# METALLURGICAL PERFORMANCE OF SINGLE AND DUAL-COIL EMS WITH SUBMERGED POUR CASTING OF HIGH CARBON STEEL BILLETS[1]

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**Abstract**

Industrial trials carried out at Contrecoeur Works, Mittal Canada Inc., demonstrated that stirring intensity produced by a single-coil EMS, should be limited to 56 percent of maximum current in order to reduce stirring intensity in the mold and avoid meniscus overstirring with resultant mold powder entrapment and excessive SEN erosion. The main stirrer of the dual-coil EMS system, in this context, performed as conventional, single-coil EMS when the upper stirring coil was turned off. Although dual-coil EMS provides flexible control of stirring intensity in the meniscus region without aforesaid complications, it also impacts stirring velocity produced by the main stirrer, i.e. reducing it. However, this velocity reduction may be offset, at least in part, by increasing current input to the main stirrer. The results of trials and production practice at Contrecoeur Works demonstrated that the centerline carbon segregation achieved with dual-coil EMS was improved in comparison to that achieved with single-coil EMS. Controlled stirring in the meniscus region also led to an improvement in meniscus level stability, a reduction in SEN erosion and oscillation mark prominence, and provided for casting conditions free from the occurrence of mold powder entrapment.

**Key words**: Continuous casting; EMS; High-carbon steel.

## DESEMPENHO METALÚRGICO DE AGITADORES ELETROMAGNÉTICOS DE BOBINAS SIMPLES E DUPLA EM LINGOTAMENTO DE TARUGOS DE AÇO DE ALTO CARBONO COM JATO SUBMERSO

**Resumo**

Testes industriais realizados na Usina de Contrecoeur, Mittal Canada Inc., demonstraram que a intensidade de agitação produzida por um Sistema de Agitação Eletromagnética (EMS) de bobina simples deveria ser limitada a 56% da corrente máxima de forma a reduzir a intensidade de agitação no molde e evitar sobreagitação do menisco com conseqüente arraste de pó fluxante e erosão excessiva da válvula submersa (SEN). A agitação principal do EMS de bobina dupla (Dual-Coil), nesse contexto, agiu como um EMS de bobina simples convencional quando a bobina superior esteve desligada. Embora o EMS de bobina dupla possibilite controle flexível da intensidade de agitação na região do menisco sem as complicações acima, ele também afeta a velocidade de agitação produzida pela bobina principal, reduzindo-a. Entretanto, esta redução de velocidade pode ser compensada, pelo menos em parte, pelo aumento da corrente da bobina principal. Os resultados dos testes e prática operacional na Usina de Contrecoeur demonstraram que a segregação central de carbono obtida com EMS de bobina dupla foi melhor do que aquela obtida com EMS de bobina simples. A agitação controlada na região do menisco também resultou em maior estabilidade do nível do menisco, redução da erosão do SEN e saliência de marcas de oscilação, e condições de lingotamento livres de ocorrências de arraste de pó fluxante.

**Palavras-chave**: Lingotamento contínuo; SEM; Aço alto carbono

[1] *Tecnhical contribution to XXXVIII Steelmaking Seminar – International, May 20th to 23rd, 2007, Belo Horizonte, MG, Brazil.*

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## 1 INTRODUCTION

Beneficial effects of high intensity in-mold electromagnetic stirring (MEMS) on improvement of as-cast product quality, carbon segregation in particular, are well recognized in the steel industry.(1,2,3) However, high intensity stirring in the mold bulk with submerged pour casting practice presents a challenge because stirring intensity at the meniscus is restricted in order to avoid mold powder entrapment and excessive erosion of submerged entry nozzle ( SEN ). Finding a balance between the required high stirring intensity in the mold bulk and the restrictions imposed on stirring velocity in the meniscus region is commonly achieved by adjusting the current supplied to the stirring coils or by installation of a less powerful stirrer.(4) This is the common approach when casting with a conventional single-coil stirrer.

