Effect of EMS on Inclusion Removal in Ladle Furnace for Specialty Steel Production

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ABSTRACT

The effect of electromagnetic stirring (EMS) on specialty steel cleanliness has been studied based on data from a number of ABB reference plants with the production route as EAF-AOD-LF-CC or EAF-LF-VD(VOD)-CC. The results show that the adjustable turbulent energy distributed in the ladle bath with EMS gives excellent mixing and rapid inclusion removal in specialty steel production. The observed inclusion reduction ratio is around 30-50% after ladle treatment with EMS. The mechanism of the enhancement of inclusion removal by EMS has been discussed. It is explained that the high turbulent energy induced by EMS in the steel bath is beneficial to the collision absorption of inclusions by slag and ladle walls and also beneficial to the collision of the small inclusions themselves. Recent research work at ABB Metallurgy Products shows that the combination of EMS and gas stirring (EMGAS) in the ladle refining process is an excellent solution for clean steel production. EMGAS has strong operational flexibility in terms of control of the melt flow velocity, gas plume shape and residence time, stirring energy, and slag/steel mixing. The industrial test shows that the desulphurization rate by use of EMGAS is increased by 20-30% compared with using gas stirring alone.

1 INTRODUCTION

Steel cleanliness is a common theme in all steel plants as problems with steel cleanliness can lead to internal rejects or customer dissatisfaction with steel products. As a result all steel plants are continually attempting to improve their practices to produce more consistent products with higher cleanliness. For stainless steel non-metallic inclusions also have a significant effect on the surface and corrosion properties of steel products. It is well known that the bath stirring conditions are of great importance for removing non-metallic inclusions from the steel. There are two major stirring methods in the ladle refining process: electromagnetic stirring and gas stirring. The choice of the stirring method to be used in ladle metallurgy will determine the operational and metallurgical characteristics of the equipment. A decision on which stirring method is going to be used should be based on a thorough analysis of the demands that the steel production will put on the equipment. For stainless steel production, the ladle furnace treatment is normally the last step before the casting process, unlike the quality carbon steel process where a vacuum degassing process is often used after ladle furnace refining. Subsequently, steel cleanliness in the ladle refining process for stainless steel is more important than that for the quality of carbon steel.

Electromagnetic stirring has a solid and well-documented reputation for producing clean steel with high reproducibility and reliability. It has been estimated that EMS will result annually in 0.2% fewer rejections for internal steel quality as compared to gas stirring [1]. Extensive research and thesis work related to the effect of induction stirring on steel cleanliness has been carried out by the universities, research institutes, and steel industries in Sweden [2-8]. It has also been demonstrated that the combination of electromagnetic stirring together with gas stirring (named as EMSGAS by ABB Metallurgy) in the ladle furnace is a good solution for clean steel production [9]. For the traditional ASEA-SKF process, the soft magnetic stirring after vacuum is especially important for inclusion removal [2,7]. In this paper the effect of electromagnetic stirring on the specialty steel cleanliness will be reviewed based on plant data collected by ABB Metallurgy Products and the data published in the literatures.

2 INSTALLATIONS AND CONTROL

ABB Metallurgy Products in Sweden has been committed to the development of new electromagnetic products for the improvement of steel cleanliness for more than 70 years. The first electromagnetic stirrer for ladle furnaces stirring (LF-EMS) was developed in 1965 and installed on a 30 ton ladle furnace at Ovako Steel AB in Sweden. More than 142 installations of electromagnetic stirrers for ladle furnaces (LF-EMS including ASEA-SKF) have been delivered to the steel industry worldwide including carbon steel, stainless steel, special steel and ferroalloy productions. This complete range of stirrers has covered a wide range of ladle furnace sizes from 10 up to 330 tonnes. The main installation components for LF-EMS system include an electromagnetic stirrer, a frequency converter, a transformer and a cooling water station. The general system overview for ABB's electromagnetic product has been presented elsewhere [10]. The ladle shell directly facing the stirrer must be made of non-magnetic stainless steel so that the magnetic field from the stirrer can penetrate into the melt. The low frequency electric current through the stirrer windings generates a traveling magnetic field, which penetrates the ladle wall thereby generating forces in the molten steel, as shown in Figure 1(left). The velocity distribution in an electromagnetic stirred ladle is more homogeneous in the whole ladle, as shown in Figure 1 (right). With induction stirring it is possible to achieve a melt flow rate of around 0.2~1.0 m/s.

