



Review Article

A review study on ladle slag detection technologies in continuous casting process

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ABSTRACT

In steel production, continuous casting method using BOF or EAF is increasing day by day. However, the complex nature of the continuous casting process poses many challenges for steelmakers. During the general steel production process of liquid steel, the state of ladle slag penetration into liquid steel is one of the most influential factors in steel quality. If the ingress of ladle slag into liquid steel cannot be controlled, undesirable results in terms of poor quality, safety and castability can occur. Generally, ladle slag consists of oxides such as CaO, SiO₂, Al₂O₃, MgO. In conventional methods, the operator prevents the slag entry by manually controlling it. This method is performed directly by the operator, so the error rate is high. For this reason, it is not desired to be used by steel producers who want high quality products. In this context, steel mills carry out various activities to separate slag from liquid steel. The development of sensor technologies has accelerated the slag detection process. Acceleration and magnetic sensors are among the most widely used methods in this field. In this study, the systems used worldwide for the determination of slag in the continuous casting process were investigated and presented. The advantages and disadvantages of these systems are discussed. The detection methods by considering investment cost, detection time, accuracy were compared and presented. In the scope of this study, it is seen that every method has own advantages and disadvantages over other.

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1. Introduction

Continuous casting of steel can be in many formats such as billet, bloom, round shape, beam blank, thin slab or slab. Whatever the semi-final product is some important points are the same. These points are also valid for both BOF and EAF route, Figure 1 [1]. Preventing ladle slag carryover transport to the tundish is one key element of them.

Ladle slag is necessary to adjust steel chemistry on ladle furnace side. A typical ladle slag consists of mainly oxide compounds. A typical slag sample is given in Table 1. The sample is taken after the final ladle treatment. For alloying and deoxidizing of steel yield it can be in certain range.

On the other hand, it can be a nightmare for continuous casting process from many perspectives regarding equipment and human safety, product and semi-product quality, and castability. To get rid of ladle slag is a major task for caster workers regarding the hazardous effects of

slag carryover [2].

As seen in the literature investigation above, there are many efficiently methods to detect of carryover slag during the transportation of liquid steel from ladle to tundish. However, in the literature, it is seen that there are not sufficient academic studies examining the advantages and disadvantages of these methods as well as the negative effects of carryover slag. In this study, a research was carried out on the negative effects of slag on production process and product quality. In order to eliminate these negative effects, a comparative overview of some common methods used in the detection of carryover slag is given. End of this study, it can be commented that the required reaction time to close ladle slide gate which controls the flow plays a vital role for separating steel and carryover slag. This issue is a key indicator for the successful rate of the slag detection system.

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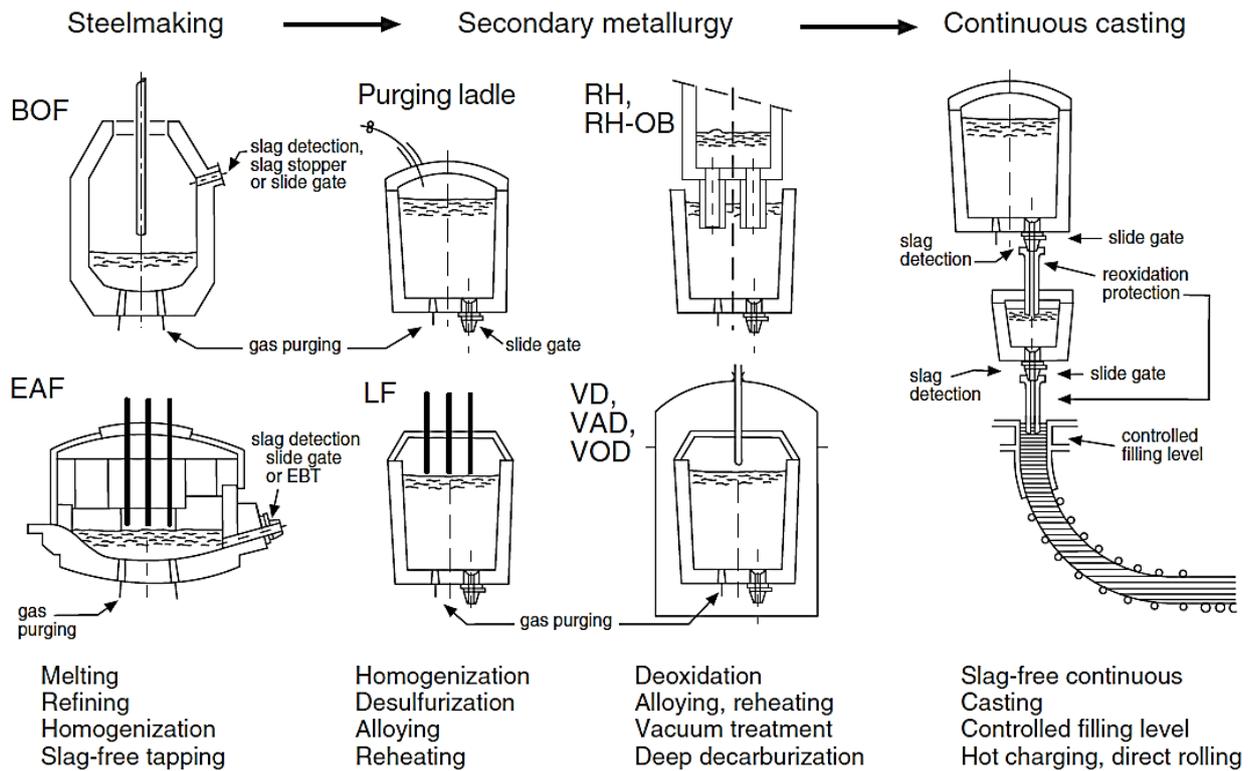