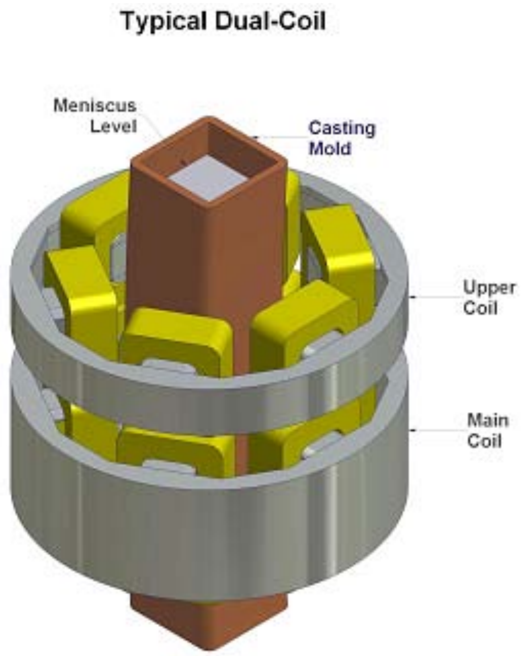


**Figure 1**. Schematic of dual-coil EMS

Dual-coil EMS, on the other hand, provides independent control of stirring intensity in the mold bulk and the meniscus region.(5) With submerged pour casting practice, the upper stirring coil of dual-coil system, (see Figure 1), operates as an electromagnetic brake in order to reduce stirring motion in the meniscus region, while the main stirrer provides high stirring intensity in the rest of the mold. A reduction of stirring velocity at the meniscus, especially when approaching the virtual zero level, also results in some reduction of stirring velocity in the mold bulk. Depending on the mold cross-section, length and other factors, this reduction in stirring velocity may be up to 20%. Therefore a question arises which of these two actions, i.e. reduction in the current supplied to single-coil EMS or the impact of braking produced by dual-coil EMS, have a more prominent effect on metallurgical performance of EMS in terms of the solidification structure and centerline carbon segregation.

This paper considers the above issues in the context of the results obtained from an industrial trial carried out at Contrecoeur Works, Mittal Canada Inc.

## 2 TRIAL SETTINGS

The trial was carried out on a 120 mm sq. section of a six-strand billet caster. One heat of high carbon steel was cast with dual-coil EMS at varying operating settings, and in addition, a sequence of three heats were cast with constant EMS settings. The chemical composition of steel cast on all four heats was identical and is presented in Table 1.

**Table 1**. Steel Chemical Composition, % wt

| C | Mn | Si | S | P | Cu | Ni | Cr | Ca | $Al_{tot}$ |
|---|---|---|---|---|---|---|---|---|---|
| 0.745 | 0.65 | 0.26 | 0.008 | 0.009 | 0.10 | 0.03 | 0.03 | 0.001 | 0.001 |

In order to eliminate the effect of other factors, different EMS settings used on the first heat were performed on the same strand. Parameters of that heat are listed in Table 2.

**Table 2**. EMS and Casting Parameters

| Parameter | EMS Setting Number | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | 4 |
| Billet section size, mm sq. | 120 | 120 | 120 | 120 |
| Casting speed, m/min | 3.53 | 3.53 | 3.53 | 3.53 |
| Tundish superheat, $^{o}C$ | 46 | 42 | 43 | 43 |
| Secondary cooling flow density, $\ell$/kg | 1.86 | 1.86 | 1.86 | 1.74 |
| Spray nozzle pressure in zone 1, bar | 18 | 18 | 18 | 11 |
| Main EMS current, A | 254 | 305 | 356 | 390 |
| Frequency, Hz | 5.0 | 5.0 | 5.0 | 5.0 |
| Brake use | No | No | Yes | Yes |

As seen from Table 2, a portion of the heat was cast with the main stirrer without using the brake. Thus, stirring conditions were produced typical for a single-coil EMS.