Two parameters influencing the stirring efficiency are current and distance between the stirrer and the ladle. The velocity of the melt in the LF is proportionate to the stirrer current. The stirring force decreases exponentially with the increased distance between the melt and the stirrer. To maximize the stirring power in the ladle, the distance between the melt and the stirrer should be minimized.

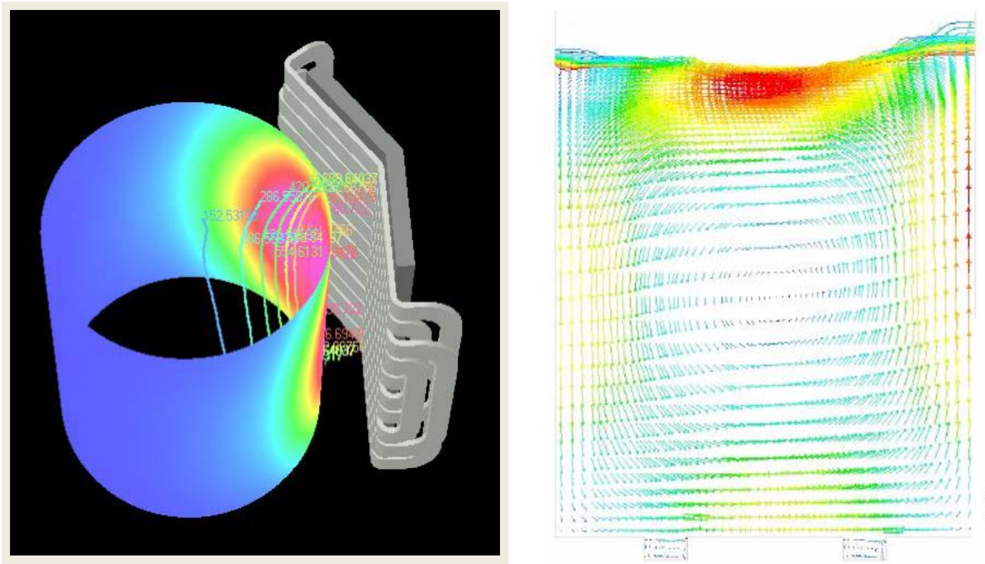
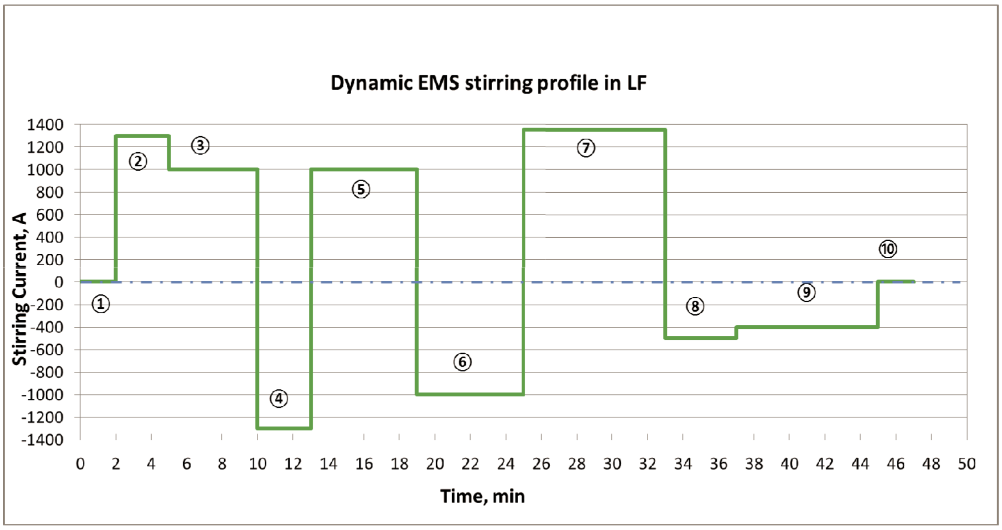


