Optimisation of Electromagnetic Stirring in Steel Billet Caster by Using Image Processing Technique for Improvement in Billet Quality

Preeti Prakash SAHOO, Ankur KUMAR, Jayanta HALDER and Manish RAJ

Research & Development, Tata Steel, Jamshedpur-831001, India. E-mail: ppsahoo@gmail.com

(Received on November 25, 2008; accepted on January 23, 2009)

Determination of best combination of current and frequency of an electromagnetic stirrer (EMS) of a billet caster is of prime importance for ensuring good internal, surface as well as subsurface quality of billets. In the present study, this optimization of current and frequency values is achieved very efficiently using image processing techniques. The EMS currents and frequency are varied between 240–300 A and 3–5 Hz respectively during casting and corresponding billet samples are collected. Samples are also collected from beginning, middle and end of casting heats in order to assess the influence of tundish superheat. The samples thus collected are scanned using ultrasonic C-scanner to get the full color image of samples. The grabbed images are processed and analysed using Matlab Image Processing Toolbox in RGB color space. Finally, data of various defects as obtained from image processing, in each grades of steel are compared for determining the best combination of EMS parameters. It has been found that length of equiaxed zone increases significantly with increasing EMS current up to 280 A, almost for all close casting grades. Increasing EMS current beyond 280 A increased the length of equiaxed zone marginally but chances mould powder entrapment at the surface of the billet and erosion of submerged entry nozzle is more. Central shrinkage number of subsurface and central crack also reduced significantly up to 280 A EMS current. Marginal improvement in billet quality is also observed when 3 Hz EMS frequency is used but the improvement in the quality is not significant.

KEY WORDS: billet casting; image processing; EMS; ultrasonic C scan; solidified structure.

1. Introduction

Electromagnetic stirring (EMS) is an established technique of improving quality of continuously cast steel. Current induced in the liquid pool of steel inside the mould generates an electromagnetic force which tends to put the liquid metal into rotation. By controlling the EMS current and frequency, stirring intensity in the liquid pool can be controlled. Following improvements in the quality of continuously cast steel due to EMS has been reported.1) 1. Improvement in the morphology of cast structure and reduction in macrosegregation and porosity. 2. Improvement in surface and sub-surface quality and suppression of blow holes. 3. Coagulation and removal of lighter non-metallic inclusions in the mould due to centripetal force induced by EMS.

1.1. Application of EMS in Continuous Casting

The solidification structure improves with an increase in EMS current and the amount of branched dendrites embedded into the equiaxed matrix is reduced and the equiaxed zone boundaries become more consistent. The centreline segregation of continuous casting of steel is much improved by low superheat casting. But the low superheat casting is not practiced because of problem of nozzle clogging. The deleterious effect of high super heat can be eliminated with the application of optimum EMS settings.2)

During solidification of metal and alloy, flow is induced in the mushy zone due to variation in composition and temperature as well as due to solidification shrinkage of the melt. Bulk movement of liquid and solid phases during solidification leads to macrosegregation and porosity in the casting. Stirring in the liquid pool minimizes temperature and concentration gradients and cause fragmentation of dendrite tips during solidification, promoting early columnar to equiaxed transition in the casting. Consequently, a wider equiaxed zone and reduced macrosegregation is obtained in steels cast with EMS.3) However, too high stirring leads to formation of a band of negative segregation, typically known as white band in cast billets. The degree of negative segregation has been found to increase with increasing flow velocity and decreasing carbon content of steel.4)

Optimum stirring intensity facilitates homogenization of composition and temperature subsequently minimization of macrosegregation.4) Rotational velocity generated by a rotary EMS depresses the position meniscus, thereby decreases the effective immersion depth of the submerged entry nozzle (SEN) and gives rise to mould flux/slag en-
1.2. Effect of EMS Frequency on Stirring Intensity and Importance of Current and Frequency Setting

Stirring intensity decreases with increasing frequency and it is related to the ‘skin effect’ according to which eddy currents are more concentrated on the outer part of the conductor as the frequency increases. The following relationship describes the effect of EMS frequency on stirring intensity \( F \):

\[
F \propto B^2_M(f)f \quad \ldots \ldots \ldots \ldots (1)
\]

where \( B_M \) is magnetic induction in the considered point inside the metal (in Gauss) and \( f \) the frequency of power supply, in Hz.