A current input of 254 amperes for the main stirrer was based on the results of an extensive study carried out earlier at Contrecoeur Works (170 heats were cast with and without the brake and 1420 samples of wire rod were examined for inclusions of mold powder origin).[6] That study aimed at finding the maximum stirring intensity with only a main stirrer which can sustain casting conditions free of mold powder entrapment and/or excessive SEN erosion. Although these casting conditions were attained at 225 amperes on the main stirrer, for the trial, it was decided to extend the current level on the main stirrer up to 254 and 305 amperes. The brake was applied while current settings on the main stirrer were 356 and 390 amperes. The latter is a typical setting for conventional dual-coil EMS operating conditions and was also used with the other three trial heats. The casting parameters of those three heats differed from those of the first heat, as shown in Table 3. As seen from Table 3, the casting speed was substantially lower and the superheat was in the wider range that it was on the first trial heat. There were also variations in the spray nozzle pressure between strands 1 and 2 due to different physical condition of the nozzles.

**Table 3**. Parameters of the Sequence Heats Cast Under Standard Production Conditions

| Parameter | Strand No. | | | | | |
|---|---|---|---|---|---|---|
| | 1 | | | 2 | | |
| | Heats | | | Heats | | |
| | 1 | 2 | 3 | 1 | 2 | 3 |
| Billet section size, mm sq. | 120 | 120 | 120 | 120 | 120 | 120 |
| Casting speed, m/min | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 | 3.05 |
| Tundish superheat, $^{o}$C | 36 | 50 | 39 | 36 | 50 | 39 |
| Secondary cooling flow density, $\ell$/kg | 1.89 | 1.89 | 1.89 | 1.89 | 1.89 | 1.89 |

## 3 EVALUATION PROCEDURES

For evaluation of the effect of stirring conditions on the solidification structure and centerline carbon segregation, billet samples were taken on the first heat for each EMS setting. The samples were cut into transverse and longitudinal sections. The transverse sections were drilled in the metallurgical center to obtain probes for carbon analysis. The longitudinal sections were used to evaluate solidification structure by sulfur printing. The probes taken from the metallurgical center were also complemented by probes drilled at 1/3 of the way between the section center and the corner to obtain material for bulk carbon analysis. Only a few transverse sections of each billet sample were used for this purpose. A drill of 5.16 mm diameter was used. The carbon analyses were performed with a LECO analyzer.

The centerline carbon segregation was characterized by a mean value of the centerline carbon analyses ratio to the bulk carbon analyses, as per equation (1):

$$K_C = \frac{\sum C_O / C_B}{n} \qquad (1)$$

where $\sum C_O / C_B$ is the sum of individual carbon segregation ratios

$n$ is the number of individual carbon segregation ratios

The fluctuation range of carbon segregation ratio was characterized by the standard deviation. Typically about 40 individual carbon segregation ratios were used to determine their mean value and standard deviation for each billet sample. In addition to solidification structure and carbon segregation evaluation, shape and severity of oscillation marks on the billet surface were also evaluated.

## 4 RESULTS

### 4.1 Oscillation Marks

Examples of oscillation marks on billets stirred with different EMS settings are shown in Figure 2. As seen from photographs (a) and (b), the oscillation marks on the billets stirred with only the main stirrer (settings 1 and 2) have a distinct wavy shape, while the billets stirred with dual-coil EMS have flat oscillation marks. It can also be seen, that the wavy shape oscillation marks are deeper than the flat oscillation marks.

a) Billet stirred with the main EMS @ 254 A

b) Billet stirred with the main EMS @ 305 A

c) Billet stirred with the main EMS @390 A plus Brake

**Figure 2**. Oscillation marks

The wavy shape of oscillation marks and a distance between the wave crest and valley characterize meniscus depression due to rotating stirring motion. Based on the distance between oscillation mark wave crest and valley, stirring without the brake created significant velocity at the meniscus.

