Separation of non-metallic inclusions from high strength low alloy steel by electromagnetic stirring

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Abstract. Non-metallic inclusions are the impurities that solidified during steel continuous casting. The compositions, sizes and shapes of inclusions significantly affect the steels’ mechanical properties such as ductility, formability and toughness. This paper mainly focuses on the observation and characterization of non-metallic inclusions in high strength low alloy steels, and especially is devoted to the homogenization of molten steel within the copper mold of continuous casters, as the primary purpose of this project is to discover the optimum operation parameters for electro-magnetic stirrers surrounding the copper mold. In this paper, non-metallic inclusions in high strength low alloy steel were observed and characterized, and separation of non-metallic inclusions from high strength low alloy steel by electromagnetic stirring was specifically studied. The nonmetallic inclusions in the billet can be greatly reduced when the electromagnetic stirring parameters of the mold are 300 A current and 3 Hz EMS frequency.

1. Introduction
Cleanliness and inclusion control has always been a major industrial motivation in fields of steelmaking and steel refining since high strength low alloy steel undergoes drawing; the presence of inclusions often results in fractures and crakes [1-4]. Non-metallic inclusions in steel are generated by the reaction between the dissolved elements in the steel or due to the contamination of the steel by other sources such as loose dirt, broken refractory materials, and ceramic linings particles. In general, most inclusions are detrimental to the mechanical properties of the steel, such as hardness, formability, machinability. Inclusions generated in steelmaking process can affect steel quality considerably [3-5]. Inclusions found in steels are mainly non-metallic compounds, such as sulphide, oxide, silicate, etc [6-8]. The existence of inclusions in steel can result in a non-homogenous distribution of composition, structure and properties of steels; hence, it deteriorates the mechanical properties and fatigue performance of steel products for different applications [9-10]. As an effective means to control the solidification process, Electro-Magnetic Stirring (EMS) has been widely applied to the continuous casting of liquid steel for a number of years [11-14]. This paper mainly focuses on the observation and characterization of non-metallic inclusions in high strength low alloy steel, as the primary purpose of this paper is to discover theory of the separation of non-metallic inclusions from high strength low alloy steel by electromagnetic stirring and the optimum operation parameters for electro-magnetic stirrers surrounding the copper mold.
2. Methods and Materials

2.1. Theory of removal of inclusion by EMS
Electromagnetic force will affect the distribution of non-metallic particles (inclusions) in molten metal. If the direction and the size of the current or the magnetic field are altered, the direction and the magnitude of stress on non-metallic particles will also change [15]. This will affect the transport velocity of particles, which translates to a change in relative transport velocity between the particles and the solidification interface and this in turn will influence the distribution of inclusions in the cast product [1]. The influence of electromagnetic force on the distribution of inclusions within the mold is shown in Figure 1. Under various forces, the particles in the molten steel will experience two velocity components: a vertical component \( V_n \), and a horizontal component \( V_x \). Viscous resistance will produce force components along these two directions, and equilibrium is reached. According to the literature [5], when the solidification velocity is higher than the motorial velocity \( V_P \), particles (represented by inclusion B in Figure 1) will be engulfed within the solidification front. Under the opposite conditions, (Inclusion A in Figure 1) the particles will move ahead of the front. The magnitude of \( V_P \) will be determined by the stress condition on the particles, and the change in velocity \( V_P \) will affect the distribution of particles within the solid steel. The change of stress on the particles can be achieved by applying the electromagnetic field, because the electromagnetic force can achieve much larger values than other existing forces imposed on the particles. Since the electromagnetic force can generate a transport velocity for the particles in molten steel that surpasses the critical rate for particle engulfment by the solidifying liquid, this electromagnetic force can be used to enhance the separation of potential inclusions from the molten metal.

![Figure 1. Influence of electromagnetic force on the distribution of inclusions within molten steel.](image)

The rotating magnetic field associated with EMS generates a rotational motion within the molten steel. The vortex created by this rotational motion promotes the movement of inclusions away from the outer edge of the molten steel and facilitates their movement upward into the slag phase, where they are collected. Inclusions at the surface of a steel product are often caused by entrapment of slag at the meniscus region induced by meniscus vibration. By adopting a suitable location for the EMS, this meniscus vibration can be modified in order to decrease the incidence of surface defects caused by slag entrapment. Thus the removal from molten steel of non-metallic inclusions which originate as deoxidation products, reoxidation products, refractory eroded material, entrained slag, or agglomerates...
from nozzle clogging, can be enhanced by electromagnetic stirring and ultimately, this should generate a cleaner steel product [6-8].

