Distribution of Macroinclusions across Slab Thickness
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1. Introduction
Large complex non-metallic inclusions (CNMI) are known to be primarily responsible for the sliver defects in hot and cold rolled steel sheets. The problem becomes more acute in case of surface critical grades of steels viz., interstitial free (IF) steels used for skin panels in automotive and white goods applications. Consistent production of such steels call for scarfing of cast slab surfaces prior to hot rolling to improve the surface quality of the finished cold rolled steel sheets. Thus, a prior knowledge about size distribution of entrapped inclusions across the slab thickness must be required to select an optimum scarfing depth. Most of the literature1,2) has been limited only to size distribution of microinclusions in the quarter or middle of slab with respect to entry nozzle. Thus, there has been no such information available in the open literature for surface macroinclusions across the slab thickness. Therefore, the present work was undertaken to determine the overall distribution of entrapped macroinclusions across the slab thickness to help in deciding the optimum scarfing depth of IF steel. Besides this, the investigation has provided deeper insight into the entrapment of various CNMI during continuous slab casting.

2. Experimental
Slab sections were finely sliced/machined using a planomilling machine at 1 mm step thickness with accuracy of step ±0.2 mm from the surface and after each machining all visible characteristics of defects were recorded. Figure 1 shows the schematic methodology of step-machining process. Though the technique was laborious and time consuming, it provided fairly accurate information about the distribution of large entrapments across the slab sections for the given steelmaking and casting practices. Total 16 numbers of slab samples of about 300 mm long and of different widths (1250 to 1550 mm) were studied in the present work. Only those slabs were selected where measured mold level fluctuations were in the range of ±5.0 mm and the average casting speed was varied from 1.0 to 1.4 m/min depending upon the section size of the slab for the same grade of steel. The chemistry of all the slabs is listed in Table 1.

3. Results and Discussion
Entrapped inclusions of macroscopic sizes often get removed along with metal chips during machining, leaving behind cavities or defects on the machined slab surfaces. Those cavities essentially represented the location as well as their approximate sizes (~0.3 to 2.0 mm) at various positions in the cast slab sections. Figure 2 shows the observed inclusions size distribution across the slab thickness (average of 16 slabs) during various step machining experiments. Inclusion populations per unit area at various depths from the top surface of cast slab are shown in the figure. It can be seen that large size of inclusions (1.0–2.0 mm) were observed close to the surface up to 6 mm of the slab depth. Inclusions of 0.5–1.0 mm size were present in relatively deeper slab depth up to 13 mm. The finer defects less than 0.5 mm size were unevenly distributed throughout the slab surfaces up to a depth of around 19 mm. Thus, the trend of inclusions beyond 0.5 mm size was found decreasing in nature across the slab thickness. It can also be seen from the figure that the overall distribution of the macroinclusions

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(0.3–2.0 mm) was maximum at the surface and went on decreasing up to 12 mm slab depth and subsequently, a second peak again appeared at around 16 mm slab depth.

It was found that large inclusions came out the surface during machining forming cavities. Some of these cavities were metallic appearance and some of them were dull appearance. Larger metallic cavities were elongated in the direction of machining but smaller ones had scratch marks extended beyond the cavity. These indicated that material present in these cavities was very hard and therefore anticipated as alumina entrapments. Closer examination revealed the presence remnant in some of these cavities. SEM-EDS analysis of these remnants confirmed the nature of inclusion present in the cavity. Remnant present in the dull cavity had Na, K, and Ca indicating the presence of flux in these cavities. Figure 3 shows a typical SEM-EDS analysis of such a dull appearance cavity showing the presence of CNMI entrapment in the cast slab.

The macroinclusions were categorised by broadly of two types: first was alumina associated entrapments and another was slag and/or mold flux entrapments. The average distribution of all these two types of defects across the slab thickness is presented in Fig. 4. It can be seen from the figure that mold flux or slag entrapments were maximum at the surface and decreasing across the slab thickness whereas alumina associated entrapments were unevenly distributed and deep seated into the slab. It was found that exogenous mold flux or slag entrapments were relatively of large sizes in comparison to alumina entrapments. It was also found that the size of slag inclusions on machined surfaces varied over a wide range from 0.3–2.0 mm, whereas entrapped alumina was relatively smaller (maximum up to 1.0 mm). Figure 5

Fig. 3. SEM-EDS analysis of entrapped slag inclusion collected from one of the cavities of a machined slab surface.

Fig. 4. Average distribution pattern of different types of macroinclusions entrapped during casting across the slab thickness.

Fig. 5. Cumulative of total number of entrapped macroinclusions observed up to 20 mm slab depth.
shows the further cumulative contribution of both types of macroinclusions entrapped into the slab up to 20 mm depth. It is clear from the figure that about 71% of total number of defects related to alumina associated entrapments and about 29% contributed to the mold flux and/or slag entrapments. A high contribution with larger size of mold flux and slag entrapments indicated the abnormality and instability of meniscus surface in the mold while the appearance of large number with relatively smaller size of deep seated alumina entrapments clearly indicated the submerged entry nozzle clogging during casting process.

During casting of aluminum killed steel there is progressive deposition of residual alumina inclusions in the casting nozzles. Those deposited alumina clusters get periodically dislodged from the nozzle surface by the shearing action of highly turbulent melt stream. Dislodged alumina clusters may get entrapped by the solidifying strand upon entry into the mold to cause more harmful macroinclusions in cast slabs. Sudden dislodgment of large alumina clusters from the nozzle surface may lead to large flow instability and undue mold level fluctuations, causing mold flux entrapment in cast slabs. Sudden dislodgment of large alumina clusters from the nozzle surface may lead to large flow instability and undue mold level fluctuations, causing mold flux entrapment in cast slabs. Thus, several complex phenomena during liquid steel processing from ladle to mold, tundish filling during ladle changeover, erosion of refractory materials, agglomeration of unfloated non-wetting alumina inclusions are some of the other important sources of macroinclusions in steel and therefore, countermeasures are to be required in the whole chain process, tundish and SEN designs as well as casting operations to produce clean steel having lowest level of macroinclusions of both endogenous and exogenous origins.

4. Summary

It can be seen that quite large entrapments (size range 1.0–2.0 mm) were randomly distributed (recorded size distribution for two subsequent surfaces of a typical slab as indicated in Fig. 6 for an illustration) and mostly confined close to the slab surface. Some of those deep seated entrapments are less likely to get removed through scale formation during subsequent soaking of slabs in the reheating furnace prior to hot rolling, and eventually may become potential sources of sliver defects in steel sheets after hot rolling. One way to get rid of them is to scarf the slab up to 4–5 mm depths prior to hot rolling (Fig. 2).

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