Stirring velocity can be assessed by using a simple equation.

$$U = \sqrt{2gh} \qquad (2)$$

where $U$ is tangential velocity, m/s
$g$ is the acceleration of gravity, 9.81m/s$^2$
$h$ is the distance between the oscillation mark crest and valley, m

The distance $h$ is estimated to be 7 to 10 mm on average with a stirring setting of 254 amperes on the main stirrer, and from 8 to 12 mm with 305 amperes. Based on these $h$ values, stirring velocity near the mold wall is estimated to be between 0.37 and 0.48 m/s. These velocity values correspond reasonably well with stirring velocity measured in mercury stirred inside of the 120 mm sq. mold of the Contrecoeur EMS installation. As seen from Figure 3, angular stirring velocity measured at the meniscus at 250 amperes of the current input was 6.1 rad/s and 6.8 rad/s at 300 amperes. With a ratio of stirring velocity in steel (calculated) to that in mercury ( measured ) equal to 1.07 and stirring pool radius of 0.058 m, these angular velocities correspond to 0.37 and 0.42 m/s of tangential velocity in steel.

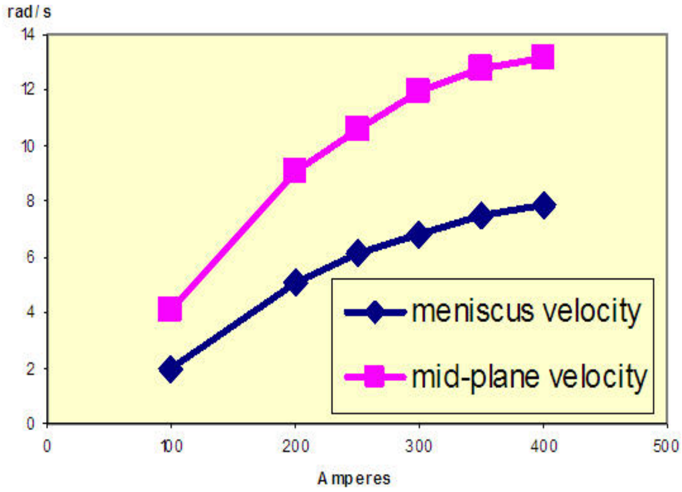
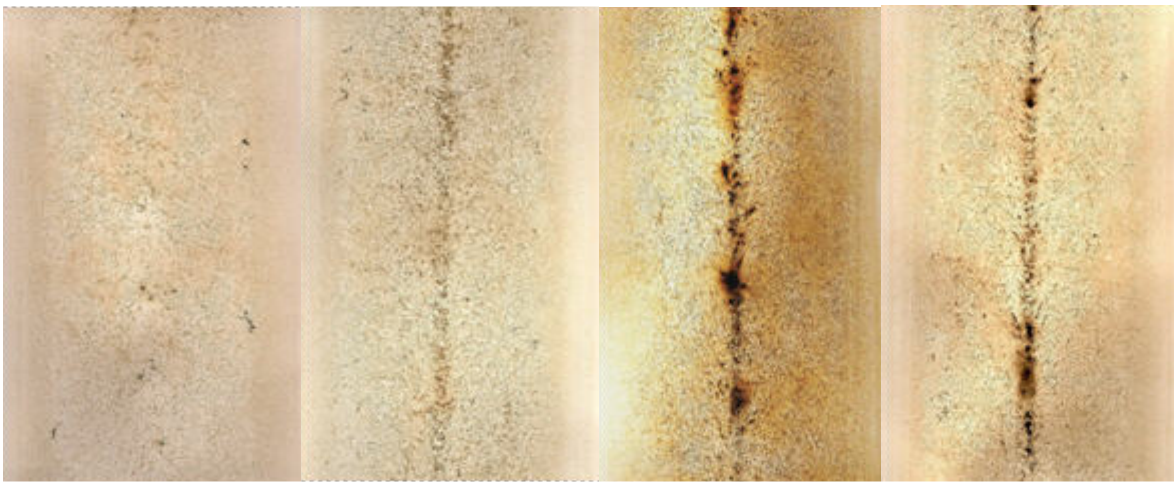