Figure 1. Liquid steel journey both in BOF and EAF route [1]

Table 1. % chemical analysis of ladle slag

| SiO ₂ | CaO | Al ₂ O ₃ | MgO | FeO | S | MnO | K ₂ O | TiO ₂ | Fe | P ₂ O ₅ | Fe ₂ O ₃ | Na ₂ O |
|------------------|------|--------------------------------|-----|-----|------|-----|------------------|------------------|----|-------------------------------|--------------------------------|-------------------|
| 11.8 | 52.2 | 23.2 | 2.9 | 2.2 | 0.52 | 2 | 0.00 | 0.13 | 3 | 0.36 | 0.50 | 0.065 |

2. Effects of Ladle Slag on Continuous Casting Process

First of all, the ladle slag carryover is very detrimental to tundish refractory material so tundish life. Even if the tundish walls are well coated with high resistant materials, the ladle slag will dissolve it due to its content, temperature and volume. If the slag carryover is not prevented at the end of draining of every ladle and gathers in the tundish during whole tundish sequence, the slag can dissolve the refractory material of tundish wall [3, 4]. The amount of slag gathered in the tundish can be increase at each ladle. At the weakest point, generally at the slag level, the liquid steel can melt the tundish wall due to dissolved refractory lining, as seen in Figure 2. Related to this issue when the slag volume increases in tundish then tundish life will be shorter [5]. In other words, due to eroded tundish refractory, casting must be stopped wall to eliminate the risk of process safety [6].

Additionally, shorter life of tundish results in casting costs. The second effect of the slag carryover is the quality due to the slag entrainment. For high-quality steel, the slag carryover must be removed. It should not be mixed with carryover slag and synthetic slag (flux) on tundish. Inclusions are divided into 2 categories, endogenous and exogenous [7, 8]. Endogenous inclusions are a result of deoxidation, on the other hand, exogenous inclusions are

the result of reoxidation. The ladle slag carryover is assumed the source of exogenous inclusions [8]. Excessive slag carryover will result in inclusions in final products such as coil or wire rod. In rolling process, inclusions resulted in by the slag carryover, which cannot be deformed, Figure 3 [8]. Crack, breaking, tears or slivers can become in view due to the presence of undeformed inclusions. Especially higher content of FeO and MnO in slag result in the greater potential of reoxidation. These weak oxide compounds react with the dissolved Al in liquid steel during steel slag interaction to form Al₂O₃. Especially slivers in the final product are attributed to Al₂O₃ content of solidified steel [9, 10].



