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Evaluation of the Effect of Electro-Magnetic Stirring on Soundness of Continuously Cast Billets Using Ultrasonic Technique

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Abstract

Effect of electro-magnetic stirring on soundness of continuously cast billets and slabs can be assessed by many methods like visual inspection of macro-etch & sulphur print evaluation. Ultrasonic assessment provides through thickness information of the test samples, whereas, macro-etching and sulphur print methods provide information in one plane only. An attempt has been made to evaluate the soundness (inhomogeneities / flaws as well as effect of columnar / equiaxed grains) of continuously cast low carbon and high carbon continuously cast billets by ultrasonic attenuation as well as high gain pulse-echo technique in transverse cut slices. One low carbon grade (Grade – LC) and one high carbon grades (Grade – HC) were selected for this purpose.

Assessment of over all flaws / inhomogeneities was done by counting number of high gain internally reflected signals (flaw-echoes) using 6 MHz twin crystal probe. Using 10 MHz probe and attenuation technique (attenuation indicated by back-wall echo drop) was used to evaluate the overall macro-structure (including columnar / equiaxed grains as well as inhomogeneities / flaws).

The result revealed no significant improvement in the equiaxed zone in case of low carbon grade billets (i.e. Grade – LC), whereas, there was significant improvement in the equiaxed zone of high carbon grade billets (Grade – HC). The ultrasonic flaws in the inclusion concentration bands in all the billets were found to decrease after electro-magnetic stirring. In low carbon billet, however, the flaws were found to increase in the central region after electro-magnetic stirring.

Keywords: *Ultrasonic technique, Electro-magnetic stirring, Macro-structure, Equiaxed zone, Columnar zone, Macro-inclusions*

1. Introduction

Usually macro-structure of continuously cast billets and slabs are assessed by the following methods:

1. Visual inspection of macro-etch (1-3),
2. Sulphur print evaluation (4).

Effect of electro-magnetic stirring on continuously cast billets and slabs can also be assessed by above mentioned methods. But ultrasonic assessment provides through thickness information of the test samples, whereas, macro-etching and sulphur print methods provide information in one plane only. For more realistic assessment these methods requires large number of test samples and hot acids which is hazardous and pollute the atmosphere also. Ultrasonic method is pollution free and eco-friendly method and may require less number of samples.

Ultrasonic waves passing through a continuously cast billet / slab test piece, which has a heterogeneous structure (dendritic, columnar, equiaxed with pin / blow holes, non-metallic inclusions, cracks etc.), interacts with all these reflectors / scatterers. The ultrasonic signal observed on the oscilloscope is a resultant amplitudes of the reflections, diffraction and scattering of ultrasound with all the above structures. When the macro-structure changes from columnar to equiaxed, there are a lot of ultrasonic losses which is shown as a sudden reduction in back-wall echo of ultrasound. On this basis columnar / equiaxed transition is identified in the test samples. Other flaws in the sample are noticed as backscattered signals on the oscilloscope.

P. C. Glaws (5) studied in detail the influence of EMS on inclusion distribution as measured by ultrasonic inspection. He preferred ultrasonic method in comparison to other methods due to the possibility of larger volume of inspection.

Determination of columnar / equiaxed zone transition is a tedious and laborious job using macro-etching / sulphur printing and by metallography. The ultrasonic method can be considered a better way of understanding the variation of such structure in continuously cast steel products due to it simplicity in use and getting quantitative results. The sensitivity of ultrasonic losses with the microstructure has been reported by the authors (6-7). The difficulty in ultrasonic inspection due to high ultrasonic losses and changes in ultrasonic velocity had been recognized earlier in presence of coarse dendrites. In the inspection of cast stainless steel a difference in ultrasonic velocity in chill / columnar / equiaxed zone were reported by J L Rose et. al. (8) and corrections were recommended in locating the defects.

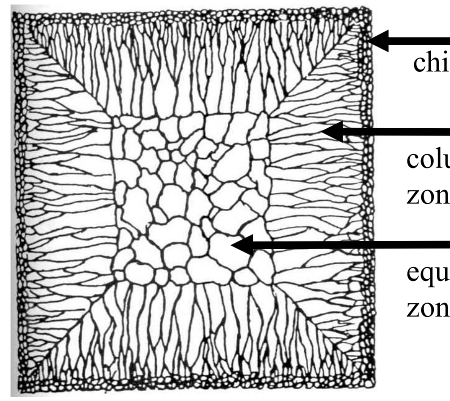

Fig. 1: Sketch of CC billet structure showing chill zone, columnar zone and equiaxed zone

Depending upon the cooling conditions a chill zone is first formed at the region in contact with mould followed by columnar and then equiaxed zone at the core (Fig. 1). A large equiaxed zone is desired to reduce inter-columnar segregation, axial segregation and central looseness.