**Figure 3.** Stirring velocity in mercury vs. EMS current

Flat oscillation marks obtained with the EMS settings 3 and 4 (with the brake), on the other hand, indicated meniscus quiescence and stability. Improved meniscus stability achieved with dual-coil EMS operating in brake mode was confirmed by the direct measurements of meniscus level fluctuations(7) and also by numerical simulation of fluid flow.(8) A significant reduction in meniscus fluctuation is considered as a measurable process improvement.(7,9)

### 4.2 Solidification Structure

Sulfur prints of the solidification structure obtained from the first trial heat are shown in Figure 4. The structure pertinent to the first three EMS settings, i.e. 254 and 305 amperes on the main stirrer without the brake and 356 amperes with the brake, shows inadequate refinement. Branched dendrites in large numbers are interspersed across the equiaxed matrix. Some improvement appeared to be obtained in the equiaxed structure with a further current increase on the main stirrer to 356 and 390 amperes. Although this structure improvement was not reflected in centerline porosity, which was more pronounced at these settings. Individual pore size reaches 2.5 mm in some instances. Notwithstanding structure quality variations, the equiaxed zone size is hardly affected by different settings of EMS operation; it remains within a range of 55 to 60 percent.



a) Main EMS @ 254 A    b) Main EMS @305 A    c) Main EMS @356 A + Brake    d) Main EMS @ 390 A + Brake

**Figure 4.** Solidification structure of the billets with different EMS settings

### 4.3 Centerline Carbon Segregation

The mean value and standard deviation of centerline carbon segregation ratios pertinent to the different EMS settings used on the first trial heat are summarized in Table 4.

**Table 4.** Mean Value and Standard Deviation of the Centerline Carbon Segregation

| EMS Setting | Segregation Mean Value, $\overline{K}_C$ | Segregation Standard Deviation St. Dev. |
|---|---|---|
| Main EMS @ 254 A | 1.142 | 0.056 |
| Main EMS @ 305 A | 1.134 | 0.047 |
| Main EMS @ 356 A plus Brake | 1.124 | 0.048 |
| Main EMS @ 390 A plus Brake | 1.138 | 0.044 |

As seen from Table 4, the worse case of segregation is related to the EMS setting 1, i.e. 254 amperes on the main stirrer without the brake. Segregation was improved with the other EMS settings, mainly by means of reduction in standard deviation. As seen from the carbon segregation profiles presented in Figure 5, the number of segregation peaks equal or exceeding 1.20 was reduced from 9 with the EMS setting of 254 amperes to 4 with EMS operating with the brake. Although there were 3 peaks with the EMS setting of 305 amperes without the brake. It is worth to note at this point that reduced intensity of secondary cooling at this EMS setting (see table 2) could have an impact on carbon segregation.