Figure 1. The 3D calculation of electromagnetic forces in a ladle installed with EMS (left) and the CFD velocity distribution in the melt (right)

Operation of the LF-EMS can be controlled in two ways: a) The direction; DOWN-wards along the stirrer side of the ladle or UP-wards along the stirrer side of the ladle. b) The stirring power; which is the square function of the current and should be controlled and optimised dynamically for each individual operating stage during LF operation. LF-EMS stirring is fully automated and controlled by the customer-specific stirring profile which includes stirring direction, stirring power, and optimized frequency. The stirring profile will be customized to the different process steps such as deslagging, heating, homogenization, removal of inclusions, alloy addition, melting of alloys, desulphurization and wire feeding. A general LF-EMS stirring profile is presented in Figure 2. The positive current in Figure 2 represents UP-wards stirring and negative current represents DOWN-wards stirring.

3 STIRRING FEATURES

It can be seen from Figure 1 (right) that the LF-EMS creates a global circulation in the melt and thereby provides efficient mixing of the complete bath melt. Compared to bottom gas stirring by porous plugs, mixing of the entire bath melt is one of the advantages of using LF-EMS. This whole melt mixing effect accelerates homogenization of the temperature and chemical composition of the steel, as well as promoting more efficient inclusion removal in the LF refining process. The LF-EMS has the following stirring features for improving the refining process and to increase process reliability.



①before ladle arrival; ②heat preparation; ③slag building and alloying; ④&⑤&⑥alloying and heating;

⑦De-sulphurisation; ⑧wire feeding: ⑨inclusion removing and waiting; ⑩ladle departure

Figure 2. A typical EMS stirring profile in LF treatment with 45mins treatment time

3.1 Strong and efficient stirring of liquid metal

LF-EMS can give a more homogeneous distributed velocity in the ladle. There is no major difference in the velocities on the bottom and on the surface of the melt, while in a gas stirred ladle the velocity at the bottom is much lower than that at the surface. The turbulent energy in an electromagnetic stirred ladle is more homogeneously distributed than that of a gas stirred ladle. Particularly in the center of the electromagnetic stirred ladle, there is a larger amount of turbulent energy which helps avoids a dead zone commonly found in the bottom of gas stirred ladle. The LF-EMS' strong and efficient stirring leads to much better mixing in the ladle, which is beneficial to the distribution of deoxidant and ferroalloys such aluminium, ferrochromium etc.

The homogenously distributed stirring energy in the melt is favorable to the formation of larger inclusions and can transport these inclusions to the steel-slag interface and steel-refractory interface where they can be captured. The effect of stirring energy and stirring method on the deoxidation rate constant has been investigated by ABB Metallurgy Products and it has been seen that the deoxidation rate constant increases with the stirring energy [11-12]. The rate constant of the ASEA-SKF process is higher than that of Ar-bubbling after the stirring energy ε is more than 10 W/ton. When ε=50 W/ton, the deoxidation rate of EMS is 5 times higher than that of Ar-gas bubbling [11]. This feature makes LF-EMS a valuable tool for clean steel production.

3.2 Minimization of reoxidation and temperature loss

The most important characteristic of EMS is that strong stirring/mixing can be performed in the entire steel bulk while maintaining an unbroken slag layer (no open eye) thus protecting the melt from the outside atmosphere. Stirring power is easily controlled from 0 to 100%. The controlled stirring in the melt without slag open eye can prevent oxygen/nitrogen from coming entering the melt and the reoxidation of aluminium and other elements. Stirring with an unbroken slag layer control also minimized temperature loss from the steel bath from the ladle top.