Figure 2. Steel leakage through tundish wall due to carryover slag erosion

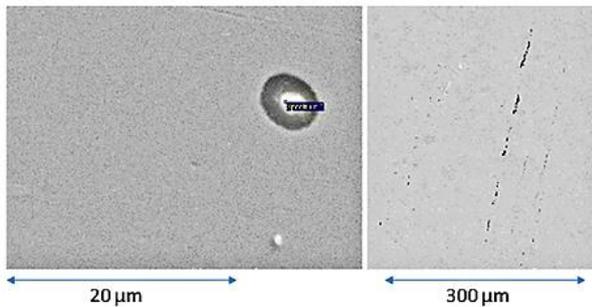


Figure 3. Example of an inclusion in spring steel in tundish sample (left) and in wire deformed in rolling direction (right) [8]

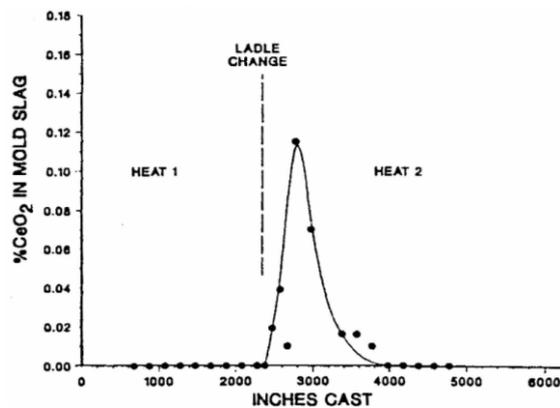


Figure 4. Tracer in mould slag in subsequent two heats [15]

Many studies investigate the strict relation between inclusions and product quality [7, 11]. For special steel products such as tire cord [12] or IF steels [13] it is very important to avoid slag carryover from the ladle to tundish. Additionally, the direct strip casting technology is growing day by day because of their many benefits. To produce thin steel strips inclusion control plays a vital role [14], in other words, slag detection becomes a very important element.

The third point is castability due to the slag entrainment into mould flux. Castability is a generic term referring how hard the casting process is. When the ladle carryover slag enters the mould zone through tundish bottom hole the mould flux behavior will be changed due to the interactions between ladle slag and mould flux. In a plant trial CeO_2 was added to tundish slag as a tracer to detect tundish slag then it was seen in mould slag, Figure 4 [15].

Lubrication behavior of mould flux very depends on its chemical content [16]. Little changes in chemical content makes big differences in mould powder performance [17] and so lubrication. When lubrication is changed the mould friction between solid shell of steel and mould wall will be higher, which is not desired. The control of mould operations will be harder for operators, at worst scenario breakout happens due to the higher friction or slag entrainment into the liquid steel [18]. Additionally, when the end of the sequence has started the possibility of breakout is higher due to the lower height of steel in a tundish. Excessive slag that is gathered during the whole sequence of casting process in the tundish promotes to

suck of it towards the steel shell. This will return us to safety, maintenance cost, and of course yield [15, 19, 20].

3. Common Ladle Slag Detection Methods in Continuous Casting Process

After above mentioned reasons it is very crucial to take under control of the ladle slag carryover in all continuous casting processes such as billet casting, slab casting or beam blank. There are many common methods used continuous casting facilities from manual detection to sensor-based detection systems.

Historically first slag control system starts with a human [21]. The manual detection is performed by caster operator. The ladle slag carryover comes after draining of steel at the end of the ladle. The operator sees the slag carryover on the tundish surface near ladle shroud. When the operator sees the slag, closes slag slide gate manually. Thus, the operator closes the slide gate after an amount of carryover slag passes to tundish. Apart from a late detection operator also need time to react. The operator distinguishes the ladle slag carryover from steel by their color differences and its behavior similar to boiling near ladle shroud submerging point. Procedure very depends on caster experience. In most cases, the same operator acts differently [22–24]. In some cases, the operator closes ladle slide gate very late and too much slag enters tundish and or mould zone or closes very early. In some plants when there is excessive slag carryover on the tundish surface, tundish is filled by steel and slag is overflowed to another empty vessel. It can be clearly seen that the slag carryover detection by a human has many open points [25].

Image processing and ultra-sonic reflection based detection [20] methods have also open points due to the late detection of slag carryover. These type of detection systems detect the carryover slag when the carryover slag enters the tundish zone that is very late for today's requirements. The only difference from the human controlled system is reaction time [26].

Unlike tundish zone detection systems, the electromagnetic slag detection system is located just bottom of the ladle near slide gate zone. Thus early detection is enabled, in other words, the slag does not reach tundish. This method is first used by AMEPA company and commonly used in steel plants, Figure 5 [27].