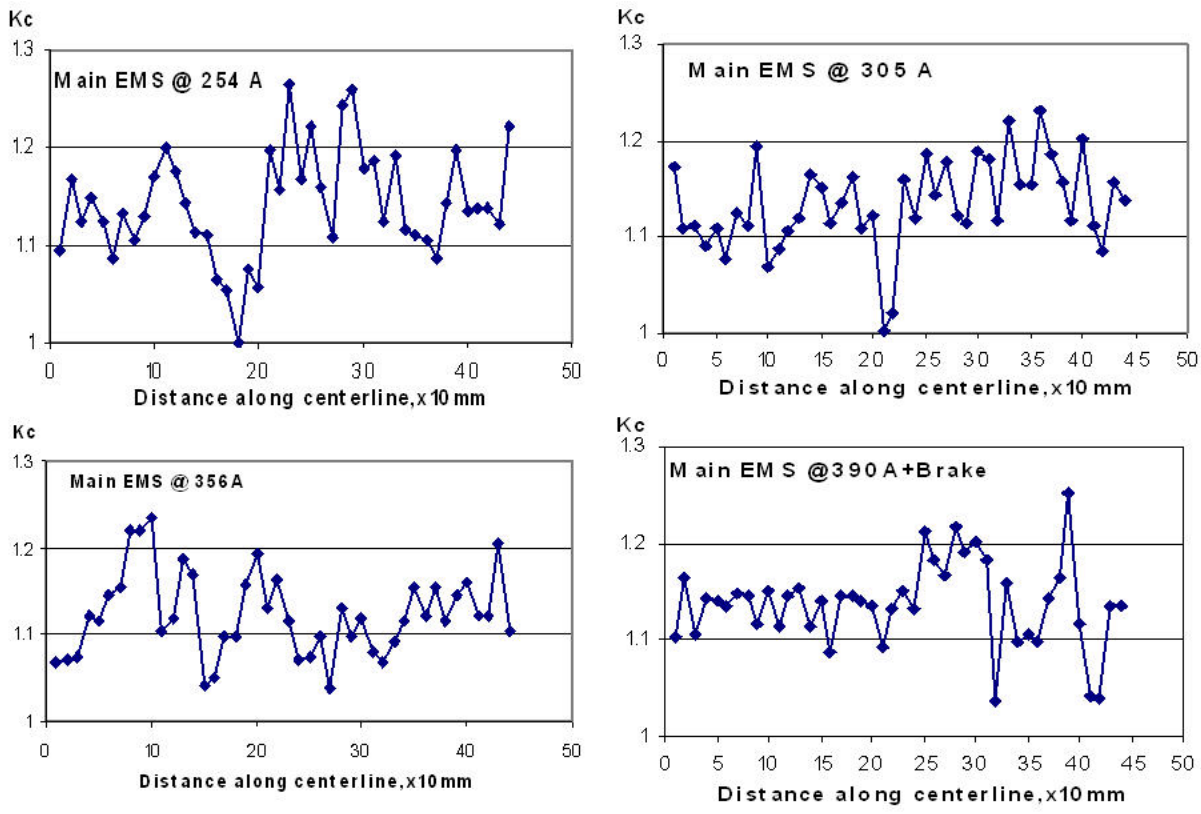



**Figure 5.** Centerline carbon segregation in the billets cast with different EMS settings

In comparison with these results, carbon segregation was notably improved in the three heats cast in sequence with the standard operating setting of 390 amperes on the main EMS plus the brake. As seen from Figure 6, there were no segregation peaks equal or exceeding 1.2 in the carbon segregation profiles obtained from these heats. Segregation mean value on those heats was reduced below the level of 1.10 and standard deviation was on average 0.04, except on strand 2 of heat No. 1, where it was 0.067. The overall improvement attained on these heats may be attributed to the fact that the casting speed was substantially lower than that of the first trial heat, i.e. 3.05 m/min versus 3.53 m/min.

