ULTRASONIC IMMERSION C-SCAN IMAGING METHODOLOGY: A NEW APPROACH FOR EVALUATION AND OPTIMISATION OF EMS PARAMETERS FOR CONTINUOUSLY CAST STEEL BILLETS QUALITY

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ABSTRACT
As the demand for clean steels increases day-by-day, the quality of steel billets, in terms of internal defects and macro structural features (central porosity, equiaxed zone, etc.), has become of paramount importance. The severity of defects, area of columnar zone as well as central porosity, in continuously cast billet can be effectively minimized by optimizing the Electro Magnetic Stirrer (EMS) parameters viz., EMS current and frequency. The result would be an increased equiaxed zone area and improved internal soundness. In the present study, to ensure good internal soundness of billets, attempts have been made to determine the best combination of EMS current as well as frequency. The EMS current and frequency were changed to different values. Corresponding billet samples were collected for macro structural examination and were scanned using an automatic computerized multi-scan immersion ultrasonic immersion ultrasonic C-scanner to get images of samples. C-scan images obtained have been used for as a tool for evaluating and obtaining optimum electromagnetic stirrer (EMS) parameters i.e. current and frequency. Macro structural features revealed by ultrasonic C-Scan were analysed for determining the best combination of EMS parameters. The most significant improvement was found at 280A EMS current and frequency 3.5Hz. Beyond this there was only a marginal improvement in the billet quality as well as equiaxed zone. Based on the experimental observations, it is recommended to operate EMS at 280A current and EMS frequency should not increase beyond 4Hz in the plant.

Keywords: Ultrasonic C-scan imaging technique, Electromagnetic stirrer, Continuous casting, Steel billets, Defects, Columnar / equiaxed zone.

INTRODUCTION
In recent years, there has been a tremendous increase in demand of clean steel. Hence, more attention has been paid to improving product quality with respect to overall cleanliness level, reliability, and quality of continuously cast (CC) steel product. A cleaner steel greatly improves many physical and mechanical properties such as fatigue life, machinability, and corrosion resistance [1]. To produce clean steel and hence, to minimise the severity of internal defects and macro structural features (central porosity, columnar zone /equiaxed zone, etc.), many steel companies have introduced electro-magnetic stirring (EMS) process. The primary benefits obtained with EMS are now well-known [2-5]. Simply put, the purpose of EMS is to homogenize the steel melt in order to obtain a favourable solid structure after solidification. The benefits are:

1. Improvement in cast structure through increased volume of equiaxed grains.
2. Reduced degree of macro-inclusions, especially in the central portion of cross sections.
3. Improved surface quality and reduced shrinkage porosity.

MATERIAL AND METHOD

Chemical Composition of Material Used
The 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 of an Indian integrated steel plant. One close casting grade of high carbon (HC) grade of steel billet was considered. The chemical composition of steel grade considered in the present work is shown in Table 1.

The experiments were conducted on the above grades of CC billets with EMS currents 240, 260, 280 and 300A, while frequency was kept constant to 3.5Hz during casting. In some of the heats EMS frequencies were set at 3, 3.5 and 4Hz while EMS current was kept constant during casting. In both the cases, the corresponding CC billet samples were collected and its effect on billet quality was assessed by using ultrasonic immersion C-Scan imaging technique. Each billet sample was sliced into transverse and longitudinal sections (approx. 20 mm thick), as shown in Fig. 1, and ground to good surface finish.
All the transverse sections of steel billet samples were examined using the ultrasonic immersion C-Scan imaging technique. All microstructural features observed, in each case, were recorded and analyzed subsequently. Finally, data of axial porosity, columnar / equiaxed zone, % defective area (which includes segregation, inclusions, pinhole, internal as well as subsurface cracks) of the total scanned area in each grades of steel were compared for determining the best combination of EMS parameters.

**Equipment Used**

The samples were tested in a water tank using a 15 mm diameter 5 MHz ultrasonic focused beam probe. The C-scan images were obtained with the help of a computer controlled immersion ultrasonic C-scan system.

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**Table 1**: Chemical composition and other details of HC grade billet

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<th>Liquidus (°C)</th>
<th>Super Heat (°C)</th>
<th>C</th>
<th>Mn</th>
<th>S</th>
<th>P</th>
<th>Si</th>
<th>Al</th>
<th>Cr</th>
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**Fig. 1**: Schematic diagram of CC billet sample (cross section, 130 x 130 mm) collected for C-scan ultrasonic evaluation.

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**Ultrasonic Immersion C-scan Imaging Technique**

During the continuous casting process, due to the differential cooling from the outside surface to the inside, the grain structure is expected to take the distribution as represented by the classic schematic shown in Fig. 2 (a). Here, the chill zone (A) is found on the outer most layer that is in contact with the mould. The anisotropic columnar grain structure (B) is found below the chill zone. The inside regions are found to be equiaxed (C). At the centre, owing to the metal shrinkage, central void (D) is found. The relative areas of these zones will depend on various casting process parameters. Ultrasonic technique was applied to evaluate the above mentioned zones of the billet samples. This method revealed the four different regions in the samples, chilled zone, columnar zone, equiaxed zone and central void, in different gray / colour scale Fig. 2 (b).