The above formula shows that the stirring force is the product of \( B^2_M(f) \) (which decreases with increasing frequency) and \( f \). At frequency zero the force is zero and at higher frequency the force approaches to zero again because the term \( B^2_M(f) \) becomes very small. In between, there is a specific frequency, the so-called optimum frequency, at which the stirring force is maximum.

The current in the EMS coil controls its performance because the stirring force \( F \), acting on the liquid steel is proportional to the square of the magnetic flux \( B_M \), which is proportional to the current. Consequently, the current setting is the main operational parameter, which is to be chosen as function of the casting conditions. Generally, the current is kept constant during casting. Theoretically, the current setting depends on the chemical composition of each steel grade. An optimization is to be done for each individual case as increased casting speed as well as increased superheat needs increased current settings. In practice, however, the justification of different current setting as function of casting speed and superheat shall have to be ascertained for each specific case.

During any metallurgical improvement obtained by EMS (such as reduction of surface and subsurface defects, increase in equiaxed zone, decrease in axial porosity or segregation etc.), too low current settings give insufficient improvements, and too high current settings give practically no further improvements and waste electrical power. Moreover, too high current settings may give rise to negative effects. Consequently, the optimum current setting is the compromise of good results and reasonable power consumption. It needs many casts and analysis under reproducible conditions with and without stirring, to establish quantitatively the exact relation between improvement and current setting.

1.3. Application of Image Processing to Continuous Casting

Image processing is an emerging technology having various applications in the field of space research, cinema, medical industry and machine vision. Nishimoto\(^6\) has shown application of image processing in iron and steel process for various purposes like defect detection, counting steel bars and rods in bundles, reading marks on plate and assessment of spatial temperature distribution. Kawakami et al.\(^7,8\) showed the use of image processing tool for morphological classification of inclusions in steel. Logunova et al.\(^9\) showed the possibility of statistical method and image processing in determining the presence and propagation of defects in billets formed in continuous casting. The present work shows the capability of image processing techniques to identify and measure the area of different zones of images. Thus, image processing is used to measure the amount of defects in cast billets corresponding to different set of process parameters. The images of samples of billets are collected from the ultrasonic C Scanner for the above purpose.

2. Experimental

2.1. Experimental Procedure of Billet Sample Collection

Attempts have been made to determine the best combination of EMS current and frequency for ensuring good surface as well as subsurface quality of CC steel billets cast at Billet Caster-1. Two casting grades, one of high carbon grade (HC Grade) and another of low carbon grade (LC Grade) of steel billet are considered. The chemical compositions of the above mentioned grades are shown in Table 1. The experiments are conducted with EMS currents of 240, 260, 280 and 300 A, while frequency is kept constant at

| Chemical composition and other casting details of the steel grades. |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
| **Other details** | **Chemical composition, wt.%** | **Mould Flux Viscosity** |
| | Liquidus, °C | Superheat, °C | C | Mn | S | P | Si | Al | Cr | Ni | (1300 °C), Pa*Sec |
| **High carbon grade** | 1475 | 48 | 0.63 | 0.53 | 0.011 | 0.013 | 0.19 | 0.025 | 0.02 | 0.012 | 0.20 |
| **Low carbon grade** | 1507 | 47 | 0.21 | 0.83 | 0.011 | 0.018 | 0.59 | 0.028 | 0.14 | 0.016 | 0.12 |
3.5 Hz during casting. In some of the heats EMS frequencies are set at 3, 3.5 and 4 Hz while EMS current is kept constant during casting. In both cases the corresponding billet samples are collected and the effect on billet quality is assessed by using ultrasonic immersion C-scan imaging technique. Each billet sample of cross-section of 130×130 mm is sliced into transverse and longitudinal sections (~20 mm thickness) and ground to good surface finish. Figure 1 shows the schematic diagram of billet samples collected. The scanned images of the billet samples from ultrasonic C-scan are analysed using image processing technique to find out the percentage of defect and percentage equiaxed zone. For each billet sample liquid steel temperature is also measured in the tundish to assess the effect of superheat on billet quality. During all the experiments, casting speed was kept around 3 m/min, EMS coil position was fixed at 80 mm below meniscus, and SEN was used for pouring liquid steel from tundish to the mould.

