Influence of Modified Casting Practice on Steel Cleanliness

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Consistently high level of cleanliness needs to be ensured, particularly in grades of steel used for critical applications. In addition, preventing the formation of alumina rich non-deformable inclusions is important in high carbon steels for the deep drawing applications. In the present work, influence of billet caster upgradation on the overall cleanliness of high carbon steel has been investigated, mechanical characteristics of oxide inclusions evaluated and assessment of the existing deoxidation practice have been done. In general, there has been improvement in the overall level of steel cleanliness due to increasing tundish capacity, submerge pouring of liquid steel and application of in-mold EMS. These measures have effectively controlled the inclusions originating from reoxidation of liquid steel. However, the characteristics of the oxide inclusions generated during the deoxidation process in ladle remained same even after the caster upgradation. The conventional deoxidation practice was found to generate mostly inclusions of variable compositions and alumina rich non-deformable inclusions, which makes the steel less suitable for very fine wire drawing applications. Appropriate measures have been proposed for further improvement in the inclusion characteristics while processing those grades of steels during the secondary steelmaking.

KEY WORDS: non-metallic inclusions; cleanliness; high carbon steel; continuous casting; Si–Mn; killed steel; deformability of inclusions; billet caster.

1. Introduction

Non-metallic inclusions are “natural” constituents of steel, which in general, impair the properties of steel. In Si–Mn killed steels for bar and wire applications, it is often crucial to avoid precipitation of hard-crystallized inclusions (alumina, spinel, etc.). Continuously cast billets are hot rolled to wire rods prior to further processing to the finished products such as wires, bolts, fasteners etc. In making steel wires billet cross section has to be reduced by a factor of 1000 to 1500 in different stages. Therefore, non-metallic inclusions present in the steel must posses the deformability behavior compatible to that of the steel in order to avoid rupture during hot rolling of billets to wire rods as well as during the final wire drawing process carried out at relatively lower temperatures. The deformability of an inclusion is primarily influenced by its composition while that of steel is a function of composition and the strain rate.1–5) As a result, the deformability of the inclusions must be such that it can accommodate the deformation rate of the steel during the slow initial hot rolling of billets as well as that of high speed finishing (i.e. wire drawing) steps.

Numerous publications have been reported on the relationship between inclusion composition and their deformability.1–4) It is usually assumed that low melting point oxide inclusions such as those in the spessartite region of the MnO–SiO2–Al2O3 system or the pseudo wollastonite-anorthite eutectic region of CaO–SiO2–Al2O3 phase diagram would exhibit ideal deformability characteristics during hot rolling.4–6) However, it has been found that merely achieving inclusions belonging to the above regions of the phase diagram during secondary steelmaking would not solve the problem completely. The characteristics of the inclusions formed during deoxidation may change upon further transformations at the subsequent stages viz., during the solidification of steel, reheating prior to hot rolling as well as crystallization characteristics of oxides.3,6) It has been reported that a supercooled inclusion that appeared soft in the cast billet crystallized and became brittle (and hard) during the subsequent thermo-mechanical treatment, indicating the crystal structure of inclusions to be a dominant factor in deciding their deformability.6) Therefore, to remain deformable during high as well as low temperature deformation processing of steel, oxide inclusions must be amorphous. Unfortunately, such preferred inclusions have been found to belong only to a narrow composition range in the relevant phase diagrams, and to achieve this essentially a precise control of deoxidation process is required.4–7)

Problem of steel cleanliness becomes more acute in continuous casting of Si–Mn killed high carbon steel owing to the following reasons.8)

1. Precipitation of alumina inclusions occur quite easily during the deoxidation treatment of liquid steel. Unless proper care is taken, alumina precipitation is practically unavoidable. They can form even at very low concentration of total aluminum even as low as 50 ppm in the liquid steel, most of which comes from the ferro-alloy additions. Hard alumina inclusions drastically impair the ductility of steel besides causing nozzle blockage during casting operation.

2. Owing to the high carbon content of the melt itself, the casting temperatures are rather low and this parameter
together with the presence of alumina deteriorates the liquid steel cleanliness and castability.

3. A very careful casting operation is necessary to avoid steel reoxidation problem. Otherwise, it would give rise to macro inclusions and scum or slag patches in the cast billets.