3.3 Flexible operation with slag open eye

The direction of the induction stirring, up or down, and the stirring power, can easily be changed. This means that an unbroken slag layer can be kept over the steel during the LF treatment but even that it is possible to open up a slag free steel surface for the time it takes to add carbon and alloys directly into the steel bath, without risking that the carbon and alloys get stuck in the slag. The industrial tests show that if the slag layer is not thicker than 10 cm, a slag free surface (open eye) in the slag can easily be created, as shown in Figure 3. One of the most critical aspects of clean steelmaking is the elimination or control of the highly oxidized furnace slag carry-over. Excessive carry-over of slag with high concentrations of iron and manganese oxides may contribute to a number of serious operational and cleanliness problems. These problems may include alloy fade, refractory wear, poor steel chemistry control, dirty steel and slivers. The most efficient method for controlling the amount of furnace slag into the ladle is slag skimming in combination with a tilting ladle car equipped with an EMS. At slag raking, the slag will be pushed towards the slag rake side under the electromagnetic force, move the steel upwards on the stirrer side of the ladle and make the slag removal more efficient and thorough.

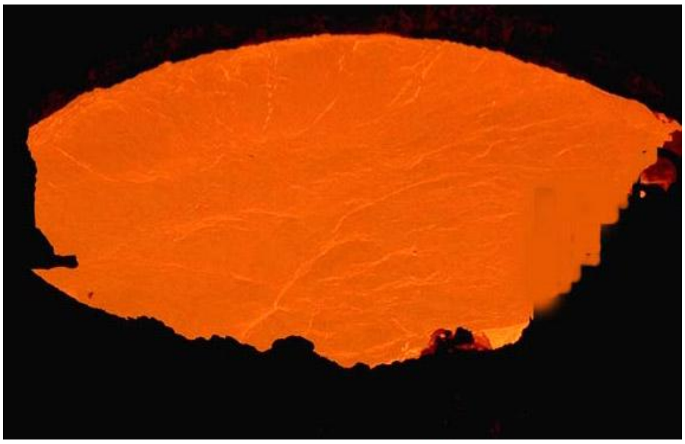


Figure 3. A slag open eye formed in the slag in a ladle surface with LF-EMS

3.4 Process reliability and reproducibility

LF-EMS operation is characterized by low stirring cost, reliable and safe operation, optimum conditions for reproducible production of high quality steel and precise logistics. As the LF-EMS has no physical contact with the melt and contains no moving parts, the need for maintenance is very low. A very strong advantage with the LF-EMS is the precision and repeatability it gives to the ladle refining process. If same current is applied to the stirrer for different ladles then almost the same stirring power will be obtained for different heats. This means that each ladle receives exactly the same stirring treatment resulting in consistent steel quality. Consequently, the risk for operator mistakes that reduce steel quality or disrupt steel flow logistics is very small. Electromagnetic stirring ensures process reliability and reproducibility for clean steel production. A gas plug in a ladle lining, by its very nature, presents a safety risk while an EMS stirred ladle lining contains no risk elements of this kind.

4 EFFECT OF EMS ON INCLUSION REMOVAL

4.1 Inclusion removal

As we all know, inclusions are nonmetallic particles with the size distribution in the range of a couple of microns to hundreds of microns which are suspended in the steel. These inclusions can be captured by the top slag, the side wall of the ladle, and/or the injected gas bubbles. The removal of inclusions during the ladle refining process is governed by: 1) the concentration of inclusions in the steel; 2) the chemical and physical nature of the depositing surface that determine how efficiently the surface can capture the inclusion particles; and 3) the turbulent and molecular transport in the boundary layer close to the phase boundary. The EMS will mainly affect the turbulent flow in the refining ladle. EMS stirring has a solid and well-documented reputation for producing clean steel. The existing results obtained from ABB references show that the adjustable turbulent energy distributed in the steel bulk gives excellent mixing and rapid removal of inclusions which makes it possible to obtain lower total oxygen content. The calculation of turbulence energy has been described by Sand et.al.[9]. The mechanism of the enhancement of inclusion removal by EMS is not completely known yet, but the turbulent energy in the melt bath beneficial to the collision of small inclusions is a common explanation. The controlled stirring with unbroken slag layer by EMS will protect the steel from the influence of the ambient atmosphere and thus minimize excess re-oxidation of aluminum and the pickup of nitrogen and oxygen, as discussed in section 3.2.

