



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 ($\geq 32^\circ\text{C}$) were generally having finer cast structures as compared to those cast at lower superheats ($\leq 21^\circ\text{C}$). 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.

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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. Macro-segregation 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 macro-segregation 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 macro-segregation 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 macro-segregation. 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 macro-segregation 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 macro-segregation 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 macro-segregation 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.

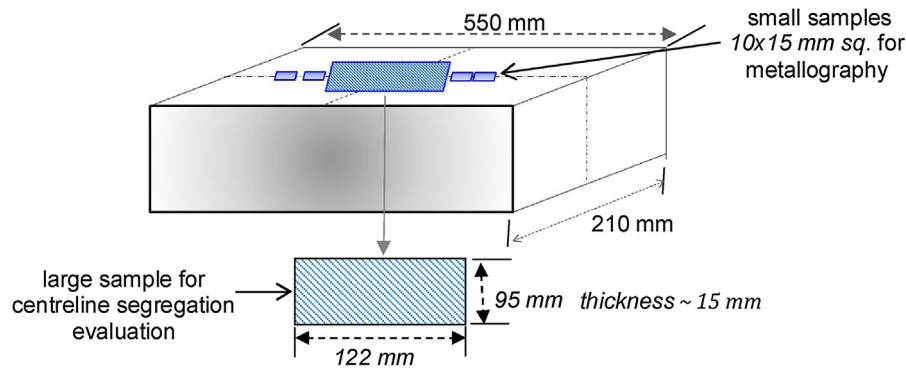
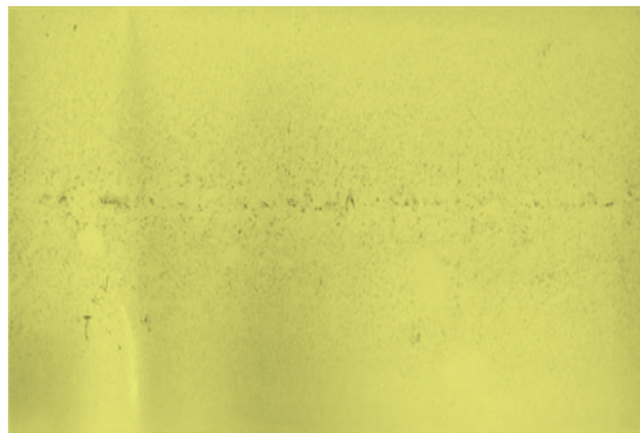


Fig. 1. Schematic of sampling details for various tests.



(a)



(b)

Fig. 2. Typical S-prints of high carbon steel slab samples.

It may be noted here that S-prints commonly fail to clearly reveal the actual morphology as well as segregation patterns at very low S-content ($<0.01\%$) of steel. Even then, in the present case, presence of centreline segregation was observed in all slab samples, and average width of segregation band was found to be approximately 10–12 mm, which is significant in nature. However, it was difficult to assess the severity of segregation in slab samples from the sulphur prints, due to the very low sulphur content in the samples (Table 1). Subsequent to this, samples were subjected to non-destructive ultrasonic testing (ultrasonic C-scanner) for evaluation of their macrostructural characteristics. Finally, all slab samples were subjected to warm acid macroetching for revealing the cast structure clearly on the polished surface around the slab centre. Figs. 3 and 4 present macrostructure obtained by the meth-

ods described above. Fig. 3 presents the cast characteristics of low carbon slabs, and Fig. 4 presents the same for high carbon slabs. It can be seen that cast structures revealed by both the techniques were almost similar. While C-scanner revealed the gross cast characteristics over about 10 mm thickness of samples, macroetching revealed morphology of cast structure very clearly on the polished surfaces. Both high and low carbon samples showed almost fully columnar structures marked by severe centreline porosity, which essentially arise from the solidification shrinkage during the final stages of solidification in continuous casting.

It is well established that wider columnar zone gives rise to severe centreline segregation in CC sections. In general, high liquid steel superheat, high casting speed, narrow cast sections and steels having richer chemistry favours wider columnar zones. It may also be noted here that of all casting parameters, liquid steel superheat has the dominant effect on its solidification characteristics during continuous casting. Commonly, wider equiaxed zone is obtained by low superheat casting. For this, liquid steel superheat must get dissipated as quickly as possible. Phenomena associated with columnar-to-equiaxed transition (CET) has been explained by the concept of seed crystals, originally demonstrated by Ohno (1987), in his classic work on formation of equiaxed structure during solidification of metals and alloys. Samarasekara et al. (1984) tried to explain the CET during continuous casting of steel. According to Ohno (1987), formation of equiaxed zone involves the following two steps:

- generation and survival of seed crystals in superheated liquid melt
- growth of seed crystals once superheat is almost dissipated.

When liquid steel is poured in the water cooled mould, a very high degree of undercooling prevails around the mould wall, resulting in generation of large number of tiny seed crystals or embryo at the mould surface. Some of those tiny crystallites immediately get detached from the mould wall due to stress associated with liquid-to-solid phase transformation. Since those tiny crystallites are almost pure, their melting points are fairly high enough than rest of the liquid pool. Therefore, the crystals tend to survive and remain floating in the liquid steel till superheat is fully dissipated. If the superheat is very high, most of the seed crystals melt back soon and only a few of them survive which results in smaller equiaxed zone and wider columnar zone in the solidified cast section. On the other hand, chance of survival of large number of seed crystals increases with decreasing liquid steel superheat or faster dissipation of superheat. Consequently, large or wider equiaxed zone is obtained in the cast steel.