The cleanliness specifications of steel, particularly for deep drawing applications are quite stringent. High carbon steels for tire wires (beads and cord) is one such demanding grade where very high level of cleanliness is required. Tyre beads are large monofilament steel cords that are wound together to form a cable or ribbon-type configuration, which secure the tires to the wheel rim of automobiles. The primary requirements for tyre bead and cord steels are toughness with very high tensile, fatigue and torsional strengths. When steel is cold drawn to fine wires it is essentially micro-sectioned.9) During cold drawing most of the inclusions are exposed to the surfaces of the die and if non-deformable, cause wire breakage and wear of the die. The presence of non-deformable inclusions can lead to reduced fatigue strength and to premature breakage of wires during service. In recent times, maximum allowable break during cold drawing has been set at 1 wire break per ton of steel. Clearly, this kind of steel requires very low levels of hard non-deformable inclusions. The size of non-deformable inclusions is also very critical for this grade of steel. The critical size of the non-deformable inclusion has been set below 10 micron for the conventional and 5 micron for the high strength tyre cord steels. As the strength of steel increases, the speed of drawing through the die increases and the critical size limit of the non-deformable inclusions decreases.3) The size of the non-deformable inclusion does not change during hot rolling of steel, whereas, deformable inclusions elongate into long thin inclusions, making them relatively harmless during cold drawing and subsequent operations.

At Tata Steel, achieving the specified cleanliness level consistently in some of the high carbon steels for the critical applications viz., tire bead, spring steel, low-relaxation prestressed concrete steel, etc. has been a major concern, and continuous efforts have been directed towards improving the quality of those steels. Recently, there has been some improvements in the steel quality leading to reduced customer complaints after the incorporation of electromagnetic stirring (EMS) and submerge casting to the billet casters (3 numbers). However, the problems related to steel cleanliness still persists. Therefore, present work was undertaken with an objective of improving cleanliness further in those grades of steel. Assessment of the existing deoxidation practice has been done on the basis of the characteristics of inclusions at various stages of liquid steel processing and influence of caster up-gradation on the overall cleanliness of steel has been assessed.

2. Experimental

To address the problem of cleanliness of steel it is necessary to first identify the source of inclusions by its generic type. Once the source has been identified, measures can be taken to minimize the problem. Fairly accurate information about the total inclusion content, their size distribution, composition and relative abundance of each inclusion type in the steel is required.

The process route for production of wire rods at Tata Steel includes: Hot Metal Desulphurization (DeS)-Basic Oxygen Steelmaking (combined blown BOFs)-Argon Stir (ARS)-Ladle Furnace (LF)-Billet Caster-Billet Reheating furnace-Hot rolling-Stelmor Cooling of Wire Rods. Figure 1 presents the schematic of the same. The current deoxidation practice for the Si–Mn killed steel involves addition of ferroalloys, lime and spar to approximately 150 tons of liquid steel at the ladle furnace followed by calcium cored wire injection. Typical duration of refining in the ladle furnace varies from 35–45 minutes. After that liquid steel is cast continuously into 130–150 mm square billets in the curved mold, six-strand billet casters (3 numbers). During casting, liquid steel from the ladle is teemed into the tundish through a refractory shroud and casting is carried out with open stream. Recently, all the three billet casters (CC1-to-CC3) have been upgraded significantly by incorporating:

1. Argon shrouding and submerged pouring of melt stream from ladle-to-tundish
2. Modified and deeper tundish (delta shaped tundish fitted with turbulence suppressing device at the pouring stream, and capacity enhancement by 5 tons)
3. Optimization of minimum residual liquid steel weight in tundish during ladle changeover
4. Close casting (liquid steel transfer from tundish-to-mold via submerge entry nozzle)
5. Oil lubrication of the mold replaced with mold flux lubrication
6. In-mold rotary electromagnetic stirring (MEMS).

