel groups were markedly improved as a result of mold stirring.

The formation of a thicker and more uniform shell with fewer and smaller inclusions was found by USS/Kobe Steel to be largely responsible for the dramatic reduction in the

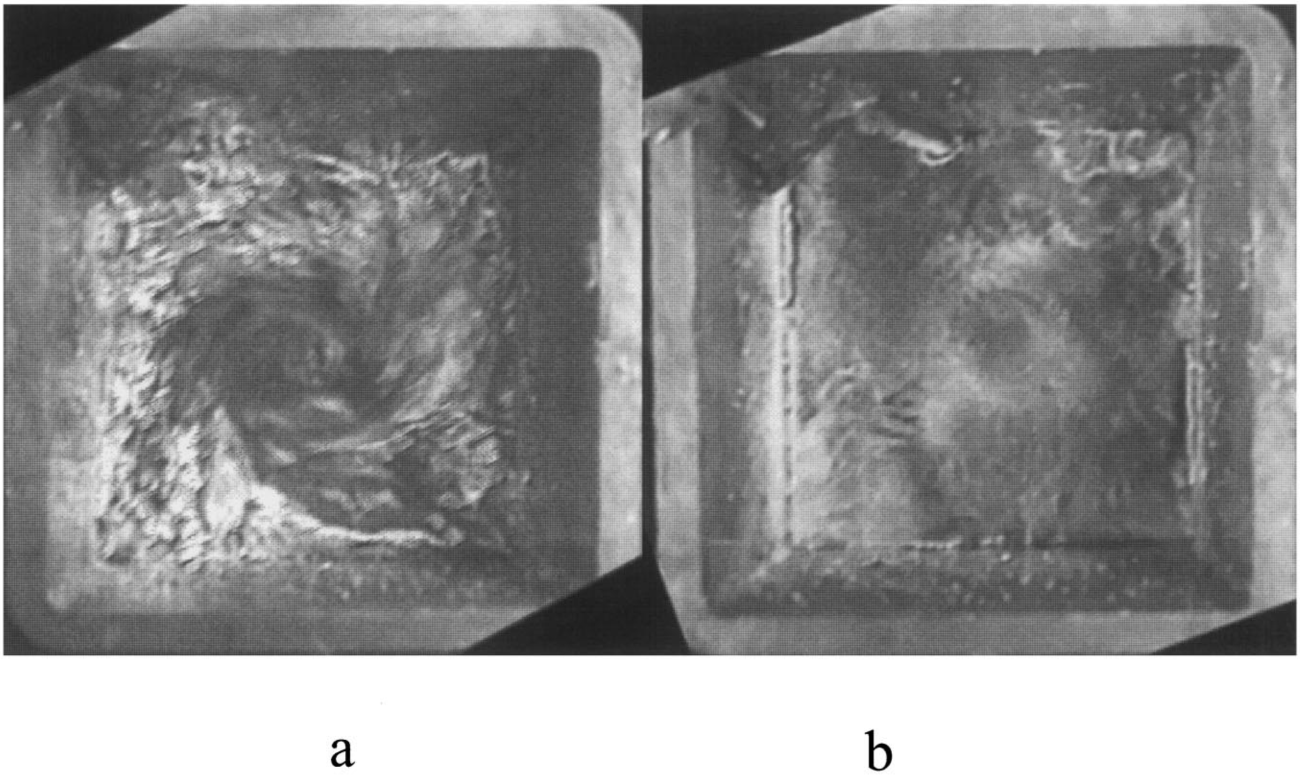

Fig. 8. Videotaped appearance of Wood's metal meniscus. The dual-coil M-EMS operation: (a) the M-EMS is at full power, the AC-SM is turned off; (b) the M-EMS is at full power, the AC-SM is operating as a brake.

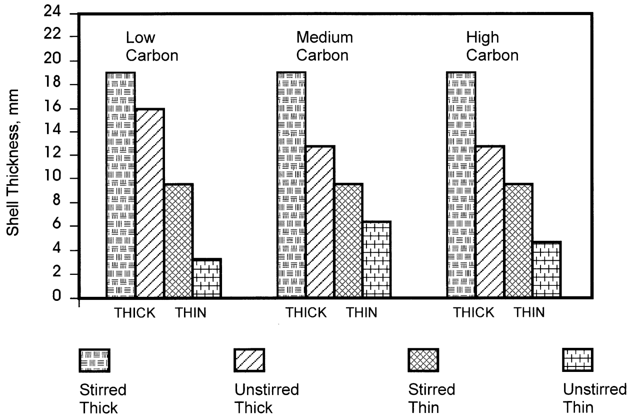

Fig. 9. Effect of stirring on chill zone thickness of low, medium and high carbon steels [13].

eddy current rejection rate of rolled bars [14] (Fig. 10). The reduction in termination of strands due to breakouts was also attributed to the shell formation improvement [14]. The improvements in shell formation allow for a casting speed increase. Depending on operating factors and steel grade, this increase is generally within a range of 15–20% for conventional casting speed practice and much greater gains are accomplished in realization of high speed billet casting.