In spite of moderate liquid steel super heat ($\sim 19\text{--}32^\circ\text{C}$), and casting speeds ($\sim 0.7\text{--}1.23\text{ m/min}$) in the present case, almost fully

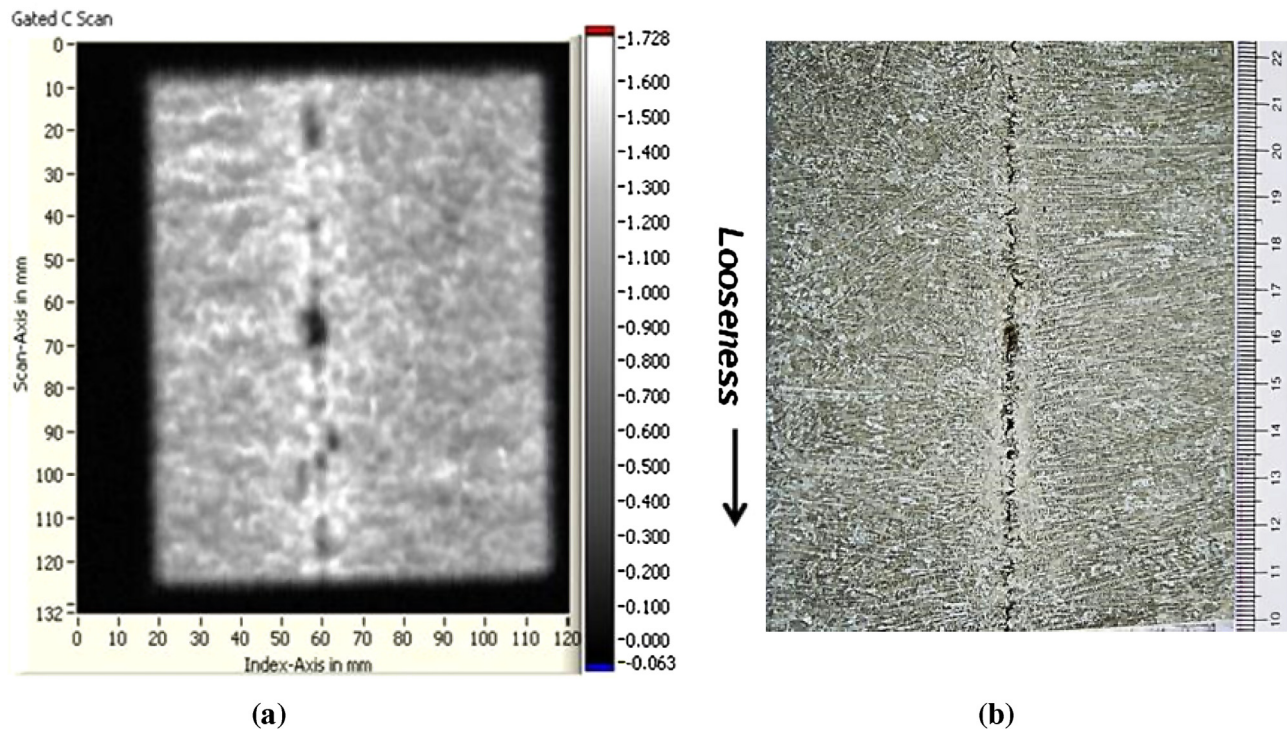


Fig. 3. Macrostructure of a low carbon steel slab determined using (a) ultrasonic scanner and (b) warm acid (1:1 HCl + water solution) macroetching techniques.