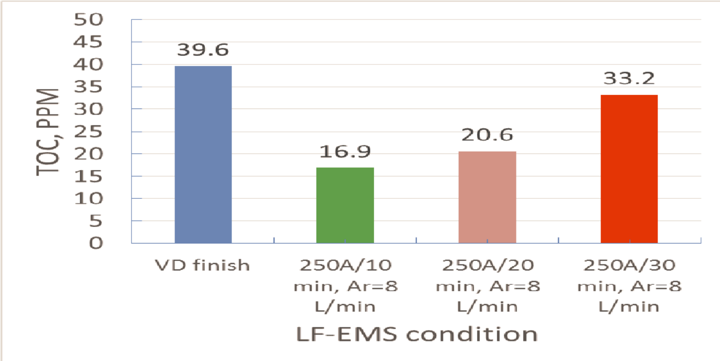


Figure. 4 The effect of soft EMGAS stirring time on the total oxygen removal in ladle refining

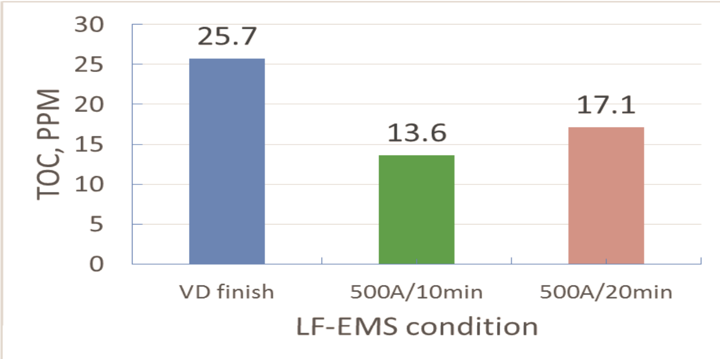


Figure. 5 The effect of EMS soft stirring time on the total oxygen removal in ladle refining

The total oxygen content (TOC) in a stainless steel grade AISI415 with low carbon content has been tested in an ABB reference steel plant A. The process route is EAF/LF/VD(VOD)/LF-EMS. The test result is shown in Figure 4. It can be seen that the total oxygen content after vacuum oxygen decarburization (VOD) is 39.6 ppm. After VD treatment the ladle was transferred to a LF furnace position which is equipped with an EMS and also bottom gas stirring. The TOC is reduced to 16.9 ppm after 10 minutes combined EMS and gas stirring (EMGAS). The stirring conditions are presented in Figure 4. After 20 minutes soft EMGAS stirring the TOC was increased to 20.6 ppm and after 30 minutes it was 33.2 ppm. The total oxygen removal ratio with LF soft EMGAS stirring after VOD treatment is about 57% within a proper 10 minutes treatment time. If the treatment time is too long then there is a risk of oxygen pickup. Similar results have been obtained for a medium carbon steel grade, as presented in Figure 5. The TOC removal ratio with only EMS soft stirring after vacuum degassing (VD) treatment is about 47%. More test work is planned in this reference plant in the near future.

The total oxygen content in ball-bearing steel produced with electromagnetic stirring and Ar-gas bubbling at an ABB reference plant B is presented in Figure 8. The process route is EAF/LF/ASEA-SKF process. It is clearly shown that the electromagnetic stirring gives much lower total oxygen content (4.7 ppm in average) than that by Ar-gas stirring (9.4 ppm in average) in the quality steel products.