Controlled stirring intensity in the meniscus region is also very effective with respect to improvement of surface quality of billets cast with a metering nozzle. The ability to attain a high level of pinhole reduction without causing meniscus overstirring is characteristic for dual-coil M-EMS operation. Figure 11 presents examples of pinhole reduction with dual-coil M-EMS in different steel grades. As seen, a rate of pinhole reduction, including pinholes with a diameter less than 1.0 mm, was up to 88% (Fig. 11). Larger pinholes were reduced by 94–100%.

A reduction in surface porosity in Si–Mn deoxidized steels results in a decline of the product rejection and/or conditioning. The rejection rate improvement due to surface porosity reduction was reported to be increased 2.8 times with a consequent yield increase of 4–6%.

In addition to the limitations imposed on casting speed by shell thickness and its uniformity in the mold, the casting

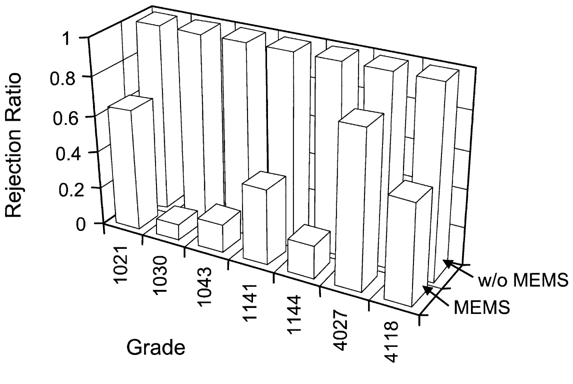

Fig. 10. Rejection rate of the rolled bars [14].

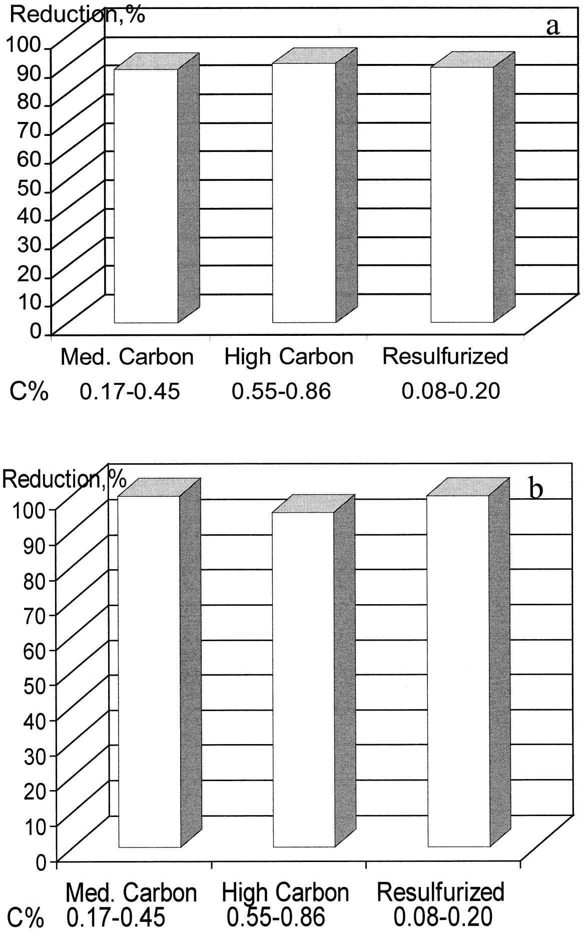

Fig. 11. Effect of stirring on pinhole reduction. (a) Pinholes of all sizes. (b) Pinholes of diameter ≥1.0 mm.