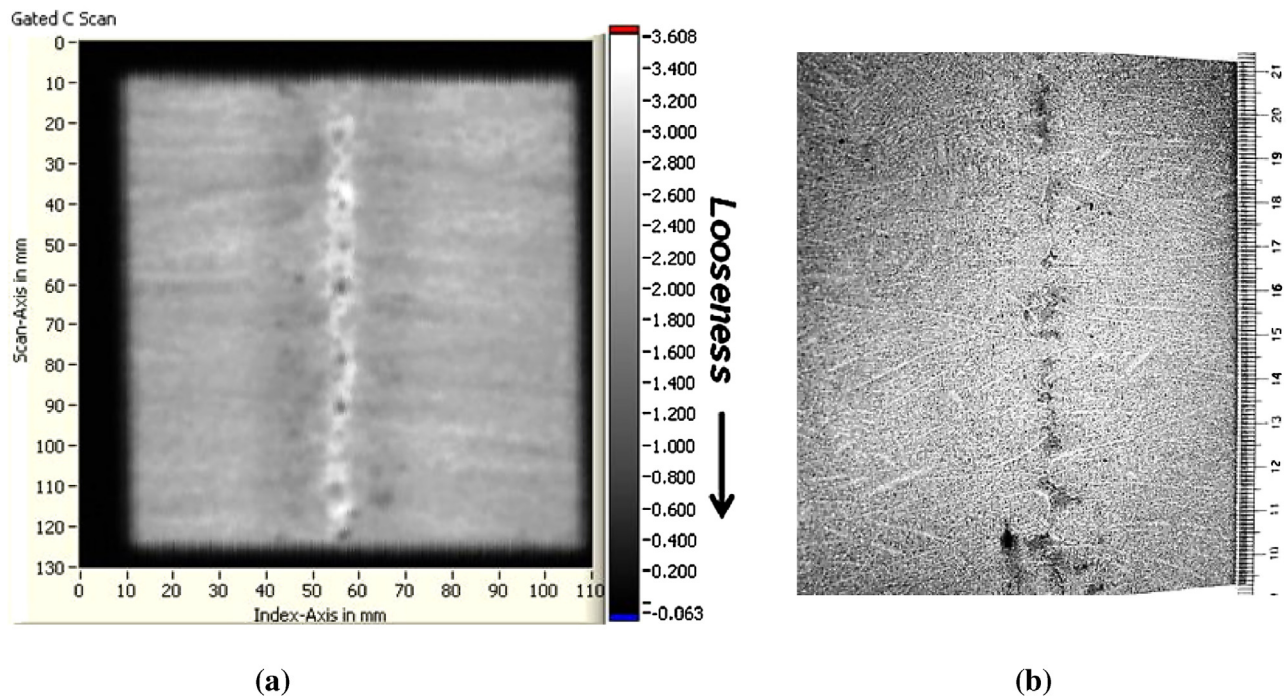


Fig. 4. Macrostructure of a high carbon steel slab determined using (a) ultrasonic scanner and (b) warm acid (1:1 HCl + water soln) macroetching techniques.

coarse columnar structures were observed in all slab samples. This clearly indicated the delayed superheat dissipation in the upper liquid pool region of CC in the present case, which tend to increase the depth of the liquidus profile of solidifying CC strands. Delayed superheat dissipation adversely impacted the survival of seed crystals required for arresting the growth of columnar dendrites and bringing out columnar-to-equiaxed transition. In addition, this also gave rise to relatively higher temperature gradients at the

solidification front owing to relatively longer liquid pool depth. The situation gets further aggravated when casting with higher downward submerged entry nozzle (SEN) port angles (e.g. using 15° or more downward port angle SEN) i.e. excessively downward inclined SEN ports. Higher SEN port inclination forces more superheated liquid towards the downward direction, increasing the overall depth of the liquid steel pool (i.e. liquidus profile depth). Also, inadequate heat extraction from the solidifying strand in the

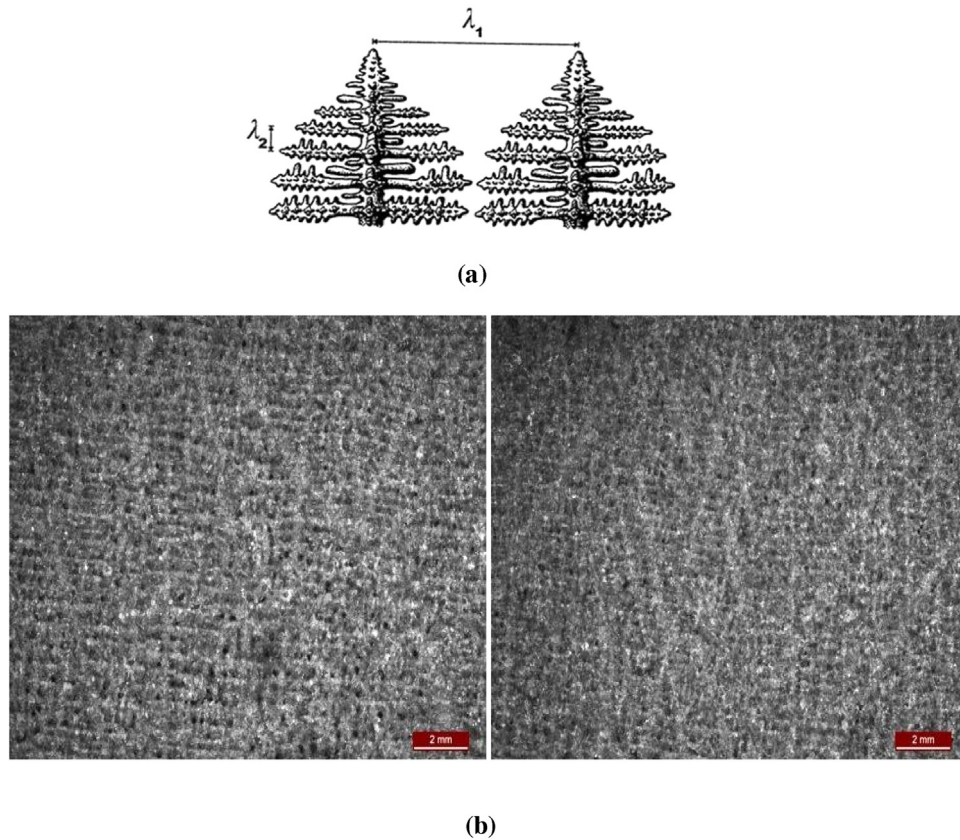


Fig. 5. (a) Schematic of primary (λ_1) and secondary dendrite spacing (λ_2) and (b) morphology of actual columnar dendrites observed in the central region of transverse section of slab samples.