To assess the impact of caster up-gradation on the overall cleanliness, one of the high carbon steel grades (Table 1) has been investigated from the steel samples taken during the pre and the post up-gradation periods. Wire rods and corresponding liquid steel samples from the ladle and the

![Fig. 1. Schematic of process route of steelmaking, billet casting and hot rolling of billets to wire rods.](image)
tundish were taken from 25 heats and examined in the present work. In addition, ladle slag samples of each heat were also collected for assessing their role on inclusion formation in liquid steel. About 15 mm long samples were cut from 5.5 mm diameter wire rods and sliced longitudinally at 1/3rd of its diameter for inclusion characterization in image analyzer (IM) and scanning electron microscope fitted with an energy dispersive spectroscopy (SEM-EDS). Samples were carefully ground and polished without using water to obtain a mirror finish surface. The overall cleanliness or the inclusion content of steel was determined from the measurement of the area percent of the inclusions in wire rod samples using image analyzer. For each sample, measurements were taken at over more than 500 fields at a magnification of 200X in the image analyzer, which corresponded to approximately 30 to 40 mm square area of the polished sample surface. Morphology and composition of inclusions were determined in the SEM-EDS. Using EDS, compositions of each inclusion were measured at its 10–15 locations and the average values of the same were considered as the approximate inclusion composition. Characteristics of inclusions in the liquid steel samples were also determined from the SEM-EDS examination of the routine lollypop samples.

3. Results and Discussion

3.1. Overall Cleanliness of Steel in Pre and Post Up-gradation Periods

The overall cleanliness of high carbon wire rod samples of pre and post up-gradation periods is shown in Fig. 2. Wide variation in the inclusion area percent of wire rod samples is evident from the figure. However, in general, there has been improvement in the cleanliness of steel after caster up-gradation (Fig. 1). Table 2 presents a typical concentration of various types of inclusions observed in the wire rod samples classified as per the Japanese standard (JIS G 0555). It can be seen that majority of the inclusions in the wire rod samples were deformable manganese sulfide i.e. A1-type inclusion. In comparison, the concentration of B-type and C-type inclusions was significantly lower. However, it is established that not only does the number of oxide inclusions that matter, their physical properties especially deformability or the plasticity as well as their size, shape and position in the steel are also of great importance.1)

In continuous casting with rotary EMS in the mould, lighter non-metallic (gas bubbles, inclusion, slag, refractory etc.) particles are driven towards the centre by the centripetal electro-dynamic force. As a result, inclusion and slag particles get accumulated in the depression or cavity created at the free surface of the melt by the EMS with progress of casting, leading to inclusion removal in the mould. In continuous casting using mold flux, inclusions accumulated at the meniscus are subsequently absorbed by the molten flux layer covering the meniscus or the free surface of the melt and get removed from the steel. In contrast to this, with oil lubrication inclusion removal does not occur in the mould on its own even with EMS mainly because of absence of any flux to absorb the inclusions floating to the melt surface. Therefore, unless inclusions accumulated at the meniscus are periodically removed by manual fishing, they would remain in the steel and impair its cleanliness. Therefore, mold flux lubrication along with the submerge casting is essential to ensure effective inclusion control in the mold with EMS.

It is to be mentioned here that all wire-rod samples of the pre up-gradation periods were produced from the billets cast with oil lubrication in the mould. It was systematically observed that the inclusion area percent was generally high (above 0.25 percent) in those wire rod samples. Presence of significantly large number of long oxide stringers (some time about 800 to 1200 microns) were quite common in those samples, which were largely responsible for very high inclusion area percent in such samples. Whereas, in liquid steel samples corresponding to the post up-gradation periods, oxide stringers were practically absent. Those oxide stringers were subsequently identified in the SEM-EDS examination to be mainly MnO-SiO2 oxide inclusions, which contained small quantity (1–2 percent) of Al2O3 and TiO2 (discussed in the subsequent section). Grossly, the composition of those stringers corresponded to the rhodonite phase in the MnO–SiO2–Al2O3 phase diagram, which was essentially a

Table 1. Chemical specification of a typical high carbon wire rod steel.

| Element  | Specification       |
|----------|---------------------|
| Carbon   | 0.7–0.8%            |
| Manganese| 0.65–0.7%           |
| Silicon  | 0.15–0.30%          |
| Phosphorus| 0.020% max.        |
| Sulfur   | 0.020% max.         |
| Nitrogen | 60 ppm max          |

Table 2. Typical concentration of inclusions in high carbon steel wire rod samples belonging to the post up-gradation periods.

| Inclusion Type | Area Percent (%) |
|----------------|------------------|
| A1-type deformable sulfide (MnS) | 0.18 |
| A2-type deformable silicate | 0.005 |
| B1 type partially deformable (deformed discontinuously along the rolling direction) | 0.015 |
| C1 type Non-deformable oxide inclusions | 0.02 |
| Total | 0.22 |
reoxidation product of the liquid steel. Therefore, apparent improvement in the cleanliness in post up-gradation periods has been attributed mainly to the effective reoxidation control measures adopted during the liquid steel transfer operations from the ladle-to-tundish and from tundish-to-mold. In addition to this better inclusion flotation due to deeper and modified tundish configuration and use of mold flux have also contributed in improving the steel cleanliness. Detailed characteristics of inclusions in various steel samples have been described in the subsequent sections.