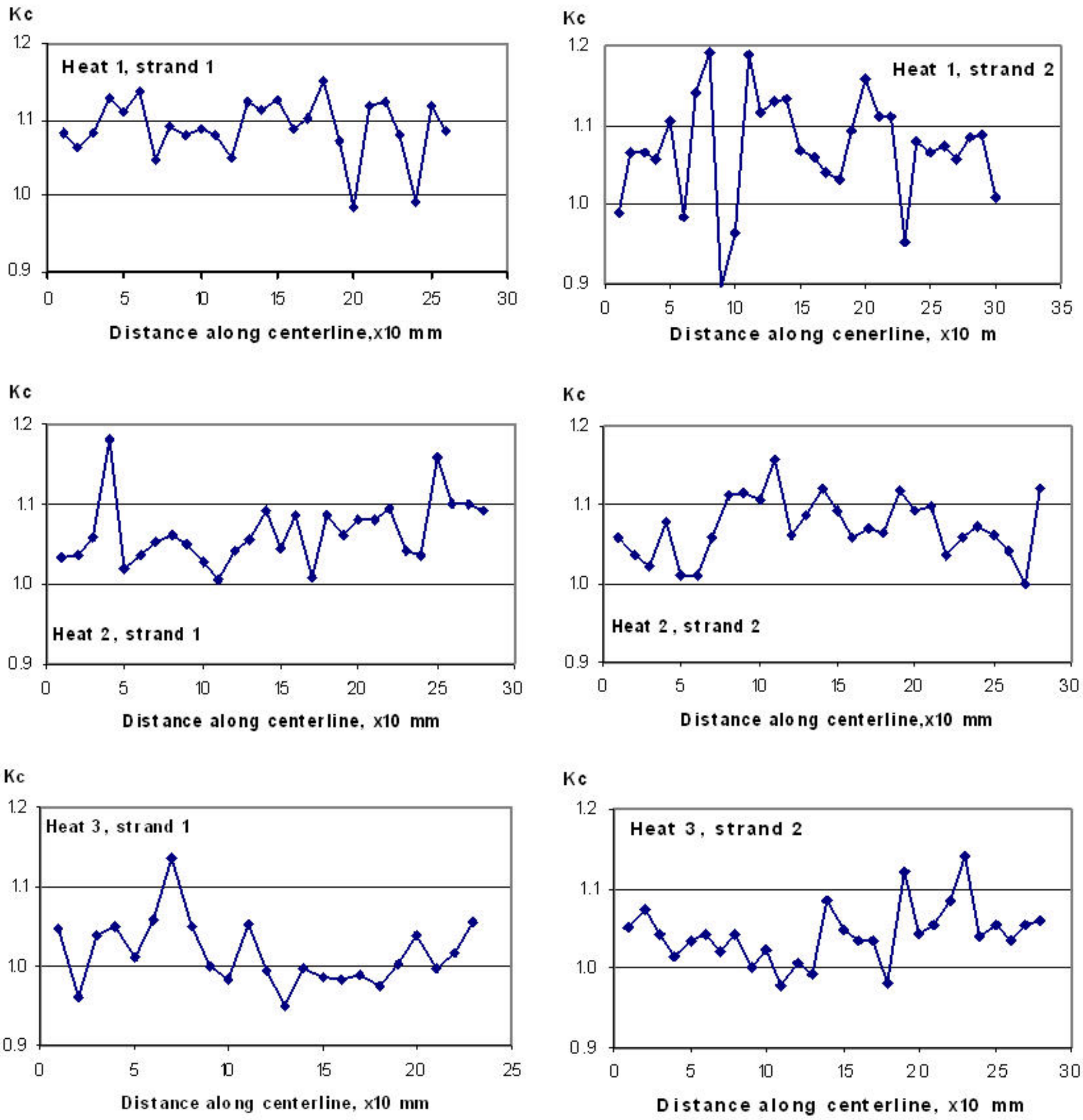



**Figure 6.** Centerline carbon segregation in the billet cast with the standard EMS setting of 390 A on the main EMS + brake

## 5 CONCLUSIONS

The results of the trial and production practice at Contrecoeur Works, demonstrated that:

1. The centerline carbon segregation in high-carbon steel billets achieved with dual-coil EMS is notably improved in comparison with that attained with single-coil EMS operating under restrictions in stirring intensity imposed by submerged pour casting practice.

2. Casting speed affects carbon segregation in high carbon steel billets, when, under the given casting and EMS parameters, it exceeds a certain level.

3. Dual-coil EMS provides conditions for submerged pour casting practice free of mold powder entrapment and excessive erosion of SEN.

4. Controlled stirring intensity in the meniscus region achieved with dual-coil EMS results in improvement of the oscillation marks and the billet surface quality.

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