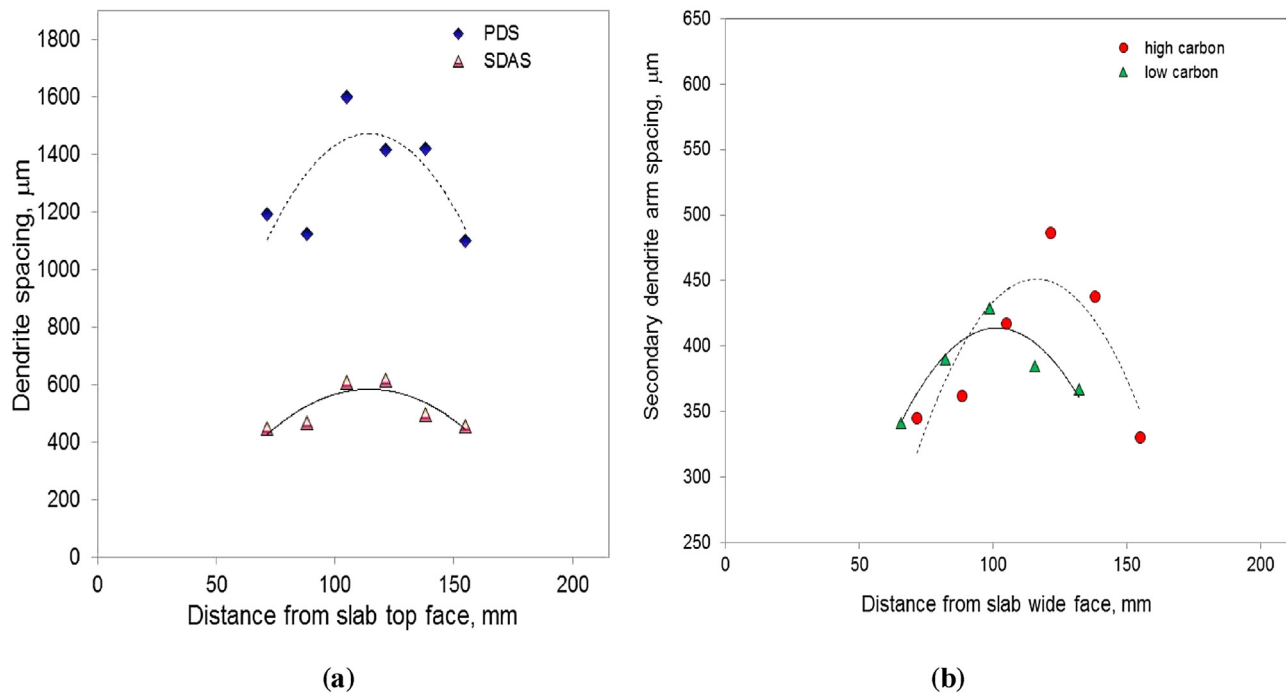


Fig. 6. Variation of (a) primary dendrite arm spacing (PDS, λ_1) and secondary dendrite arm spacing (SDAS, λ_2) along the thickness direction around the centre of a slab section and (b) SDAS in high and low carbon steel slabs.

mould (primary cooling) as well as in the upper sub-mould (upper secondary cooling) regions of the slab caster hinders the superheat dissipation leading towards columnar growth, thereby affecting the

segregation. In previous work, [Zhao et al. \(2005\)](#), [Thomas and Zhang \(2001\)](#), [Xu and Zhu \(2015\)](#) have discussed the related transport behaviour and described the associated phenomena in detail.

3.2. Coarseness of cast structure

Coarseness of cast structure determines the individual size of the segregation spots present in the central segregated zone. Several research studies and reviews on the subject are available in the literature which deals with the functional dependence of segregation phenomena on the morphology and cast structure. Ghosh (2001), Lesoult (2005), Choudhary and Ganguly (2007) have discussed the effect of superheat and morphology of cast structure on macrosegregation of cast products. It is well established that fine dendritic structure helps in minimising the severity of CLS. Not only the columnar dendrites aggravates macrosegregation, even the coarse equiaxed dendrites tend to form solidification bridges and may entrap highly segregated liquid inside. The entrapped liquid pockets subsequently gets isolated from rest of the mushy zone, causing feeding problem during final stage of solidification. Consequently, those isolated liquid pockets solidify as segregation spots associated with solidification shrinkage cavities. Therefore, fine dendritic structure are always preferred for the minimisation of macrosegregation and isotropic mechanical properties of steel.

Coarseness of dendrites is determined by the dendrite arm spacing (DAS). Schematic diagram of the primary dendrite arm spacing (PDS, λ_1) and secondary dendrite arm spacing (SDAS, λ_2) is shown in Fig. 5(a). Dendritic structure of some of the slab samples observed in the present work are shown in Fig. 5(b). Fig. 5(b) shows the columnar dendrites as observed in the central region of transverse section of slab samples. It may be mentioned here that SDAS is a strong function of rate of heat extraction (cooling rate) at a given position in the cast sections. Cicutti and Boeri (2001) estimated the relationship between primary and secondary dendrite arm spacing in cast products and compared the results with experimental data published in literature. Won and Thomas (2001) presented an analytical model to predict secondary dendrite arm spacing as a function of cooling rate and carbon content. Size of SDAS is inversely proportional to the cooling rate and depends relatively weakly on the steel composition. Faster cooling promotes finer dendrites to grow. Therefore, measurement of SDAS facilitated an indirect determination of cooling rate at any locations in the solidified castings.

In the present work, DAS was measured in all samples at magnification 10X using a stereo microscope fitted with an image analyser software. All samples were repolished and etched with 5% nital solution for revealing the cast structures. Measurements were made around the central region at various places along the slab thickness direction. At each location, measurements were carried out at about 100 points and their average values were taken as the dendrite arm spacing at the given location. In general, the overall variation in the measured PDS and SDAS exhibited relatively wide range with standard deviation varying from 12 to 60 μm between all samples considered in the present case. Such deviations in measurements are quite common in industrial samples and has also been observed by Won and Thomas (2001).