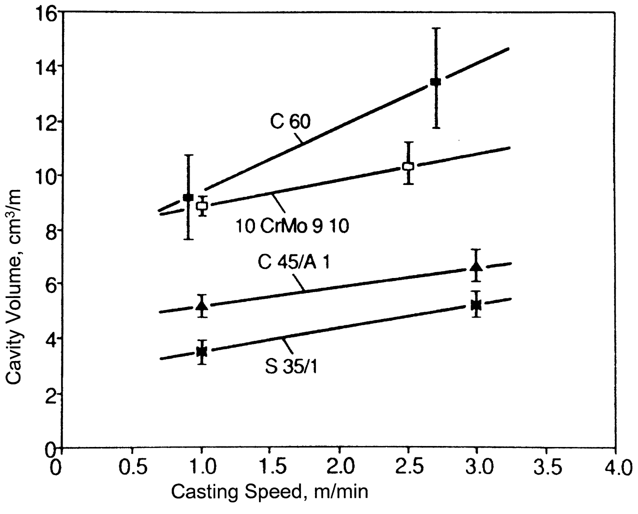

Fig. 12. Effect of casting speed on axial porosity in the columnar dendritic structure [15].

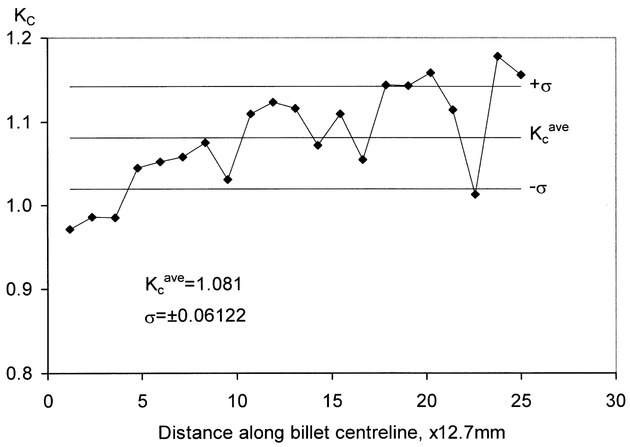

Fig. 13. Profile of centerline carbon segregation in AISI 1080 grade 120 mm sq. billet cast with the submerged pouring and dual-coil M-EMS at the casting speed of 3.1 m/min and superheat of 30°C.

speed is also commonly reduced in production of high carbon and alloy steels in order to prevent its negative impact on strand internal quality. Wunnenberg *et al.* [15] found that the axial porosity in the dendritic structure of different steel grades was increased with casting speed (Fig. 12). This finding corroborates the results obtained for axial carbon segregation in unstirred high carbon steel [12].

The in-mold stirring results in dendrite-to-equiaxed structure transition and subsequent improvement of the axial porosity and segregation. Thus axial porosity in the equiaxed structure of the same steel grades evaluated in the aforementioned study [15] was reduced by a factor of 2 in comparison to that in the dendritic structure of unstirred steels. Further improvements in billet solidification structure and carbon segregation can be achieved by combination of M-EMS with intensive secondary cooling [16]. A low segregation level in high carbon steels was also attained with high withdrawal speed casting at Co-Steel Sheerness. The average value of centerline carbon segregation was measured as 1.06 in steels with the carbon content C ≤ 0.70% and 1.11 in steels with C ≥ 0.70% in 140 mm sq. billets cast with the withdrawal speed of 3.2–3.6 m/min and intensive secondary cooling [17]. These low segregation levels were achieved with open stream casting and intensive stirring provided by a single-coil M-EMS. A possibility of meniscus overstirring was negligible in that case due to a large distance between the stirrer and the meniscus available in a 1 m-long mold, however, by the very same reason, the pinhole control was much less satisfactory. With conventional length molds (i.e. 0.8 m long), similar low segregation levels can be achieved only with a dual-coil M-EMS when meniscus calmness is