3.2. Estimation of Mechanical Characteristics of Inclusions

Non-deformable inclusions act as stress raisers by forming cavities or micro voids in the steel matrix. Therefore, deformability of inclusions is an extremely important property required in steels for deep drawing applications. In a simplified way, an inclusion is called non-deformable when its aspect ratio (length/width ratio) is less than three after hot rolling.\(^5\) Frequency of distribution of aspect ratio of inclusions in the wire rod samples of high carbon steel is shown in Fig. 3. Significant population of non-deformable inclusion is evident from the figure. However, the inclusion aspect ratio is only an indirect measure of the inclusion deformability.

The fundamental knowledge about the true deformation characteristics of inclusion resulting from the deformation of the steel phase (or matrix) is complex and difficult to determine owing to following reasons,

(a) knowledge of the physical properties of different inclusion phase is necessary,

(b) influence of temperature and pressure on the inclusion properties must be known precisely,

(c) complicated stress-strain pattern at the inclusion steel interface must be known,

(d) steel itself composed of several phases with different properties

(e) knowledge of absolute plasticity of inclusion phase is still lacking; till date available information is too small.

Fortunately, the absolute inclusion plasticity is not so important, but the plasticity of inclusions in the steel matrix/surrounding is more important for all practical purposes.

Malkiewicz and Rudnik\(^{10}\) proposed the following expression for the deformability index \((\nu)\) of inclusion in steel.

\[
\nu = \frac{\varepsilon_i}{\varepsilon_s} = \frac{2 \ln \lambda}{3 \ln h}
\]

\(\text{Fig. 3. Distribution of inclusion aspect ratio in the high carbon steel wire rod samples.}\)

\(\text{Fig. 4. Deformability index (\(\nu\)) of oxide inclusions in high carbon steel wire rod samples.}\)

Where \(\varepsilon_i\) and \(\varepsilon_s\) are the true elongation of inclusion and steel respectively. \(\lambda\) is the aspect ratio of inclusion and \(h\) is the reduction ratio of steel.

The deformability index can vary from \(\nu=0\), when the inclusion does not deform during the working of the steel (i.e. \(\varepsilon_i=0\)) to \(\nu=1\), when the inclusion respond to working in the same way as the steel and \(\varepsilon_i=\varepsilon_s\). From the deformability index, behavior of different types of inclusions can be determined at different working temperatures of steel. Rudnik\(^{11}\) studied the discontinuities in the hot rolled steels caused by non-metallic inclusions with different deformability indices. He\(^{11}\) reported that for a deformability index close to 1, inclusions lengthen in the same way as does steel. In this case the binding force at the inclusion-steel interface is never broken, and the inclusions elongate without causing any discontinuities in the steel matrix. Such inclusions are not harmful at all to the properties of the steel. On the other hand, if the index of deformability decreases, the inclusions do not elongate uniformly during rolling of the steel. Inclusions with an index of deformability \(\nu=0.5–1\) have been found to deform normally with a low frequency of microracks at the inclusion-steel interface and those with \(\nu=0.03–0.3\) often gives fishtails and conical voids. Inclusions with \(\nu\) lower than 0.03 remain undeformed during hot working of steel. Such inclusions are frequently associated with voids and, are largely responsible for the hot tear and cracks in steel. The work of Rudnik\(^{11}\) suggested that the index of deformability of inclusions \((\nu)\) should be preferably 0.5–1 for the inclusions to remain harmless or even to be of advantage during the hot rolling of the steel.

The deformability index of oxide inclusions in the given high carbon steel wire rod samples is shown in Fig. 4. It is evident from the figure that the deformability indices were mostly equal to or below 0.3, indicating presence of mostly non-deformable \((\nu \leq 0.03)\) oxide inclusions in the wire rod samples of present high carbon steel. Oxide inclusions in steel is mainly a function of the deoxidation process. Clear-
ly, an appropriate modifications in the existing deoxidation practice is required to avoid generation of those harmful non-deformable oxide inclusions in steels, particularly for the deep drawing applications.