Ultrasonic C-scan can image different intermediate layers of billet samples and plot the results in two dimensions. Therefore, all the internal defects appear as well giving an advantage over normal macro-etching where only the top etched layer of the sample can be inspected. One major advantage of ultrasonic C-scan over A-scan is that classification of different kinds of defects is possible by imaging of the defects by this method.

A series of C-scan tests were carried out with varying parameter settings. The instrument variables for these tests were as follows:

- **PRF**: 100Hz
- **Gain**: 40 dB
- **Energy**: 50 μj
- **Damping**: 100 ohms
- **Voltage output (amplitude)**: +3 to -3
- **Resolution**: 0.2 mm x 0.2 mm

Grey scale was used to evaluate and analyze the results obtained 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 different macro structures by the darker areas. Although not very sharp,
each and every one of the areas is reproduced with a certain degree of dimensional accuracy. However, the boundary of each defect is not well defined. The two dimensional image obtained from the C-scanner distinguished different macro structural regions e.g. equiaxed, columnar and chilled zones, and casting defects, if any [6].

RESULTS AND DISCUSSIONS

To determine the optimum combination of EMS current and frequency to produce billet with good internal quality consistently, EMS current was set to 0 (non-EMS), 240, 260 (existing practice), 280 and 300A during casting and billet samples were collected to examine to find out the effect of change in current.

Optimization of EMS Current

Fig. 3 shows the ultrasonic C-Scan image of transverse section of non-EMS billet sample of HC grade. It can be easily observed that there is a very small equiaxed zone with a large columnar zone and a huge defective area in non-EMS billet samples when compared with the EMS billet samples. After use of EMS, there was significant improvement in quality of CC billets in terms of larger % equiaxed zone, small axial porosity and low % defective areas, which is desirable. It is also evident from the Figs. 4-7 which show the C-Scan images of transverse sections of CC billet sample of HC grade, at EMS current 240, 260, 280 and 300A. The quantitative values of the effect of EMS current on the quality of HC grade billet samples in term of% equiaxed zone and the % defective area of total area has been depicted in Fig. 8.

It can be, therefore, concluded that the % of equiaxed zone increases sharply and % total defective area, with respect to the total area of billet section, also decreases considerably with the increase in EMS current up to 280A.

Optimization of EMS Frequency

After optimization of EMS current at 280A, EMS frequency was, then, set to 3, 3.5 (existing practice) and 4Hz during

![Fig. 3: Non-EMS billet sample](image)

![Fig. 4: EMS current 240A and freq. 3.5Hz](image)

![Fig. 5: EMS current 260A and freq. 3.5Hz](image)

![Fig. 6: EMS current 280A and freq. 3.5Hz](image)
Fig. 7: EMS current 300A and freq. 3.5Hz.

Fig. 8: Effect of varying EMS current (freq. 3.5Hz) on the % equiaxed zone and % defective area.

Fig. 9: EMS current 280A and freq. 3Hz

Fig. 10: EMS current 280A and freq. 3.5Hz

Fig. 11: EMS current 280A and freq. 4Hz

Fig. 12: Effect of varying EMS freq. (current 280A) on the % equiaxed zone and % defective area.
casting and billet samples were collected for ultrasonically evaluation.

Figs. 9-11 show the ultrasonic C-Scan image of transverse section of billet samples of HC grade at EMS current 280A and EMS frequency 3, 3.5 and 4Hz respectively. It was found that quality of the billet samples appears sounder, in terms of the % equiaxed zone, axial porosity and the % defective areas, when the EMS frequency was 3.5Hz, when compared to the same with the EMS frequency 3Hz and 4 Hz. Fig. 12 demonstrates the quantitative values of the effect of EMS frequency on the quality of billet samples of both the grades in term of the % equiaxed zone and the % defective area of total area. Hence, it can be concluded that, in this case also, the % equiaxed zone increases and % total defective area in the billet sample, with respect to the total area of billet section, also decreases considerably with the increase in EMS frequency till 3.5Hz and after that it increases marginally.

CONCLUSIONS

The analysis of ultrasonic C-scan images for optimizing EMS parameters during continuous casting of different grades of steel indicated the following:

1. The % equiaxed zone increases significantly with increase in EMS current up to 280A for the high carbon grades of steel considered in the study.

2. The % defective area (which includes segregation, inclusions, pinhole, internal as well as subsurface cracks) of the total scanned area reduced considerably up to an EMS current 280A.

3. The change in EMS frequency from 3.5Hz to 4Hz, at EMS current 280A, did not result in further improvement in billet quality. 4Hz frequency of EMS caused reduction in the equiaxed zone and large axial porosity in the billet samples.

4. The qualitative as well as quantitative evaluation of defects and columnar/equiaxed zone in the continuously cast billets were possible using ultrasonic immersion C-Scan imaging technique.

REFERENCES