1.1 Theoretical Aspects

1.1.1 Dendrite Solidification (9)

Dendrite means 'tree-like' and it has stem, branches, sub-branches (known as primary, secondary and tertiary arms). According to Flemings, dendrite may be said to form when secondary arms appear. Dendrite arm spacing is an important parameter in the morphology of cast structure.

1.1.2 Chill Zone

This consists of equiaxed crystal and randomly oriented dendrites (Fig. 1). As soon as the molten metal comes in contact with mould wall, there is rapid chilling of the outer layer.

1.1.3 Columnar Zone

When the under cooling is low i.e. the temperature of the liquid is above the nucleation temperature, further nucleation almost ceases and growth starts from the existing crystal at solid liquid interface. Such growth preferentially takes place along the heat flow direction which gives rise to the columnar zone. Since, the number of crystal becomes fewer as we move inwards, the grain size also increases. Dendrites located near the outer chill zone have more random orientation than these further inward in the columnar zone. Columnar zone also contains some equiaxed crystals (10).

1.1.4 Equiaxed Zone

In this zone, the equiaxed crystals as well as the dendrites are oriented at random.

2. Experiment

For evaluation of the effect of Electro-Magnetic Stirring (EMS) on soundness of continuously cast billets, Al-killed low carbon steel (Grade-LC) and high carbon steel(Grade-HC) of non-EMS and EMS continuously cast (CC) steel billets of section 130 mm x 130 mm, from the strand # 3 of Billet Caster of TATA STEEL Ltd., Jamshedpur were selected. Table 1 shows EMS parameter details and the chemical compositions of the steels are listed the Table 2.

Table 1: EMS details of continuously cast billets

EMS Parameters	CC Billets Grade			
	LC		HC	
Super heat (°C)	55	44	43	43
Pouring temp. (°C)	1566	1559	1508	1508
Casting speed (m/min)	NA	2.87	3.1	2.7
Ar-purging duration	5'	1'22"	1'	40"

Table 2: Chemical composition of continuously cast billets

Chem. Comp. (% wt.)	CC Billets Grade			
	LC		HC	
C	0.058	0.068	0.78	0.78
Mn	1.45	1.45	0.36	0.67
S	0.01	0.117	0.012	0.018
P	0.014	0.017	0.017	0.015
Si	0.86	0.845	0.17	0.205
Al	0.004	0.003	0.003	0.004

Test samples of length 300 mm were gas cut from the head end of the CC billets of section 130 mm x 130 mm for LC and HC grade with and without EMS. Billet samples were then cut to make total 48 numbers of test samples of size 130 mm x 130 mm x 40 mm. The transverse faces were made parallel and ground finished for ultrasonic and macro-etch testing. The details of the samples investigated are shown in the Table 3.

Table 3: Details of investigated CC billet samples

Grade	Sample No.
EMS Grade-LC	S18, S19, S20, S21 & S22
Non-EMS Grade-LC	S23, S24, S25, S26 & S27
EMS Grade-HC	S8, S9, S10, S11 & S12
Non-EMS Grade-HC	S13, S14, S15, S16 & S17

EPOCH 4, Panametrics, USA make ultrasonic flaw detector was used to carry out the investigations. A 15mm diameter single crystal normal probe of 10 MHz was used at 60 dB gain for identification of the equiaxed to columnar transition whereas for the overall flaw detection, a 15mm diameter twin crystal normal probe of 6MHz was used at 65.1dB gain. The couplant used was SAE 40 machine oil. In order to achieve reproducible result during ultrasonic evaluation of macro level flaw counts, the amplitude from 0.4 mm flat bottom hole

(FBH) in ASTM calibration block was set to 80% of full screen height (FSH) on oscilloscope of the ultrasonic equipment.