Billet samples are examined using a computerized ultrasonic C-scanner. Top and bottom surfaces of each billet samples as well as three intermediate layers are scanned at an interval of 5 mm in the ultrasonic C-scan. Ultrasonic C-scan gives two dimensional images of internal as well as surface defects for each billet sample. Total number of defects (which includes segregation, inclusions, pinhole, internal as well as subsurface cracks) in a given billet section are obtained from the scanned image of C-scan. The two dimensional image obtained from the C-scanner distinguishes different regions such as equiaxed grains, columnar grains, chilled zone and casting defects in different color so that the area covered by each color can be easily distinguished. Moreover, any defects which are at the intermediate layer of the billet sample also appear in the final 2D image. It provides gross information about the defect concentration. All the steel billet samples are examined using the ultrasonic immersion C-scan imaging technique. The color image obtained from the ultrasonic C scanner is analysed using image processing technique. The color images are first enhanced for color clarity and then pixels of different colors indicating different zones are counted to measure the area of defective zone and the equiaxed zone for different billet samples.

3. Methods of Analysis

3.1. Ultrasonic Immersion C-scan Imaging Technique

A series of tests are carried out with the billet specimens to evaluate and optimise the EMS current and frequency with respect to CC steel billet quality. These specimens are subsequently tested in a water tank using a 5 MHz ultrasonic focused beam probe. The C-scan images are obtained with the help of a computer controlled ultrasonic immersion C-scan system. This technique is applied to evaluate the quality of steel billet samples. Ultrasonic C-scan can image five different intermediate layers of the billet samples and plot the final image in two dimensions. Therefore, all the internal defects appeared at the final image, where as in macroetched structure revealed only top etched layer of the samples. One major advantage of ultrasonic C-scan is that classification of different kinds of defects is possible by imaging of the defects by this method. This method also reveals three different regions in the samples such as chilled zone, equiaxed zone and columnar zone in different grey/color scale.

A series of C-scan tests are carried out with varying parameter settings. The instrument variables for these tests are as follows: resolution: 0.4×0.4 mm; voltage setting: 20 V and gain: 33 dB. Grey scale is used to differentiate the results from the gated area. Referring to ultrasonic C-scan images, and based on a grey scale that depicts attenuated signals darker, one may see clear identification of defects by the darker areas. Although not very sharp, each one of the areas is reproduced with a certain degree of dimensional accuracy. However the boundary of each defect is not well defined.

Ultrasonic C-scan equipment was calibrated by comparing the images taken for billet samples with this equipment, with the layer wise macro-etched samples of the same specimens. The defects and different zones in the C-scan images were matched exactly with those macro-etched samples.10)
cepted way to specify a particular color by defining a coordinate system and a subspace within that system where each color is represented by a single point. The most commonly used color models in practice are RGB (red, green, blue), HSV (hue, saturation, value), CMYK (cyan, magenta, yellow, black). RGB color model is selected for current study. RGB color model is an additive color model in which each color appears as the combination of red, green and blue. The color subspace in RGB color model is represented by color cube shown in Fig. 2 in which RGB values are at three corners, cyan, magenta and yellow are at three other corners, black is at the origin and white is farthest from the centre. The color values here are written as numbers in the range 0 to 255, simply by multiplying the range 0.0 to 1.0 by 255. Thus the full intensity red is (255, 0, 0) full intensity green is (0, 255, 0) and full intensity blue is (0, 0, 255). A pixel whose color components are (0, 0, 0) displays as black, and a pixel whose color components are (255, 255, 255) displays as white. Each pixel of image stores 24 bits of information which is apportioned with 8 bits each for red, green and blue, giving a range of 256 possible intensities.

3.2.2. Image Enhancement

Image enhancement is the process for improving the digitally stored images by manipulating it with the objective to get the more suitable result than the original image for a specific application. This is done either by increasing the signal-to-noise ratio or by making certain features easier to see by modifying the colors or intensities. For the present images intensity adjustment is done to make them clearer. Intensity adjustment is a technique for mapping an image's intensity values to a new range. Image histogram is used for showing the distribution of intensities of any image. Figure 3 shows that the image has rather low contrast and histogram of this image shows that the intensity is distributed from 0 to 255. The remapping of entire value of intensity is done in new range and the new image with increased contrast as shown in Fig. 4. The histogram of new image in shows that most of pixels have either zero of 255 intensity values increasing the contrast of the image.