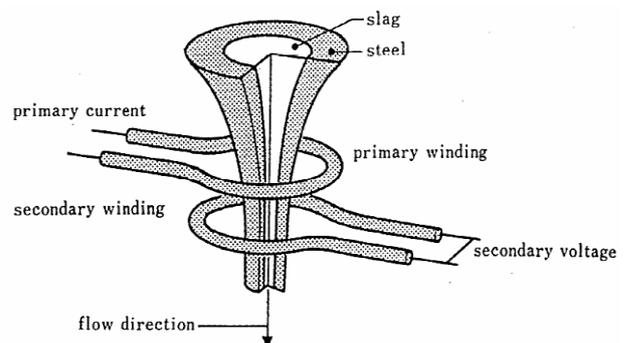


Figure 5. Electromagnetic ladle slag detection [27]

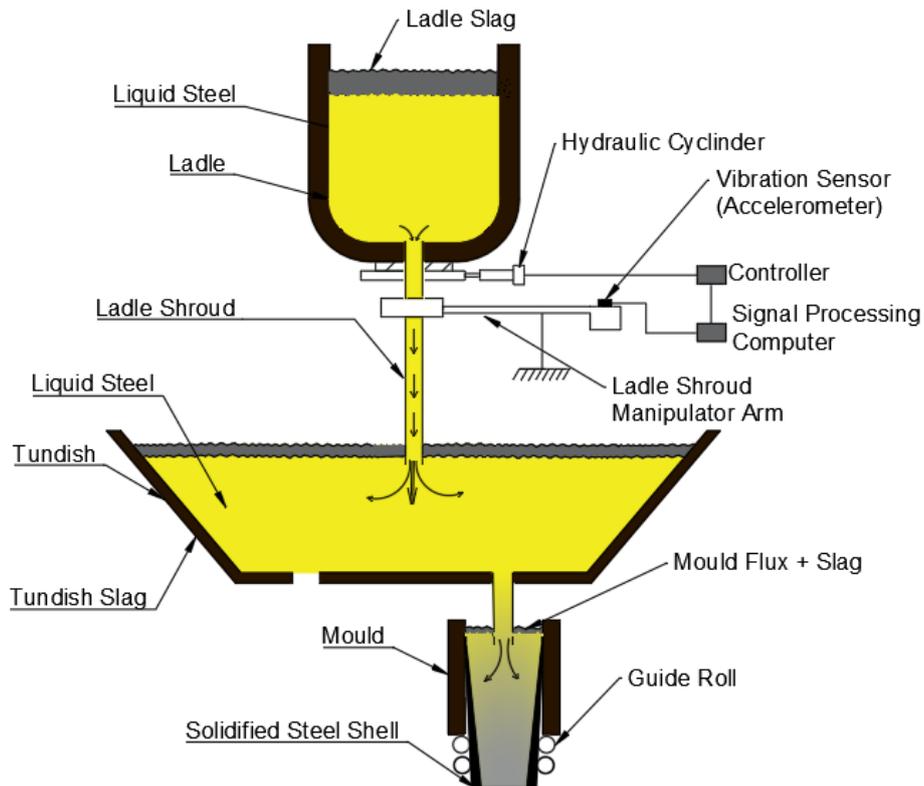


Figure 6. Schematic of continuous caster

Basically, there are two coils in the system: one of them is the current supplier and the second one is the secondary coil. When the current passes through the first coil an electromagnetic field is generated in the steel flowing through ladle nozzle. The electrical conductivity of slag is lower than that of liquid steel, the ratio is 1:10.000 at 1600°C [28]. Before slag entering stage entire flowing composition is liquid steel having high electrical conductivity wherein larger magnetic field. When slag starts to come through coils, the magnetic field will decrease. The magnetic field is converted and collected via secondary coil [27, 28]. The deviation in electrical conductivity of the flowing stream means the amount of slag. By online monitoring of magnitude and phase of voltage that is induced in secondary coil, carryover slag can be detected very early [29]. Like other methods, this method has some disadvantages. Because of the high-temperature environment, all components including coils must be thermal insulated. High temperature harms the coils [30] wherein system malfunctions can occur. Apart from this, all the ladles have to be equipped with necessary detection equipment, in other words, investment cost and maintenance cost are higher. Additionally, continuous casting is a sequence casting process. Whenever a new ladle arrives at the turret, an operator must plug the communication cable of the electromagnetic detection system. Lastly, according to a study [29], the slag must be close enough to the measuring coils to get a guaranteed detection otherwise wrong results can be gotten[4].

One of the promising methods is vibration based slag detection system. To overcome many above-mentioned disadvantages of another type of detection systems that are high cost, hard installation, short service life, etc. vibration based detection system arose[31, 32].