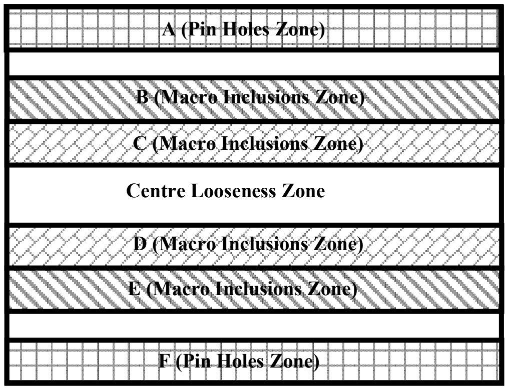

Fig. 2: Cross section of 130x130 mm CC billet showing different zones of 15x 130 mm in which ultrasonic evaluation was done using 6 MHz, 15 mm diameter, twin crystal normal probe

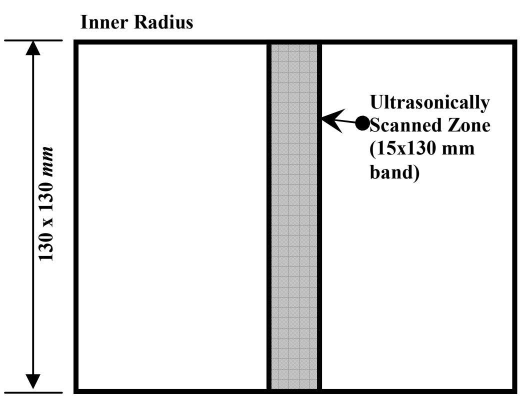

Fig. 3: Schematic diagram showing locat-ion of 15x130 mm band on which back-wall echo amplitudes were measured using 10 MHz, 15 mm diameter, single crystal normal probe

For ultrasonic evaluation of macro level flaw counts, the sample was divided into six scanning bands as shown in Fig. 2. The overall ultrasonic evaluation of flaws indicated by number of back scattered signals was performed on each band (A, B, C, D, E & F). For each sample, the overall flaws (N_{over}) were calculated as given below:

$$N_{over}=(N_A+N_B+N_C+N_D+N_E+N_F) \quad (1)$$

The equiaxed / columnar zone in test samples was assessed, as shown in the Fig. 3, by subsequent change in ultrasonic back-wall echo amplitude using a 15 mm diameter single crystal normal probe of 10 MHz. After every 5 mm increment on the shown band, the amplitude of the back-wall indications was recorded. The verification of ultrasonic results was done by the conventional macro-etch test.

3. Results and Discussion

3.1 Detectability of Columnar / Equiaxed Transition Zone [13]

Changes in wave propagation speed and energy losses from interaction with material microstructure are two key factors in ultrasonic determination of material microstructure and material properties. Ultrasonic velocity and attenuation measurement are basic. Relatively small variation of velocity and attenuation are often associated with significant variation in microstructural characteristics and mechanical properties.

Scattering and absorption are the energy loss mechanism that governs ultrasonic attenuation in the frequency ranges of interest for characterizing most engineering solid. Diffusion, Rayleigh and Stochastic (Phase) scattering losses are extrinsic to individual grains such as crystallites.

3.2 Extrinsic Mechanism

Scattering usually accounts for the great portion of losses in engineering solids. The scatter attenuation coefficient α is function of frequency 'f' and usually expressed in the term of the intensity 'I' of sound after traversing a distance X through a material:

$$I = I_o \exp(-\alpha X) \quad (2)$$

In polycrystalline aggregates (metals and ceramics), there are three scatter attenuation processes defined by the ratio of mean grain size $\overline{D}$ to the dominant wavelength λ.

For the Raleigh scattering process where $\lambda >> \pi \overline{D}$:

$$\alpha_r = C_r D^3 f^4 \quad (3)$$

In this case, excessive scattering may cause drop in back-wall echo.

For the Stochastic (Phase) scattering process where $\lambda \cong \pi \overline{D}$:

$$\alpha_r = C_p D f^2 \quad (4)$$

In this case, scattering may cause slightly less drop in back-wall echo % if compare with the same in case of Raleigh scattering process.

For the Diffusion scattering process

where $\lambda << \pi \overline{D}$

$$\alpha_r = C_d D^{-1} \quad (5)$$

In this case, there is a small fraction of scattering which may cause increase in back-wall echo.

The constant C_r, C_p and C_d contain geometric factors, longitudinal and transverse velocities, density and elastic anisotropy factors.

The above grain scattering formulae are not valid for the columnar / dendritic structure. However the morphology of such structure will affect the ultrasonic losses. A dendritic structure will scatter more ultrasonic energy than columnar. Large equiaxed grains will scatter more than small equiaxed grains as per the grain scattering formula as mentioned in above equations.