4. Results and Discussions

The required current setting depends on the chemical composition of each steel grade; therefore selection of optimum current setting is important for each individual grade of steel to achieve desired results. The liquid flow velocity can be controlled by varying the field strength i.e., the EMS current, suitable for a particular grade of steel. The actual current setting is determined by different casting parameters. In case of open casting (without SEN) practice, liquid
steel is more prone to reoxidation in the mould. Due to high stirring motion in the liquid pool the reoxidation products which are generally lighter than the steel are centripetally forced towards the center of the liquid core where they are more readily removed by the mold flux. Therefore, strong stirring action at meniscus level and high stirring power are required for open stream casting. An increase in casting speeds and superheat needs intense stirring therefore higher current settings is required. High stirring intensity in the mould effectively depresses the meniscus resulting decrease in the effective length of immersion depth of the submerged entry nozzle for close casting grades causing entrapment of mould flux in the surface.

4.1. Optimisation of EMS Current

4.1.1. High Carbon Grade

Before this work, the Billet Caster-1 used a setting of 260 A EMS current and 3.5 Hz EMS frequency for all the shrouded casting grades. In this work EMS current was set to 240, 260, 280 and 300 A during casting and billet samples were collected and examined to find out the effect of change in current. Samples without EMS were also collected. This is aluminium killed steel with carbon content 0.63%. The other details of the grade are shown Table 1. Figure 5 shows the ultrasonic C-scan image of transverse section of non-EMS billet sample. It can be easily observed that there is a very small equiaxed zone with a large columnar zone and a large defective area. After use of EMS, there was significant improvement in quality in terms of larger per cent of equiaxed zone, small axial porosity and low per cent of defective areas, which are desirable. This is also evident from Fig. 6, Fig. 7, Fig. 8 and Fig. 9 which show the ultrasonic C-scan images of transverse sections of CC billet sample of HC Grade, at EMS current 240, 260, 280 and 300 A. Figure 10 shows the quantitative values of the effect of EMS current on the quality of HC Grade billet samples in term of per cent of equiaxed zone and the per cent of defective area. It is clear that the equiaxed zone in non-EMS sample is lower whereas with EMS and with current setting of 240 A, 260 A, 280 A and 300 A percentage of equiaxed zone increases from 240 to 300 A. Similarly, the defective
area in the non-EMS billet sample is much higher than with EMS as can be seen from Fig. 10. In non-EMS sample, as there is no stirring motion in the liquid pool of steel, the solidification period is dominated by dendrite growth and the solidified structure consists of mainly columnar grains with high central looseness.

4.1.2. Low Carbon Grade

This is a cold heading quality grade for high tensile fasteners. The details of this grade are shown in Table 1. Figure 11 shows the ultrasonic C-scan image of transverse section of a non-EMS billet sample. It can be observed that there is a very small equiaxed zone with a large columnar zone and a large defective area when compared with the EMS billet samples. When EMS was used, there was significant improvement in quality in terms of larger per cent of equiaxed zone, small axial porosity and low per cent of defective areas, which is desirable. It is also evident from Fig. 12, Fig. 13, Fig. 14 and Fig. 15 which show the ultrasonic C-scan images of transverse sections of billet sample of LC Grade at EMS current 240, 260, 280 and 300 A. Figure 10 demonstrates the quantitative values of the effect of EMS current on billet quality in term of per cent of equiaxed...
zone and the per cent of defective area of total area. It is evident from these figures that when the EMS current is kept at 280 A and 300 A the percentage of equiaxed zone is highest and percentage defective area is lowest. But at high current of 300 A the SEN life was shorter than 280 A. So 280 A EMS current is the best value to operate to get lower defective area and higher equiaxed zone.