Fig. 6(a) shows the variation of dendrite arm spacings in high carbon (0.78%C) steel. The nominal composition of the steel grade used for the measurements are given in Table 1. It can be seen that DAS gradually increases from surface to centre along the thickness direction owing to gradual reduction in the cooling rate (i.e. heat extraction) along the radial direction. In the present case SDAS was found to be quite large, indicating relatively slow radial heat transfer in the present slab casting operation. In addition, the overall ratio (λ_1/λ_2) varied from 2.3 to 3.5 in all the slabs considered in present case. This ratio was found to remain almost constant along slab thickness direction, and was not affected much by changes in the continuous casting parameters. Fig. 6(b) presents comparison of SDAS in high carbon (0.79%C) and low carbon (0.08%C) steel slabs. Both high as well as low carbon steel exhibited almost similar trend across the slab cross-section.

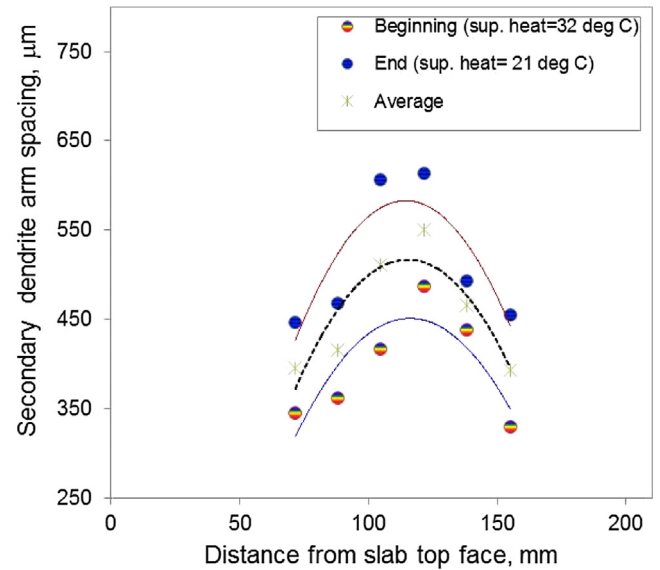


Fig. 7. Influence of superheat on dendrite coarsening as observed in the present work.

It has also been found that for the same grade of steel, the heats cast with higher liquid steel superheat ($\geq 32^\circ\text{C}$) showed relatively finer dendritic structures as compared to those cast at relatively lower superheats ($\leq 21^\circ\text{C}$), as illustrated in Fig. 7. Possible explanation for this behaviour is that higher superheat provides relatively large undercooling of the melt, facilitating more nuclei to form due to higher free energy driving force of nucleation, and higher rate of solidification, in addition to larger temperature gradients in the melt. Faster solidification cause remelting of few dendrites, which doesn't get enough time for coarsening. On the other hand, at lower superheat, rate of solidification is relatively slower and temperature gradient within the melt is also low. Therefore, dendrites forming at lower superheat get enough time for coarsening. Consequently, relatively coarse dendritic structure is obtained in those heats which were cast with relatively low superheats.

3.3. Centreline segregation in slab samples

Commonly, centreline segregation in slab constitutes an array of isolated as well as interconnected closely spaced small clusters of solute enriched regions/spots of varying sizes ranging from few hundred microns to several millimetres. Therefore, for precise determination, the required size of the sample for segregation measurement must correspond well to the size of those segregation spots; otherwise erroneous results would be obtained, which may not truly represent the actual level of segregation in the sample due to the averaging effect caused by mixing with non-segregated areas. It is practically impossible to collect samples from those spots exactly by any mechanical means (e.g. drilling, machining, etc.) for chemical analysis. In the past, researchers have reported use of modern analytical tools for investigation of morphology and segregation in CC sections. Yoshida et al. (2003) have used optical microscopy and electron probe micro-analyzer (EPMA) for evaluation of solidification structures. Preßlinger et al. (2006) have adapted a spectroscopy PDA (pulse discrimination analysis) technique for segregation assessment. Sengupta et al. (2006) have demonstrated the use of electron backscattering diffraction, X-ray spectroscopy, and electron probe microanalysis techniques for examining the microstructure evolution and sub-surface features in continuously cast steel product. In the present study, Glow Discharge Optical Emission Spectroscopy (GDOES) has been used

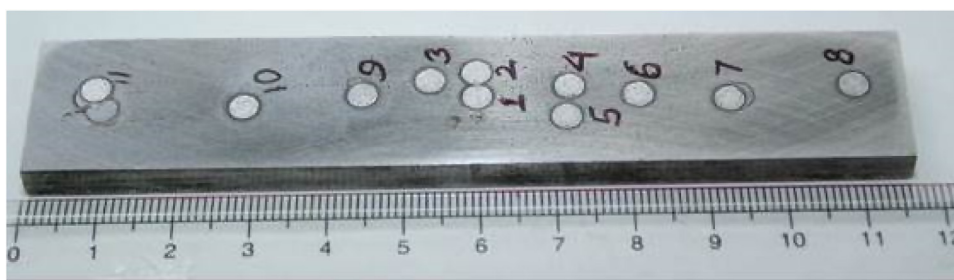
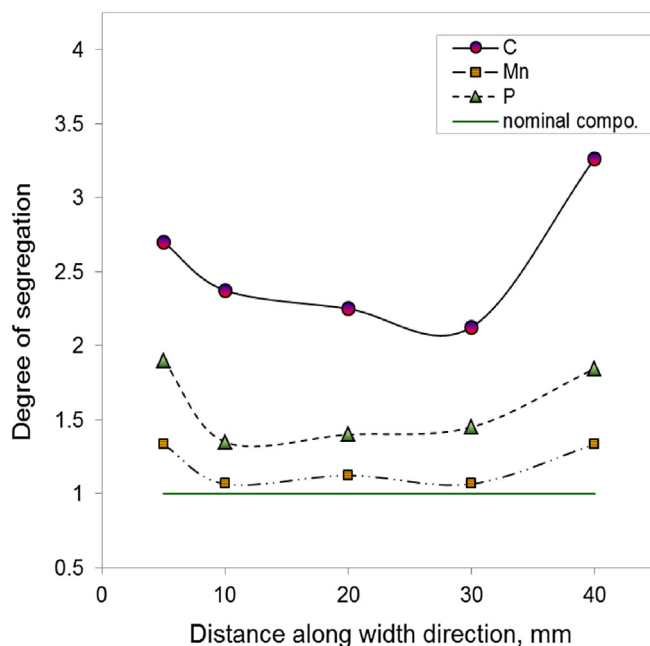