3.3 Evaluation of Grade-LC CC billets

3.3.1 Overall flaws

Total Numbers of ultrasonic indications, coming from the flaws, in different zones on the transverse section of EMS and non-EMS CC billet samples of LC grade are shown in Fig. 4 and Fig. 5 respectively. It can be seen that the zones A and B towards the inner radius (top surface) and E and F towards the outer radius (bottom surface) of the strand showed less flaw counts in EMS billet when compared with non-EMS billet. The scanned zones C and D towards the central portion of the strand show more flaw counts in EMS billet when compared with non-EMS billet.

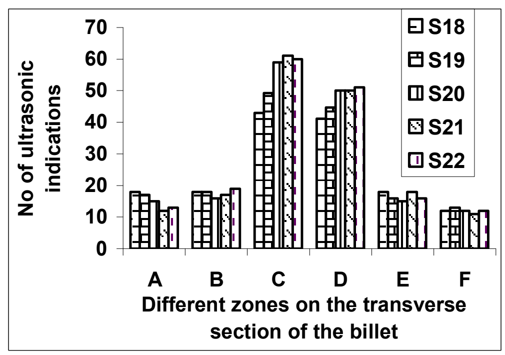

Fig. 4: No. of ultrasonic indications, coming from the flaws, in EMS CC billets samples of grade – LC

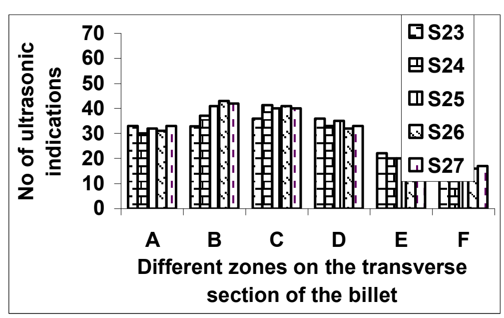

Fig. 5: No. of ultrasonic indications, coming from the flaws, in Non – EMS CC billets samples of grade - LC

3.3.2 Equiaxed zone

Ultrasonic back wall echo drop vs. distance from inner radius to outer radius showing the equiaxed /columnar transition in the EMS and the non-EMS of LC steel billets are shown in the Fig. 6 and Fig. 7 respectively. There was no clear indication of equiaxed zone in non-EMS sample whereas in EMS sample, there was an indication of a small equiaxed zone (15 x 10 mm) which was found away from the centre and towards the outer radius.

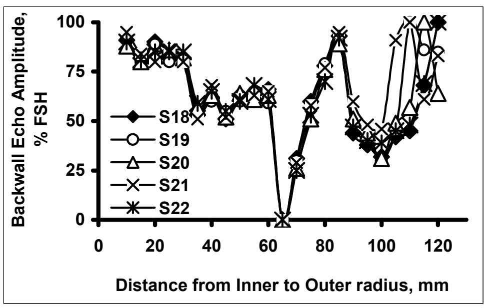

Fig. 6: Ultrasonic back wall echo drop vs. distance showing the equiaxed / columnar transition in EMS CC billets samples of grade - LC

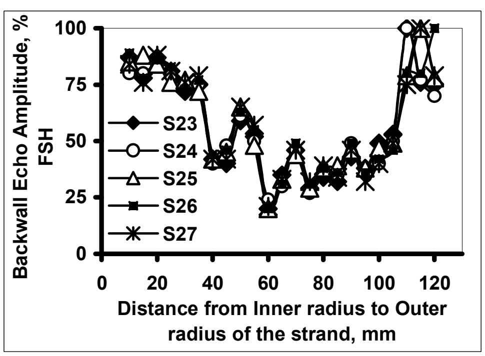

Fig. 7: Ultrasonic back wall echo drop vs. distance showing the equiaxed / columnar transition in Non - EMS CC billets samples of grade - LC

3.4 Evaluation of Grade-HC CC billets

3.4.1 Overall flaws

Zones A and E of the billet samples was found less flaw counts in EMS billet when compared with non-EMS billet. The scanned zone C and D towards the central portion of the strand showed no flaw counts as evident from the Fig. 8 and Fig. 9.