4.2. Optimisation of EMS Frequency

After optimisation of EMS current, EMS frequency was, then, set to 3, 3.5 (existing practice) and 4 Hz, keeping EMS current constant at 280 A during casting and billet samples were collected. These billet samples were also ultrasonically analysed and evaluated. Figure 16 and Fig. 17 show the ultrasonic C-scan image of transverse section of billet samples of HC Grade at EMS current 280 A and EMS frequency 3 and 4 Hz respectively, whereas Fig. 18 and Fig. 19 show the ultrasonic C-scan image of transverse section of billet sample of low carbon grade at EMS current 280 A and frequency 3 Hz.
of billet samples of LC Grade at EMS current 280 A and EMS frequency 3, 3.5 and 4 Hz respectively. In both the grades, it was found that quality of the billet samples appears sounder, in terms of the per cent of equiaxed zone, axial porosity and the per cent of defective areas, when the EMS frequency was 3.5 Hz, when compared to the same with the EMS frequency 3 and 4 Hz. Figure 20 demonstrates the quantitative values of the effect of EMS frequency on the quality of billet samples of both the grades in term of the per cent of equiaxed zone and the per cent of defective area of total area. The equiaxed zone in non-EMS HC Grade samples is 18% whereas, samples collected with EMS have higher equiaxed zone. Percentage equiaxed zone is 35, 51 and 52% at the EMS frequency 3, 3.5 and 4 Hz respectively. Similarly, the defective area in the non-EMS billet sample is as high as 18% of the total area of the billet sample, while, in EMS billet samples, at the EMS frequency 3, 3.5 and 4 Hz, it is 17, 12 and 13% respectively. In case of LC Grade, in non-EMS samples percentage equiaxed zone is 15% only whereas, in EMS billet samples, it is 30, 45 and 46% at the EMS frequency 3, 3.5 and 4 Hz respectively. Similarly, the defective area in the non-EMS billet sample is as high as 16% of the total area of the billet sample, while, in EMS billet samples, at the EMS frequency 3, 3.5 and 4 Hz, is 15, 10 and 11% respectively. It is observed that billet sample contains huge central looseness with lot of subsurface defects when operated at 4 Hz frequency. Therefore EMS frequency is not raised further.

5. Conclusions

It is important to control of stirring motion within the meniscus and bulk regions of the casting to achieve the desired product quality and operating flexibility. The stirring of molten steel by EMS is effective to improve the homogeneity of the cast, which solidifies with enough amounts of equiaxed crystals. In this work it has been found that length of equiaxed zone increases significantly with increasing EMS current up to 280 A for both low and high carbon grades. Increasing EMS current beyond 280 A could increase the length of equiaxed zone marginally. Central shrinkage is reduced significantly for all grades while using EMS current of 280 A. Number of subsurface and central crack also reduced significantly up to 280 A EMS current. The change in EMS frequency from 3.5 to 4 Hz, at EMS current 280 A, did not result any further improvement in billet quality. Electromagnetic stirrer frequency 4 Hz caused reduction in the equiaxed zone and large axial porosity in the billet samples. Image processing tool can be efficiently used for qualitative as well as quantitative evaluation of defects and columnar/equiaxed zone in the continuously cast billets.

REFERENCES

1) M. Yoshimura, S. Suzuki, S. Takagawa and H. Ueno: *Tetsu-to-Hagané*, 66 (1980), S802.
2) K. Ayata, H. Mori, K. Taniguchi and H. Matsuda: *ISIJ Int.*, 35 (1995), 680.
3) K. Heck and C. Q. Williamson: Proc. of the Electric Furnace Conf., AIME, Detroit, (1979), 137.
4) H. Takeuchi, H. Mori, Y. Ikehara, T. Komano and T. Yanai: *Trans. Iron Steel Inst. Jpn.*, 21 (1981), 109.
5) H. Takeuchi, Y. Ikehara, T. Yanai and S. Matsumura: *Trans. Iron Steel Inst. Jpn.*, 18 (1978), 352.
6) Y. Nishimoto, T. Koyama and H. Nakata: *CAMP-ISIJ*, 5 (1992), 1369.
7) M. Kawakami, T. Nishimura, T. Takenaka and S. Yokoyama: *ISIJ Int.*, 39 (1999), 164.
8) M. Kawakami, E. Nakamura, S. Matsumoto and S. Yokoyama: *ISIJ Int.*, 36 (1996), S113.
9) O. S. Logunova, V. V. Pavlov and K. K. Nurov: *Elektrometall*, 5, (2004), 18.
10) M. Raj and J. C. Pandey: *Tata Search*, (2005), 153.