When steel flows through the ladle nozzle it creates a certain vibration. The same condition is also valid for the slag. The vibration is transported through all solid part equipment. The continuous casting process, which is drawn not to scale, is also described in figure 6.

Vibration due to the steel and or slag flow are transmitted through the manipulator arm oscillates the accelerometer inside the vibration sensor which converts the motion to electrical signals [33], Figure 7 [34].

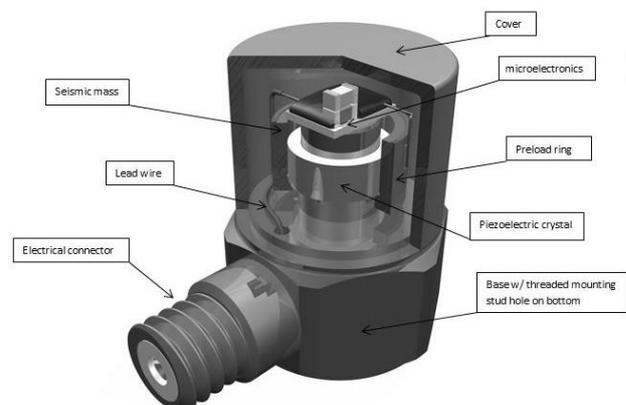


Figure 7. An accelerometer converts vibration to electrical signal [34]

Tablo 2. Comparison of detection methods

| Main Properties | Human Eye Based | Ultrasonic Reflection Based | Image Processing Based | Electromagnetic Based | Vibration Based | Acoustic Based |
|--------------------|----------------------|-----------------------------|------------------------|-----------------------------------|-------------------|-------------------|
| Investment Cost(C) | 0.5 | 1 | 0.75 | 1.5 | 0.75 | 1 |
| Detection Time(T) | 1.5xT | 1xT | 1.5xT | 0.5xT | 0.5xT | 0.5xT |
| Accuracy(A) | 0.5 | 0.75 | 0.75 | 0.9 | 0.9 | 0.75 |
| Bad Aspects | Operator Experiences | Old Technology | Raw Signal Tuning | Hard Installation and Maintenance | Raw Signal Tuning | Raw Signal Tuning |

The vibrations originated from steel and slag there are many vibration sources in the steel plant. These other sources can trigger false alarm leading to being closed slide gate very early. At the end remaining steel in the ladle will increase, which will result in decreasing overall yield. Thus, advanced signal processing including denoising is very crucial. In this study, nothing will be mentioned about signal processing, but the results of trials. There are many companies in the market dealing with this business and every one of them has a different algorithm [35].

Apart from the accelerometer based detection system, there is one another. It is almost the same like accelerometer type detection system. The only difference is sensor type which is acoustic. Sound waves created by steel and or slag makes pressure changes through the ladle shroud manipulator arm [36, 37]. The sound waves pass through the manipulator arm like vibration. These pressure changes are converted to the certain electrical signal via an acoustic sensor which is mounted directly onto manipulator arm surface. The latter is same just like in accelerometer-based detection system. Main disadvantages of this system are fine-tuning [18].

4. Results and Discussion

The ladle slag carryover must be under controlled due to the process safety, quality and castability. There are many methods used in steel plant today and there is no perfect system nowadays. Every method has its own advantageous and disadvantageous. Ideal detection system should have lower investment cost and maintenance, longer service life, easy to installation. Some advantages and disadvantages were given in Table 2 created by considering investment cost, detection time, accuracy and bad aspects.

As shown Table 2, each method has its advantages and disadvantages over the other. However, generally sensor-based detection system seems feasible and affordable.

5. Conclusion

It can be clearly concluded from review:

- The slide gate controlled by man is not stable and feasible due to the increasing customer demands.
- Ultrasonic-reflection and image processing methods

[20] are not suitable due to the late detection.

- Electromagnetic type detection system is common method among steel producers. On the other hand, it has very high costs, maintenance problems and hard installation procedures [27–30].
- Vibration based slag detection system is cheaper than electromagnetic slag detection system regarding investment and maintenance cost.
- Acoustic based detection system is like vibration based detection system. They have same advantageous and disadvantageous.
- Fine-tuning is still a challenging issue for vibration and acoustic based detection system. The performance of the systems very depends on their fine-tuning regarding signal processing.
- For 5 and 6, early alarm can be triggered due to the external vibrations such as human interventions, operator tasks, turret movement, etc. There are many vibrations a sound sources in steel plants causing false alarm. Due to the external sources in some heats, the ladles can be closed early without there is slag. This will lead to decrease yield.

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