2.2. Experimental Materials

EMS was installed below the top of the mold at 300mm and connected to an external three-phase AC source. The working frequency is adjustable; the stirring direction is clockwise; the stirring strength may be changed by adjustment of the applied current and its frequency. Basic specifications of the EMS are 4.8 kW power, 300 A rated current, 310V rated voltage, 2-8 Hz EMS frequency. The trials were conducted on a continuous casting machine with five billet strands whose annual production of steel was 600,000 tons; billet section was 150 mm×150mm, experiments were conducted on nine heats of high strength low alloy steel. The main components of sample of high strength low alloy steel are shown in Table 1.

| Table 1. Chemical composition of high strength low alloy steel. (%) |
|-----------------|-------|-----|-----|-----|-----|-----|-----|
| C               | Si    | Mn  | P   | S   | Ni  | Cr  | Cu  |
| 0.59-0.63       | 0.20-0.30 | 0.60-0.70 | ≤0.020 | ≤0.015 | ≤0.20 | ≤0.20 | ≤0.30 |

2.3. Experimental methods

The effect of different EMS current intensity on the removal of inclusion in high strength low alloy steel was analyzed by contrast experiment. Considering that the rated EMS current of continuous casting mold is 300 A, EMS currents used for the experiment are respectively 0 A, 150 A, 250 A under 3 Hz EMS frequency. 120 samples of high strength low alloy steel were detected, and they were taken for energy spectrum analysis to study the influence of different stirring currents on the removal of inclusions in high strength low alloy steel.

3. Results and discussion

3.1. Effect of EMS on separation of non-metallic inclusions

Three different EMS currents (200 A, 250 A and 300 A) were used to carry out the inclusion separation and removal experiments on the billets of high strength low alloy steel, and the samples were taken for energy spectrum analysis. Defects in steel, such as inclusions, segregation, porosity, pinholes, etc., are difficult to be identified with the naked eye because of their small size or plastic deformation, which make them connected to the steel matrix. In this study, a suitable etching agent was used to produce selective etching effect on defects and steel matrix. Due to the difference in the degree of erosion between the defect and the matrix, the color of the defect on the sample or the paper is different from that of the matrix, which can be distinguished by the naked eye or about 10 times of magnification. The acid leaching results of macrostructure of steel under different electromagnetic stirring strengths in this experiment are shown in Figure 2. The distribution of non-metallic inclusions in the high strength low alloy steel billet during electromagnetic stirring in the mold is shown in Figure 2.
Figure 2. Inclusion distribution under different EMS currents. (The acid leaching results of macrostructure)

It can be seen from Figure 2 that when the EMS frequency is 3Hz and the current is 0 A, 200 A, 250 A and 300 A respectively, the non-metallic inclusions in the high strength low alloy steel billet gradually decrease. The experimental results show that the nonmetallic inclusions in the billet can be greatly reduced when the electromagnetic stirring parameters of the mold are 300 A current and 3 Hz EMS frequency. Non-metallic inclusions are brought by the deoxidized products, secondary oxidation products and the inner wall refractory materials or protective slag of the gating system which are washed into the molten steel during smelting. According to the analysis of acid leaching results of macrostructure of steel under different electromagnetic stirring intensity, most of the non-metallic inclusions, such as deoxidation products, scour of refractories and nodulation at the nozzle, brought in with the steel flow during the pouring process, can be discharged after electromagnetic stirring.

3.2. Effect of EMS on occurrence frequency of non-metallic inclusions
The occurrence frequency of inclusions in high strength low alloy steel during electromagnetic stirring in the mold is shown in Figure 3. When EMS current I is 0 A and EMS frequency f is 0 Hz, the influence of mould electromagnetic stirring on the occurrence frequency of inclusions in high strength low alloy steel is shown in Figure 3a. When EMS current I is 150 A and EMS frequency f is 3 Hz, the influence of mould electromagnetic stirring on the occurrence frequency of inclusions in high strength low alloy steel is shown in Figure 3b. When EMS current I is 250 A and EMS frequency f is 3 Hz, the influence of the mould electromagnetic stirring on the occurrence frequency of inclusions in High Strength Low Alloy steel is shown in Figure 3c.

Figure 3. Effect of M-EMS on the occurrence frequency of non-metallic inclusions.
Figure 3 shows that when EMS current $I$ is 0 A and EMS frequency $f$ is 0 Hz, the occurrence frequency of non-metallic inclusion of grade $\geq 1.0$ is 11.11%, and the occurrence frequency of non-metallic inclusion of grade $\geq 0.5$ is 33.33%. When EMS current $I$ is 150 A and EMS frequency $f$ is 3 Hz, the occurrence frequency of non-metallic inclusions of grade $\geq 1.0$ is basically eliminated, and the occurrence frequency of non-metallic inclusions of grade $\geq 0.5$ is reduced to 16.67%. When EMS current $I$ is 250 A and EMS frequency $f$ is 3 Hz, the occurrence frequency of non-metallic inclusions of grade $\geq 1.0$ is eliminated, the occurrence frequency of non-metallic inclusion of grade $\geq 0.5$ is reduced to 8.47%.

4. Conclusions
In the current paper, the separation of non-metallic inclusions from molten high strength low alloy steels under mould electromagnetic stirring was investigated using plant experiments. The following conclusions were obtained:

1) Electromagnetic forces affect the distribution of non-metallic inclusions in molten metal. When the direction and the size of the current or the magnetic field are altered, the direction and the magnitude of stress on non-metallic particles also change. Electromagnetic forces affect the transport velocity of particles, and this influences in turn the distribution of inclusions in the cast product.

2) The experiments show that most of the non-metallic inclusions in the high strength low alloy steel was separated by the electromagnetic stirring force. The nonmetallic inclusions in the high strength low alloy steel can be greatly reduced under 300 A EMS current and 3 Hz EMS frequency.

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