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Solidification morphology and segregation in continuously cast steel slab

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ABSTRACT

Solidification morphology and centreline macrosegregation in continuously cast, thick steel slab samples were investigated in order to evaluate the liquid steel solidification characteristics and determine the severity of macrosegregation in cast slabs. Experimental studies were undertaken to establish the true solidification behaviour of industrial slab caster without electromagnetic stirring. Several slab samples collected from the continuous casting shop were utilized to characterize the solidification macrostructure, morphology of cast structure, and macrosegregation patterns. Macrostructural examination revealed predominantly coarse, columnar structure associated with high level of segregation which is detrimental to internal soundness of cast slabs. Liquid steels cast at high superheat ($\geq$32 °C) were generally having finer cast structures as compared to those cast at lower superheats ($\leq$21 °C). Degree of centreline segregation of Carbon (C), Phosphorus (P) and Manganese (Mn) were significantly high. Several unwanted phases (cementite, sulphide and phosphide) were also observed in the central segregated region of slab samples. An attempt was made to correlate the experimental observations with the operating parameters of the caster, and appropriate measures for improving the product quality were suggested.

1. Introduction

During solidification of liquid metals and alloys, redistribution of solutes occurs between liquid and solid phases leading to non-uniformity of composition. Segregation of solute elements is an inherent characteristic of alloy solidification. The solubility of solutes in the solid phase is relatively small in comparison to the liquid phase at a given temperature during solidification. Therefore, solidifying phase rejects excess solutes in the coexisting liquid phase at the solid-liquid interface, leading to gradual solute buildup/enrichment in the residual liquids with progress of solidification. Consequently, the portion of liquid which solidifies in the final stage contains significantly higher solute contents as compared to the nominal composition of alloy/steel. Segregation can be classified into *microsegregation* and *macrosegregation*. Flemings (1974) gives an insight into the details of different types of segregation and the effect of heat transfer and fluid flow on solidification characteristics. Ghosh (1990) describes microsegregation as mostly confined to the microscopic area i.e. within the interdendritic spaces of the solidifying melt. Microsegregation have much lower scale of segregation (few micron size), can be relatively less harmful as some of the segregated elements (only small atoms) get homogenized up to some extent during subsequent reheating and thermo-mechanical working (i.e. hot rolling) of cast sections. Réger et al. (2006) have indicated that macrosegregation in castings is non-uniformity of composition over macroscopic or large areas, and their size can vary from few hundred to several thousand microns. Such macrosegregation can be extended throughout the length of castings i.e. they can be so large that their size can be equal to the size of castings. Due to large sizes, macrosegregation are considered more harmful to finished steel properties, as they cannot be eliminated even with prolonged heat treatments.

In general, overall segregation in continuously cast (CC) sections is much smaller as compared to conventional ingots but severe macrosegregation occurs around its centre. It essentially originates from solute rejection at the solid-liquid interface (zone refining action) coupled with movement of residual solute enriched liquid and coexisting solid phases in the mushy zone during solidification. Flow of residual solute enriched liquid in the mushy zone is induced by suction created by the solidification shrinkage, solutal convection, sedimentation of free crystallites (almost pure and denser), bulging of solidifying strands between the support rolls, deformation of dendrites, etc. Lesoult (2005) has reported macrosegregation studies in steel strands and ingots. Kulkarni and

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Table 1
Specification of cast slab samples considered in the present work.

S. No.	Grade of steel	Heat No./ slab i.d	Casting speed, m/min	Tundish temp, °C	Liquid steel super-heat in tundish °C	Nominal Composition of liquid steel, mass% (measured using liq. steel sample from tundish)						
						C	Mn	S	P	Si	Al	N, ppm
1	high C	*A*/1st slab of a heat	0.78	1500	28	0.78	0.64	0.007	0.017	0.231	0.04	66
2		A/7th slab of a heat	0.8	1491	19							
3		*B/2nd* slab of a heat	0.7−1	1498	26	0.79	0.66	0.004	0.023	0.244	0.045	84
4		*C/2nd* slab of a heat	0.79	1502	32	0.81	0.66	0.002	0.019	0.26	0.05	70
5		*C/7th* slab of a heat	0.71	1491	21							
6	low C	D/4th slab of a heat	1.23	1549	24	0.08	1.07	0.005	0.017	0.044	0.037	25
7		E/5th slab of a heat	1.2	1549	24	0.08	1.05	0.007	0.02	0.036	0.037	24