3.3. Types of Inclusion in High Carbon Steel

The plasticity of inclusion compared to the plasticity of steel phase has a strong influence on the behavior of steel during mechanical working. If the steel phase and the inclusions are not working together during all steel working operations, the inclusions will become a potential source of future defects in finished products. On the other hand, inclusions may enhance steel properties by their ability to participate in the plastic flow of steel. Owing to these reasons, knowledge of metallography of inclusion is very important. If a detailed knowledge about the behavior of different inclusions is available, the steel-inclusion composite could be tailored to different operations and purposes such that considerable economic and technical advantages could be achieved.

The SEM-EDS examination of high carbon wire rod samples revealed primarily 2 types of inclusions:

1. Stringers of sulfide (MnS) inclusion (A1-type) and
2. Oxide inclusions (partially deformable B1-type and non-deformable C1-type)

3.4. Manganese Sulfide Inclusions

As mentioned earlier, majority of inclusions in the wire rod samples were manganese sulfide (Table 2). Fine stringers of MnS were observed throughout the wire rod samples in each case. MnS essentially originates from segregation of Mn and S during the solidification of steel and, at present there is no mechanism to eliminate them completely. The only solution is to reduce the sulfur content of steel during steelmaking and minimize segregation during billet casting. In general, MnS has been rated as a highly deformable inclusion with an index of deformability close to unity, which is independent of temperature over a wide range from room temperature and upwards. Since MnS and steel both have comparable deformability, it is normally considered harmless in deep drawing steels.

3.5. Oxide Inclusions

In comparison to MnS inclusion, oxide inclusions exhibited quite complex characteristics in the wire rod and liquid steel samples. Primarily, they have been identified to be of the following two types:

1. large oxide stringers (B-type, partially deformable) and
2. globular oxides (C-type, non-deformable).

![Image](image_url)

Fig. 5. X-ray map of constituent elements of oxide and sulfide stringers in wire rod sample.
3.5.1. Oxide Stringers

This type of inclusion appeared as bulky stringers composed of several closely spaced fragments, which were aligned along the rolling direction of wire rod. Such stringers were found in almost all pre up-gradation wire rod samples. In the post up-gradation samples they were observed relatively less frequently. SEM image of one of such oxide stringers is shown in Fig. 5 along with the X-ray map of its constituent elements. These inclusions have been classified as B-type non-deformable inclusion that exhibited variable deformability due to variations in their chemical composition. From their composition, those oxide stringers were identified as the rhodonite phase of the MnO–SiO2–Al2O3 system which contained 35–40% MnO, 55–65% SiO2, 1–2% Al2O3 and traces of CaO and TiO2. As mentioned earlier, this type of inclusion has been found to be largely responsible for impairing the cleanliness of wire rod samples of the given steel samples. Presence of rhodonite has also been identified in the corresponding liquid steel samples from the ladle as well as the tundish. Figure 6 presents the SEM image of a typical liquid rhodonite inclusion of liquid steel sample collected from the LF. The rhodonite inclusions found in the liquid steel samples were actually round duplex inclusions, which contained several crystallized SiO2 phases in the silicate matrix (Fig. 6). The phase separation seen in the image occurred on cooling although initially at liquid steel temperatures these inclusions were liquid and of similar chemistry.

Thermodynamically, rhodonite is formed at relatively higher oxygen potential arising from the reoxidation of Mn–Si–Al killed liquid steel.12,13) Unless proper care is taken in handling and during all operations subsequent to the ladle treatment, reoxidation of liquid steel is practically unavoidable. The reoxidation product, rhodonite, is mainly responsible for the slag patch or scum formation during casting of steel.
high carbon semi-killed steel billets. In many instances mould breakouts have occurred mainly due to entrapment of scum by the solidifying shell in the mold. Owing to its lower melting point rhodonite inclusions deform easily and discontinuously at the hot rolling temperature, giving rise to very large oxide stringers in the wire rods. Presence of such bulky stringers adversely affects the ductility of steel. Fortunately, occurrence of such inclusions has been effectively controlled in the modified practice.