Fig. 8. A typical GDOES sample after composition measurements at various points.



(a)



(b)

Fig. 9. (a) Variation of degree of segregation of C, Mn and P along the (b) central segregated region of a low carbon steel slab.

to determine the solute composition in the slab samples. GDOES has the special advantage of being very useful for routine analysis in an industrial environment. Sample may be directly analysed without any stringent sample preparation. It has several advantages of automated positioning of samples, automated cleaning of electrodes (without any manual intervention) and efficient and automated water cooling for the cathode and the sample, permitting an optimised analysis. The analytical precision achievable with glow discharges is excellent compared with other spectrochemical sources. Moreover, the analysis by GDOES is fast, accurate and cost competitive as compared to other related techniques. A Leco GDS-850A glow discharge spectrometer was used in the present work for analysing the samples. A typical sample used in GDOES analysis is shown in Fig. 8. Prior to actual experiments, trials were carried out for selecting optimum settings of the equipment for improved reliability of chemical analysis. Finally, measurements were taken at several points along the centreline of each sample over 1 mm square (probe size) area of each spot. This probe size (GDOES) was found to match fairly well with the average sizes of segregation spots as revealed in their corresponding sulphur prints and macrographs. In addition, measurements were repeated 4–5 times in each case

for ensuring reproducibility of the measurements. On an average, overall variation was found to be $\pm 5\%$.

The extent of segregation commonly known as degree of segregation is given as the ratio of the concentration of solute at the location under consideration to the nominal concentration of solute. Variation of degree of segregation of various solute elements (C, P & Mn) in the central segregated region along the wide face direction of one of the low carbon steel slabs is shown in Fig. 9. Fig. 10 presents the same around the slab central region along the thickness direction of the slab. It is evident that severe centreline segregation is present in the steel slab. The degree of segregation of C, P, and Mn were found to be significantly higher than their nominal composition, which was well above the accepted prescribed limits of various elements in this grade of steel. Such high level of segregation in the present casting practice was largely attributed to almost 100% coarse columnar solidification of both low as well as high carbon steel slab cast sections (Figs. 3 and 4). As already discussed in previous sections, in spite of moderate superheat (average superheat $\sim 25^\circ\text{C}$), almost complete columnar (almost nil equiaxed structure) solidification were observed in all slab samples. It may however be noted here that for the effective minimisation of cen-

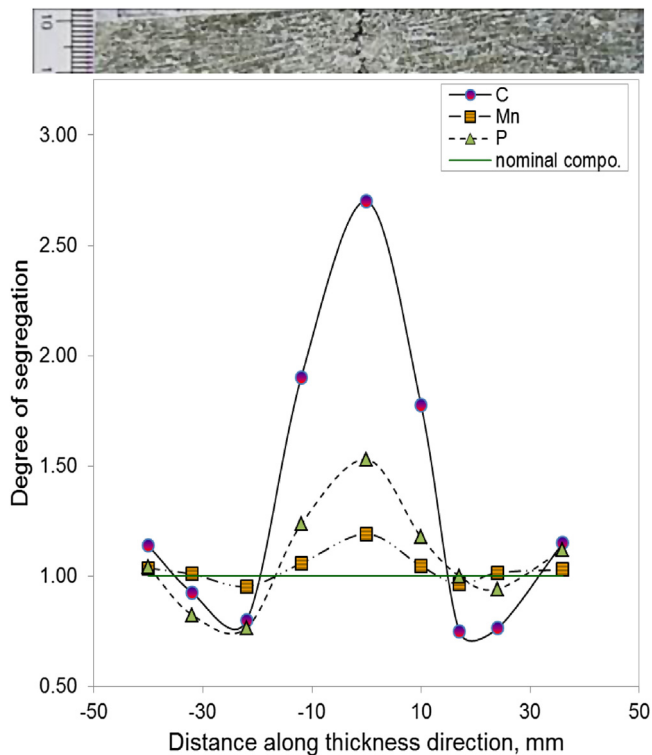


Fig. 10. Variation of degree of segregation of C, Mn and P along the centreline segregated region of a low carbon steel slab.

Table 2
SEM-EDS analysis (wt%) at various points of coarse carbide precipitate (Fig. 11).

Point	C	Si	P	Mn
1	7.63	0.13	0.11	0.70
2	7.53	0.30	0.00	0.67
3	10.09	0.43	0.01	0.45
4	10.42	0.33	0.03	0.71
5	4.99	0.43	0.03	0.81
6	10.00	0.29	0.05	0.71

treline segregation, an early columnar-to-equiaxed transition (i.e. a wider equiaxed zone) is required.