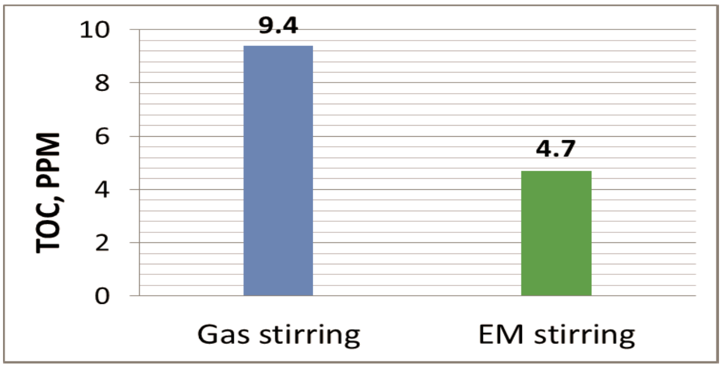


Figure 6. Total oxygen content in ball-bearing steel produced with gas and electromagnetic stirring respectively

The number of non-metallic inclusions after LF-EMS respective Ar gas stirring station at an ABB old reference plant C is presented in Figure 7. The process route is EAF/AOD/LF-EMS or Ar stirring. The D-type of inclusions with a size of more than 5.4 microns after LF-EMS is reduced by 50% compared to that after argon gas stirring ladle station, while the C-type of inclusions with a size of more than 5.4 microns after LF-EMS is reduced by more than 70% compared to that after argon gas stirring. It is clearly shown that electromagnetic stirring gives a much lower number of non-metallic inclusions in the stainless steel production process.

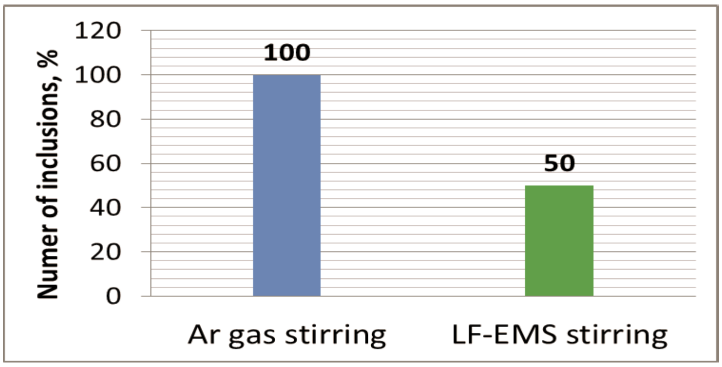


Figure 7 Number of non-metallic inclusions after EMS respective Ar gas stirring in the ladle furnace

4.2 Desulphurization

It is often claimed that induction stirring is not suitable for efficient desulphurization in the ladle. It is true that stirring of the steel with argon often yields a better degree of sulphur removal. Gas stirring tends to give maximum turbulent stirring effect in the slag/metal interface, whereas the stirring effect in the lower part of the steel bath is rather modest. Induction stirring, on the other hand, produces a more evenly distributed stirring effect in the entire steel bath. It is expected at this point that the combination of Ar-gas stirring and EMS will result in good desulphurization in the ladle furnace treatment. Recent research by ABB Metallurgy Products shows that the combination of EMS and gas stirring (EMGAS) in the ladle refining process is a good solution for clean steel production [9]. CFD simulation (left) and water modeling (right) results are presented in Figure 8 [11]. The simulation results show that EMGAS has a strong flexibility regarding control of the melt flow velocity, gas plume shape, stirring energy, and slag/steel mixing. The industrial test at an ABB reference plant D shows that the desulphurization rate by use of the EMGAS is increased by 25% compared with only using Ar-gas stirring, see Figure 9. The desulphurization time from 47 ppm to 7 ppm is 20 min for only using Ar stirring and is 15 min for EMGAS together with reduced Ar consumption. It can be concluded that EMGAS will increase the desulfurization rate which in turn will shorten process time and produce cleaner steel.