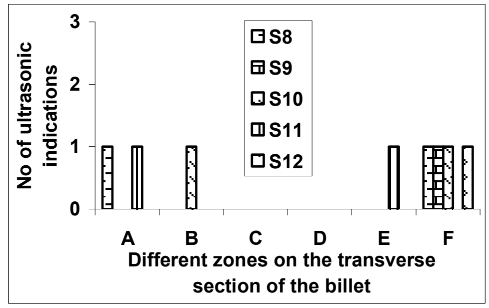

Fig. 8: No. of ultrasonic indications, coming from the flaws, in EMS CC billets samples of grade - HC

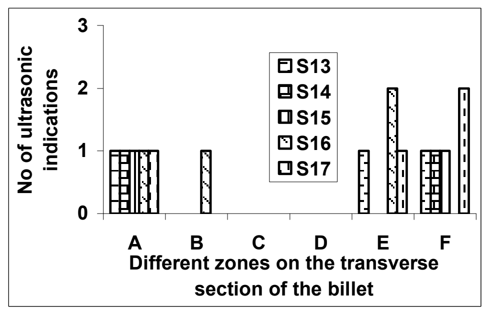

Fig. 9: No. of ultrasonic indications, coming from the flaws, in Non - EMS CC billets samples of grade – HC

3.4.2 Equiaxed zone

Ultrasonic back wall echo drop vs. distance from inner radius to outer radius showing the equiaxed /columnar transition in the EMS and the non-EMS of LC steel billets are shown in the Fig. 10 and Fig. 11 respectively. There is an indication of a small equiaxed zone (approx. 25 mm x 25 mm) in non-EMS sample whereas in EMS sample, there is an indication of a comparatively larger equiaxed zone (approx. 50 mm x 50 mm). This is evident from the typical ultrasonic immersion C-scan images for high carbon grade non-EMS billets and those for EMS billets as shown in Fig. 12 (a) and (b) respectively using 5 MHz focused beam probe.

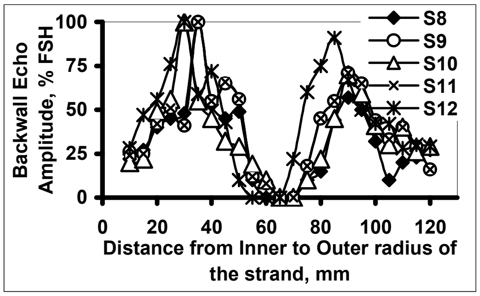

Fig. 10: Ultrasonic back wall echo drop vs. distance showing the equiaxed / columnar transition in EMS CC billets samples of grade - HC

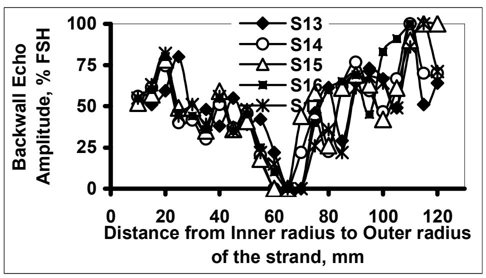

Fig. 11: Ultrasonic back wall echo drop vs. distance showing the equiaxed / columnar transition in Non - EMS CC billets samples of grade – HC

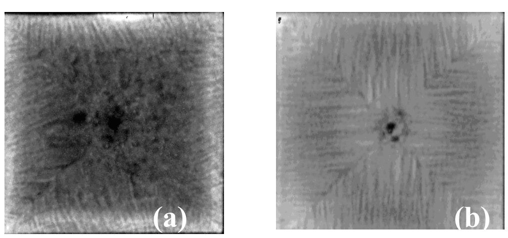

Fig. 12: Ultrasonic C-scan images for an EMS and Non-EMS CC billet sample of grade – HC showing: (a) large equiaxed and small columnar zone and (b) small equiaxed and large columnar zone respectively

4. Conclusions

To study the effect of EMS on soundness of CC billets has been done by a non-destructive ultrasonic technique has been developed which would assist in modifying the process parameters to improve the billet quality. The conclusions derived from the ultrasonic results are given below:

4.1 Grade -LC

Because of the EMS system, the billet portion towards the inner and outer radius found to be cleaned. The cleaning effect was more towards the inner radius than that towards outer radius. Ultrasonic investigation reveals more numbers of flaws in the central region when compared with rest portion of the sample.

EMS system was found less effective during the process of equiaxed zone formulation in low carbon samples.

4.2 Grade -HC

EMS is found to be quite effective towards the surface. High carbon grade steel is much cleaner than the low carbon grades.

It seems that because of EMS practice, there is a 2 folds increase in the equiaxed zone if compared with non –EMS sample

5. Acknowledgement

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