3.4. Identification of phases precipitated in the centreline segregated region

Segregation often gives rise to precipitation of various phases or inclusions viz., oxide, sulphide, carbide, nitride, phosphide, etc., during solidification of liquid steel. Some of these phases may be detrimental to the various properties of steel. Therefore, it is important to know the different types of phases formed during solidification for the successful application of steel. Choudhary and Ghosh (2009) developed a thermodynamic model for prediction of type and amount of various inclusions formed during solidification of liquid Mn-Si killed low carbon steel. In the present work, various phases/inclusions found in the segregated region of slab samples were examined using SEM-EDS and X-ray elemental maps of their constituent elements.

Fig. 11 shows typical coarse carbide (Fe_3C) phases, which were observed systematically in all high carbon steel slabs and occasionally in low carbon steel slabs. Table 2 presents the results of point analysis (in mass%) of coarse carbide precipitate shown in Fig. 11. Pure sulphide (MnS) and oxi-sulphide phases were also observed in all steel slabs (Fig. 12). Some of these inclusions were observed in both low and high carbon steels. However, due to low sulphur

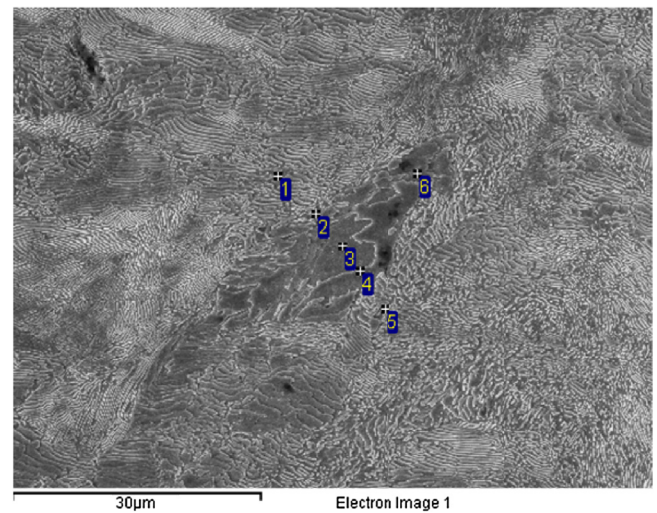


Fig. 11. Patch of carbide precipitate in the pearlite matrix found in high carbon steel slabs.

contents ($<0.008\%$) in the slab samples (Table 1), sulphide inclusions were fairly small as compared to others. In addition, several phosphide (primarily Fe_3P) inclusions were observed exclusively in high carbon steel slabs. Fig. 13 presents an image and X-ray maps of constituent elements in one such precipitate. It was noticed that almost all phosphides were precipitated over the pre-existing small oxides and sulphide inclusions in the segregated regions during the final stage of cast slabs. Kurosawa and Taguchi (1990) reported the presence of eutectic iron phosphide inclusions in medium as well as low carbon steel slabs.

Due to their very low melting points, iron phosphide eutectic commonly appear at the grain boundary of austenite and may impart hot shortness at high temperature and cold shortness at low temperature in the finished steel. Phosphides generally play an important role in deciding the high temperature ductility of steel. Even if the steel shell is fully solidified, liquid phosphide films may be present in the columnar interdendritic spaces of the steel shell in the mould, which may tear and cause initiation of cracks at temperatures fairly well below the solidus temperature of steel.

4. Conclusions

Present study was undertaken to investigate the solidification characteristics of conventional continuously cast steels. Several slab samples were collected from the beginning as well as towards the end of the casting of a heat in order to determine the role of superheat in the present situation. Slab samples were subjected to sulphur printing, ultrasonic C-scanning, warm acid macroetching, and finally concentration variations around the slab centre were measured using glow discharge optical emission (GDOES) machine in few cases. Some of the salient findings of the present study are summarized below:

- Macrostructural examination revealed quite coarse columnar structure in almost all slab samples and equiaxed zone was found to be almost negligible. Such coarse columnar structures are known to be associated with centreline porosity and macrosegregation.
- Steel cast with higher superheats ($\geq 32^\circ\text{C}$) were having generally finer cast structures as compared to those cast at lower superheats ($\leq 21^\circ\text{C}$). Very high level of undercooling in the melt close to the vicinity of mould wall coupled with high temperature gradients within the liquid phase, and high rate of solidification