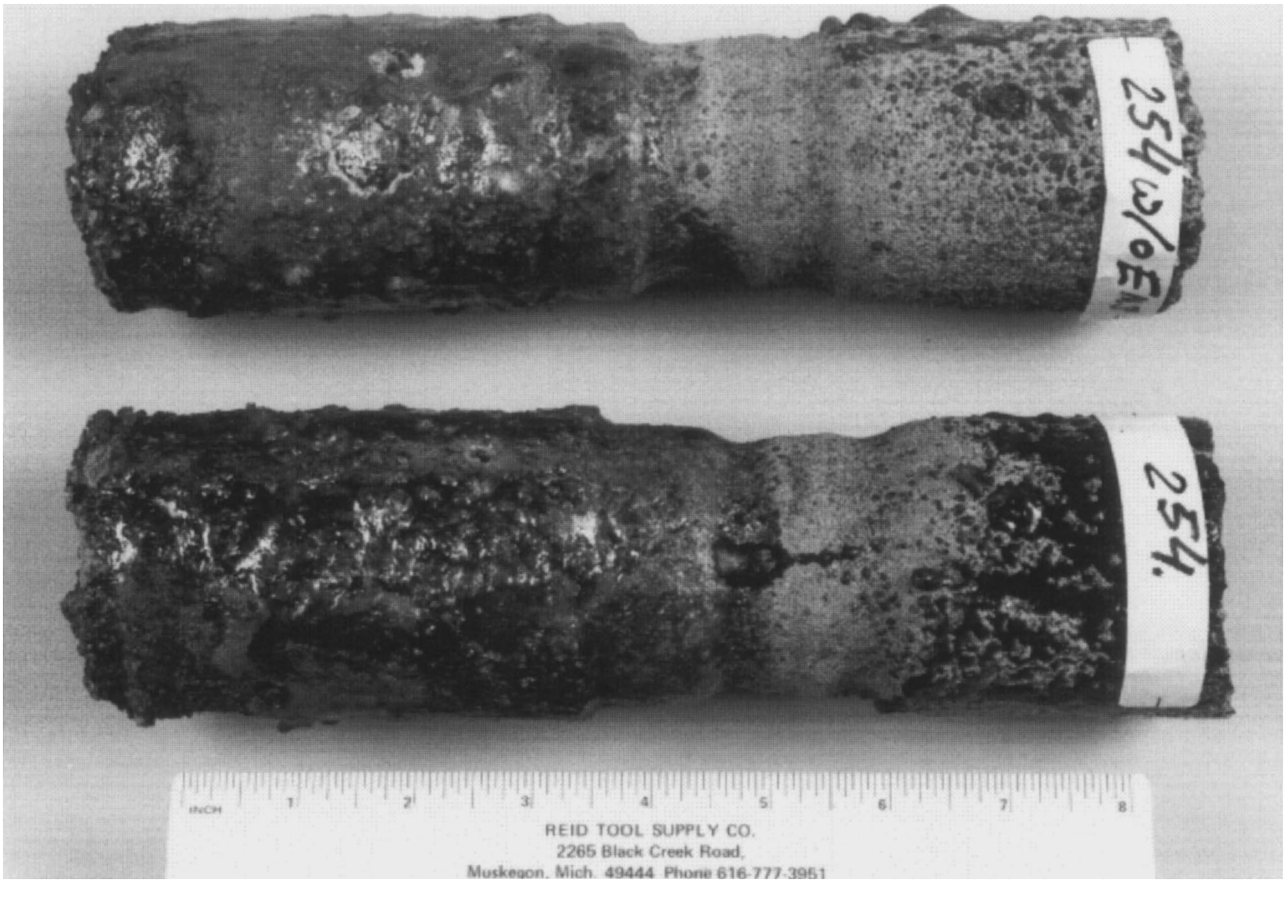

Fig. 14. Erosion of the SEN [12]: (a) without stirring; (b) with dual-coil M-EMS.

attained by the braking action of an AC-SM. Figure 13 shows the centerline carbon segregation in a 120 mm sq. billet of 1080 steel cast under powder into a 0.8 m-long mold at the casting speed of 3.0 m/min.

Another important feature which makes the dual-coil M-EMS highly compatible with the submerged pouring practice is reduced erosion of SEN. This reduction takes place as the rotative stirring motion at the meniscus is controlled by the magnetic brake.

The trials carried out at ISPAT Sidbec [12] confirmed that there was no difference in erosion of the SEN tubes used on the same heats in the strands without any stirring and the strands with stirring and magnetic brake. An example of such a comparison is presented on the photograph in Fig. 14. The trial results confirmed the steel production experience that the SEN life with the dual-coil M-EMS has not changed as compared to that established prior to M-EMS implementation.

CONCLUSIONS

Based upon the above considerations, the following conclusions can be drawn.

1. Stirring intensity produced by M-EMS and its metallurgical performance at a given kVA input are determined by the relationships between stirrer core length and diameter and casting mold size and its electrical conductivity. The importance of these parameters must not be underestimated.
2. Maximum stirring effectiveness and operating flexibility can only be achieved through independent control of stirring intensity in the meniscus region and the rest of the mold. This control provides total compatibility of a stirring system with open stream and submerged pouring casting practices. The dual-coil M-EMS provides such control.
3. Metallurgical and operating results proved that the dual-coil M-EMS is highly effective in the following.
   - ○ Pinhole reduction without meniscus overstirring and surface defects.
   - ○ Improvement in internal quality of billets cast with submerged pouring which brought it on a par with the quality of open stream cast billets.
   - ○ Improvements in caster productivity due to reduction of yield losses related to the surface porosity, increased casting speed and reduced SEN erosion.

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