3.5.2. Globular Oxides Inclusions

Large numbers of globular oxide inclusions of 5–20 micron sizes were seen in all wire rod samples. In the SEM-EDS examination, those globular inclusions were found to contain CaO, SiO₂ and Al₂O₃ and minute quantity (less than 2 percent) of MgO and TiO₂. Figure 7 presents the X-ray map of constituent elements of two such inclusions. Cavity associated with cracks in the steel matrix can be clearly seen in the figure. Also, a sulfide ring of CaS-MnS precipitated around those inclusions. Presence of such inclusions in the wire rods would become potential sites for cracks at the subsequent fine wire drawing stage. In addition to these, almost pure alumina inclusions were also found in some of the wire rod samples. In spite of an apparent improvement in the steel cleanliness, the gross behavior pattern of globular oxide inclusions remained almost same in wire rods produced from the billets cast during the pre and post up-gradation periods.

Inclusion characterization of the corresponding liquid steel samples established the origin of above non-deformable inclusions to the deoxidation process itself (Fig. 8). In spite of large scatter in the data, most of the inclusions found in liquid steel samples corresponded well with those of the corresponding wire rod samples. The average composition of all inclusions determined from the SEM-EDS examination of wire rod and liquid steel samples was projected over the ternary CaO–SiO₂–Al₂O₃ phase diagram (Fig. 9). While determining the average inclusion composition other minor oxide components, mentioned already, of inclusions less than 2–3 percent was ignored and the inclusion composition were normalized. The overall performance of the present deoxidation practice has been assessed on the basis of considering only those regions of the CaO–SiO₂–Al₂O₃ phase diagram which corresponded to most of the inclusions observed in the present work. The regions of the phase diagram to which most of the inclusions composition belonged (Region I) are shown along with the region of most favorable inclusion composition (shaded area) in Fig. 10. It can be seen that in general, the inclusion composition (Region-I) obtained in the existing deoxidation practice was away from the ideal composition range. Precipitation of alumina rich inclusion (Region-II) is also quite common in the exist-
ing deoxidation practice. Such behavior pattern is quite common feature of the conventional calcium treated Si–Mn killed steel. It also indicated the scope of further improvement in the characteristics of those inclusions.

3.6. Deoxidation Practice

Wide scatter in the composition of inclusions observed in the liquid steel samples from the ladle furnace indicated that equilibrium was not readily attained during the calcium treatment. It also indicated the stochastic nature of calcium treatment in different heats from the inclusion control point of view. Contrary to this, inclusions observed in liquid steel from the tundish and wire rods were fairly close to each other, indicating that attainment of equilibrium took sometime subsequent to the deoxidation process. Considering only the general trend, mostly liquid anorthite and gehlenite inclusions were found to be generated during the calcium treatment. Anorthite and gehlenite inclusions have been reported to be relatively unstable and prone to easy crystallization during cooling. Their globular shape indicated that they were liquid initially, which crystallized upon subsequent cooling and became non-deformable. It has been reported that the most desirable inclusions for fine wire drawing are obtained when they belong to the narrow region of the ternary eutectic between pseudo-wollastonite, tridymite and anorthite regions of the CaO–SiO₂–Al₂O₃ phase diagram (i.e. the shaded area in Fig. 9). This region has been reported to be more stable and inclusions obtained remain amorphous and plastic over a wide temperature range. That is why this type of inclusion is preferred in high carbon semi-killed steels for deep-drawing applications. Necessary condition to obtain such desirable inclusions has been found to be the precise control of soluble oxygen and aluminum contents of liquid steel in a restricted maximum-minimum range. Strong deoxidizers such as calcium, aluminum and magnesium not only precipitate non-deformable inclusions, but also make maintaining the dissolved oxygen content within the necessary narrow limit practically impossible. For these reasons, strong deoxidizers need to be avoided for deoxidizing those grades of steel. Clearly, the existing calcium treatment is not an appropriate deoxidation process ideally suited for the production of deep drawing quality high carbon semi-killed steel.