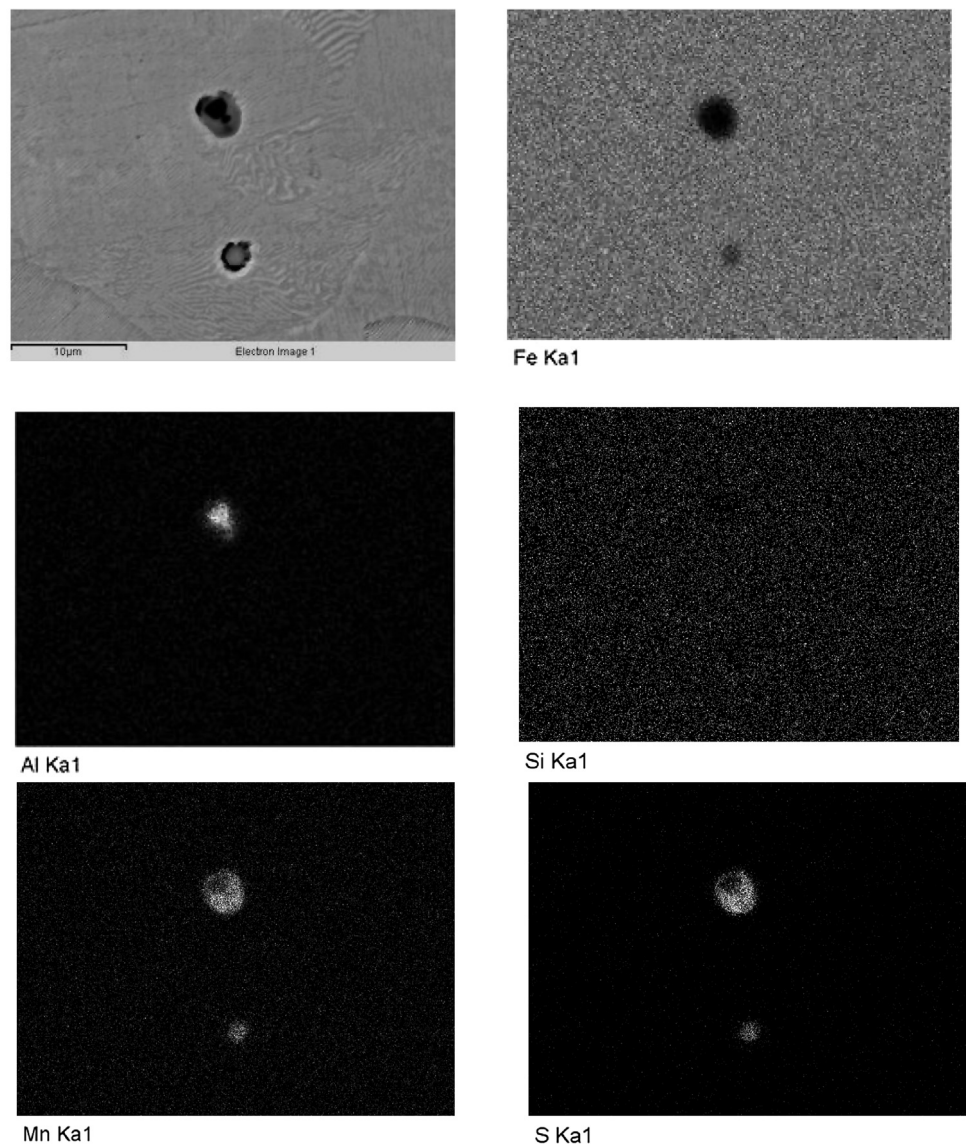


Fig. 12. SEM image and X-ray elemental maps of oxysulphide ($\text{Al}_2\text{O}_3 + \text{MnS}$) and pure MnS inclusions observed in steel slab samples.

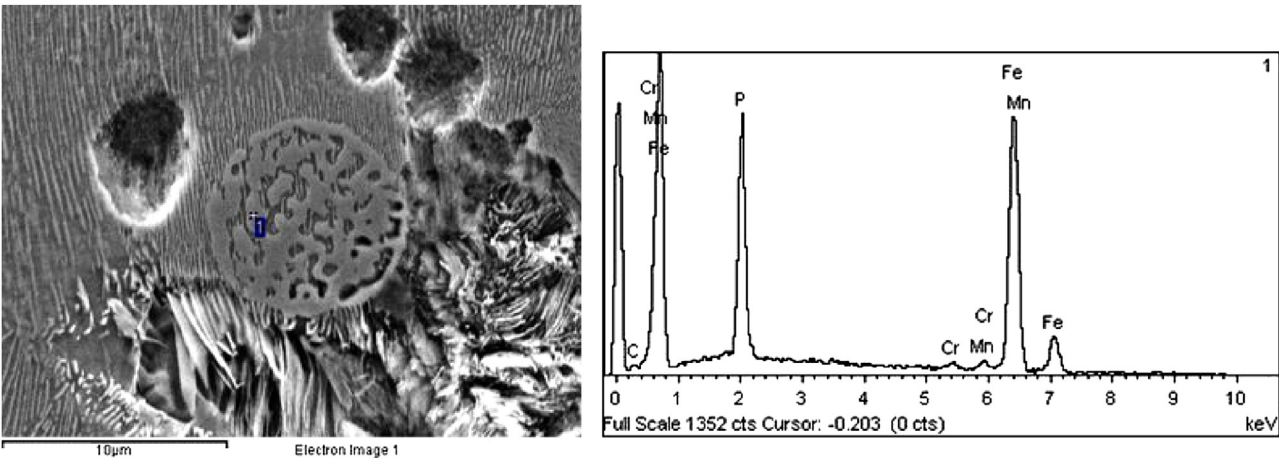


Fig. 13. SEM image and EDS analysis of one of the globular phosphide phase observed in high carbon steel cast slabs.

have been attributed to the reason behind the observed finer cast structures of slab samples.

- Degree of centerline segregation of C, P and Mn were found to be significantly higher (about 2–3.5 times) than their prescribed limits in the specifications. The degree of centerline segregation was so high that it gave rise to formation of several unwanted phases like cementite, sulphides and phosphides in the cast slabs.
- Delayed dissipation of liquid steel superheat in the mould as well as inadequate heat extraction from the solidifying strand were attributed to be the prime cause of above problems. In addition, high SEN port angle inclination also seemed to play an important role in delaying the superheat dissipation in the present slab casting operation.

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