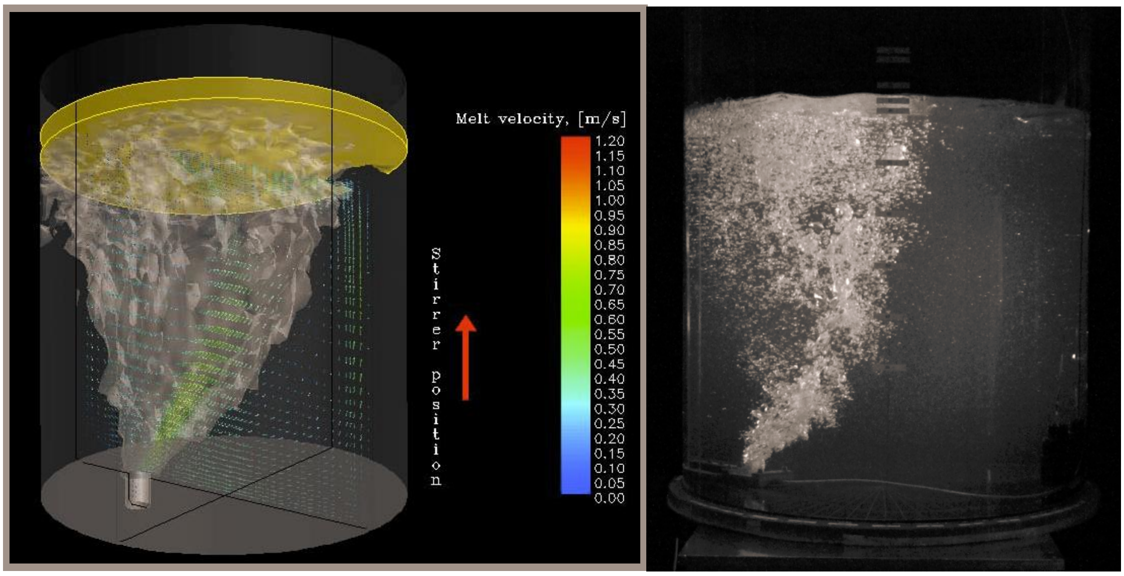


Figure 8. CFD simulation (left) and water modeling (right) results for EMGAS stirring in ladle furnace [11]

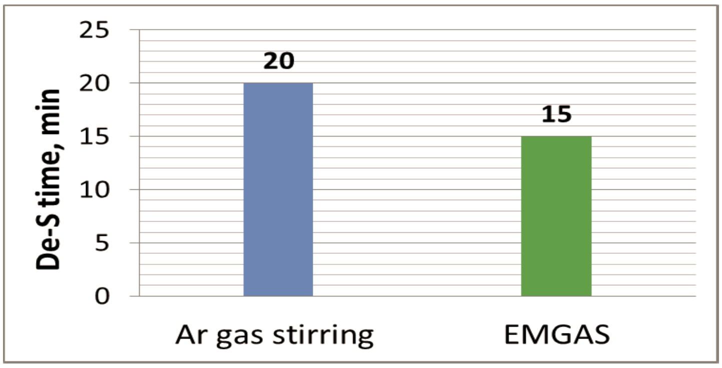


Figure 12. De-sulphurization time needed for sulfur reduction from 47 ppm to 7 ppm under Ar-gas and EMGAS stirring for a 150t ladle furnace

4 CONCLUSIONS

Electromagnetic stirring (EMS) has a solid and well-documented reputation for producing clean steel. The positive effect of electromagnetic stirring on specialty steel cleanliness has been discussed based on data from a number of ABB reference plants. The results show that the adjustable turbulent energy distributed in the steel bath gives excellent mixing and rapid removal of inclusions, making it possible to obtain a low total oxygen value and a smaller number of non-metallic inclusions. The controlled stirring with unbroken slag layer by EMS will protect the steel from the influence of the ambient atmosphere and thus minimize excess re-oxidation of aluminium as well as the pickup of nitrogen and oxygen. The combination of EMS and gas stirring (EMGAS) in the ladle refining process is an effective solution for clean steel production. A number of ABB reference plants producing high quality clean steel, stainless steel and tooling steel have successfully applied this LF-EMS technology to improve their steel cleanliness. The effect of EMS on steel cleanliness in the ladle refining process for stainless steel is more important than that for specialty carbon steel. Compared with argon gas stirring, the improvement ratio of inclusion removal with LF-EMS is typically around 30-50%. The industrial test shows that the desulphurization rate by use of the EMGAS is increased by 20-30% compared with using gas stirring alone.

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