Slab central transverse section studied: portion of slab length = 0.25 m, Width = 1.1 m and Thickness = 215 mm

Subash Babu (2005) analysed the process parameters for producing quality products in a continuous casting system. Ganguly and Choudhary (2009) have correlated the solidification microstructure with quality of the cast product. Macrosegregation poses serious quality problems in continuously cast products, which may exhibit high degree of segregation in the central region of cast sections (centreline segregation), unless proper measures are adopted for its minimisation. Sang et al. (2010) have emphasized on methods of effectively reducing macrosegregation so as to meet future requirements for high quality product. Accordingly, Sang et al. (2010) have demonstrated a novel technique of adding solid steel balls with a specific composition to the ingot during pouring process. Commonly, in continuously cast product, centerline segregation (CLS) becomes more pronounced in case of high carbon steels cast at relatively higher superheats and at high casting speeds in narrow cross-sections. Krauss (2003) studied the segregation and banding phenomenon in carbon steel. Mayer et al. (2010) have investigated the formation of centerline segregation in continuously cast steel product. In a recent study, Piccone et al. (2016) have described the quantitative methods for evaluation of centerline segregation. High centerline segregation gives rise to undue phase transformations (bainite or martensite etc.), which may lead to cracks or failure during subsequent thermo-mechanical working of cast section or premature failure of the finished steel products in service. They are largely responsible for the anisotropic mechanical properties, hydrogen induced cracking (corrosion resistance), cracking during welding, etc. Choudhary and Ghosh (1994, 2009) found that pronounced segregation leads to *banding* in the hot rolled sheets and heavy plates, where cracks can run easily parallel to the banded region of cast section. According to Brimacombe (1999), problem of macrosegregation becomes more acute in case of high carbon steels, in *high strength low alloy* (HSLA) steels, as well as in high alloy steel.

Morphology of the cast structure plays a very important role in governing the severity of macrosegregation. Large columnar structure gives rise to higher degree of centerline segregation. Equiaxed crystals, unlike columnar dendrites, are unattached dendrites with no specific growth direction. Such free dendrites tend to redistribute the residual impure liquid rejected by the solidifying dendrites uniformly throughout the mushy zone, and thereby minimize the buildup of segregation. Therefore, an early columnar-to-equiaxed transition (CET) i.e. a wider equiaxed zone at the core of the cast section has been found to be beneficial for controlling the centerline segregation in continuous casting of steel.

In the present work, solidification behaviour of continuously cast steel slabs has been investigated in order to evaluate the liquid steel solidification characteristics and determine the severity of macrosegregation in cast slabs. It may be noted here that in the past, studies carried out by the researchers were mostly centered on the fundamentals of alloy solidification and segregation phenomena. Studies concerning the quantification of macrosegregation pattern and morphological characteristics in an industrial scale, continuously cast steel products have largely been ignored. In this regard, a systematic study addressing the pertinent issues in continuously cast steel slabs is still very much limited. In view of these, the present research has been undertaken with an objective to establish the casting behaviour of slab caster for improving the product quality through optimization of casting parameters.

2. Experiment

The present work involves the following activities:

- Collection of cast slab samples and relevant plant data
- Micro and macro-structural examination of samples
- Examination of morphological characteristic of cast structure
- Evaluation of central macrosegregation and identification of phases originating from chemical reactions in the segregated regions during casting

Slab samples were collected and examined for establishing the characteristics of liquid steel solidification during continuous casting. The cast slabs considered in the present work were 11 m long, 1.1 m wide and 0.21 m thickness. The specification of all slab samples used in the present work is given in Table 1. The slab sections are quite heavy and difficult to handle manually. Therefore for the ease of handling, only half portion from the central region were cut after sulphur printing and the remaining portions towards both the edges were discarded. Sampling details for various examinations are shown schematically in Fig. 1. The central large samples (Fig. 1) were first subjected to ultrasonic examination for gross cast characteristics, and secondary dendrite arm spacing (SDAS) were measured using an optical stereo-microscope fitted with an image analyser.

Subsequently, they were macroetched with 1:1 warm hydrochloric acid-water solution for revealing the cast features more clearly. After recording the various macrostructural features, samples were again reground, fine polished and etched with 5% nital solution for about 5 min for revealing dendrite arm spacing (DAS).

3. Results and discussion

3.1. Morphology of cast structure

In order to determine the macrostructural characteristics of both high and low carbon steel slabs, sulphur prints (S-prints) of polished slab samples were taken and analysed. Fig. 2 shows some of the typical sulphur prints of slab samples.