In the complex deoxidation of the semi-killed steels, besides silicon and manganese additions the chemistry of the ladle slag may also determine the oxygen content of steel, provided effective slag-metal intermixing is ensured so that the equilibrium is readily attained between the slag and metal. This is essentially the basis of slag-aided-deoxidation process. Equilibrating liquid steel with a slag of appropriate chemistry can control the soluble oxygen and inclusion characteristics of steel more precisely. Also, it is important to control the trace quantity of Al, Mg and Ca in the liquid semi-killed steel to avoid generation of non-deformable inclusions. Thermodynamically, soluble Al as low as 5 ppm and Mg less than 0.5 ppm is quite sufficient to precipitate non-deformable alumina and spinel inclusions respectively in the liquid steel. To this end, basicity of slag has a significant effect on the Al, Mg and Ca content of steel. Stouvenot et al. reported the strong influence of the ladle slag basicity on the dissolved Al, Mg and Ca content of steel and types of inclusion (Fig. 11). They have reported that the optimum slag basicity should be close to 1 in order to get the desirable inclusion characteristics in those steels. However, the adjustment of slag basicity would strongly depend upon the MgO and Al₂O₃ contents of slag. For a CaO/SiO₂ ratio of 1.1 in the slag, an increase of the alumina content from 1 to 3 percent has been reported to leads to an increase of the residual Al from 2 to 5 ppm in the liquid steel. In the magnesia ladle, control of the magnesium content of the steel to a very low or insignificant level is somewhat difficult. The magnesium content of the steel may increase due to reduction of the magnesia in the ladle lining and a corresponding increase in the MgO content of the slag. Therefore, optimum slag basicity for MgO lined ladle has been recommended to be 0.9 (almost neutral slag) for the slag-aided-deoxidation of semi-killed steel. In the present practice, on an average the slag basicity is
maintained above 2 during the treatment of high carbon of steel. Obviously, such a high basicity is not suitable from the viewpoint of inclusion chemistry control. As discussed already, ideally ladle slag basicity should be maintained close to 1 for getting completely deformable inclusions. However, with such neutral slag it is not possible to achieve any significant desulphurisation of liquid steel. At the most only a marginal 10–15% desulphurisation can be achieved with this slag. Clearly, the requirements of desulphurization and inclusion control during the ladle treatment of steel contradict each other. Therefore, basicity of the slag needs to be carefully adjusted in order to achieve optimum desulphurization as well as better inclusion control during the ladle treatment of high carbon steel. In addition, there is practical limitation viz., amount of carry over slag, etc, in achieving such a low basicity consistently. In view of these, trials with various types of synthetic slags coupled with effective control of BOF carryover slag and reduced ladle slag basicity have been planned for achieving the desired inclusion characteristics in those grades of steel.

In earlier investigations by the present author, it has been shown, on the basis of thermodynamics that the alumina content of inclusions depends up to a large extent on the soluble oxygen content of Si–Mn killed steel. In this has also been confirmed experimentally by Simpson et al. at the BHP steel plant for the high carbon rail steel. Those inclusions were identified as the rhodonite phase of the MnO–SiO2–Al2O3 system, which was initially liquid at the liquid steel temperature and subsequently involved precipitation of several crystalline silica phases in the amorphous matrix on MnO·SiO2, making those only partially or of variable deformability.

Influence of ladle slag composition on the soluble Al, Ca, Mg, and O content of liquid steel and on the composition of inclusions in high carbon steel. (Reproduced with permission from ISIJ, Warrendale, Pa, USA)

4. Conclusions

Present work was carried out to investigate the influence of billet caster up-gradation on cleanliness of high carbon steel. Wire rod and corresponding liquid steel samples from several heats were subjected to inclusion characterization using image analyzer and SEM-EDS. The salient findings are as follows:

(1) There has been a wide variation and overall improvement in steel cleanliness after the billet caster up-gradation. This improvement was found to be largely due to minimization of liquid steel reoxidation during transfer operations viz., during ladle-to-tundish and tundish-to-mold liquid steel transfer, and mold flux lubrication during casting.

(2) Reoxidation inclusions were quite voluminous and responsible for large oxide stringers in wire rods. They were found to be primarily MnO·SiO2 with and without alumina. Those inclusions were identified as the rhodonite phase of the MnO·SiO2–Al2O3 system, which was initially liquid at the liquid steel temperature and subsequently involved precipitation of several crystalline silica phases in the amorphous matrix on MnO·SiO2, making those only partially or of variable deformability.

(3) Inclusions originated during current deoxidation practice were globular and non-deformable, which primarily contained CaO, SiO2, and Al2O3 in variable quantity. They belonged mostly to alumina rich anorthite and gehlenite phases of the relevant phase diagram. Such inclusions are not suitable for high quality deep drawing grades of steel.

(4) The current deoxidation process was found to be inadequate for controlling the precipitation of alumina rich non-deformable inclusions. Therefore, based on relevant literature findings appropriate modifications in the present deoxidation practice have been recommended for those grades of steel. Trials are underway to implement those recommendations in the plant.

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