Electromagnetic stirring in ladle refining processes

Electromagnetic stirring during ladle refining (LF-EMS) provides excellent control of deoxidation, ladle composition and temperature through its efficient and controllable stirring action. Use of LF-EMS in conjunction with gas stirring for desulphurisation optimises the advantages of both processes.

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The main demands on ladle metallurgy are good control of steel cleanliness, temperature, chemical analysis, alloying yields and degassing. Various refining methods have been developed to meet these demands, such as RH, ASEA-SKF, VOD and CAS-OB; and there are different ways to agitate and move liquid steel in the ladle, such as vacuum lifting, gas stirring and electromagnetic (induction) stirring.

First introduced in 1965, LF-EMS has been installed in 100 plants and has achieved great success both in the production of high quality steel, in acting as a buffer between steel plant and caster and enabling a reduction in furnace tapping temperature to be achieved.

In this paper the principles, components and characteristics of the LF-EMS system are described. The metallurgical performance of LF-EMS is discussed and compared with argon gas stirring. Finally, the implementation of LF-EMS in a steel plant with a thin slab casting machine will be discussed.

LF-EMS SYSTEM

The main components of the LF-EMS system are an electromagnetic coil, frequency converter, transformer and a water station for the cooling of the electromagnetic coil (see *Figure 1*). A low-frequency two-phase current generated by the converter is fed into the coil to generate the electromagnetic field. The magnetic field is strengthened by an iron core located behind the coil which is made of tubes that are cooled by low-conductivity, de-ionised water. The ladle shell in front of the coil must be made of non-magnetic stainless steel so that the low-frequency magnetic field can penetrate into the melt. The coil and iron core are placed in a stainless steel box and are protected from the heat in the ladle by a layer of refractory material. The coil box should be placed as close as possible to the ladle in order to achieve the highest possible magnetic field in the melt.

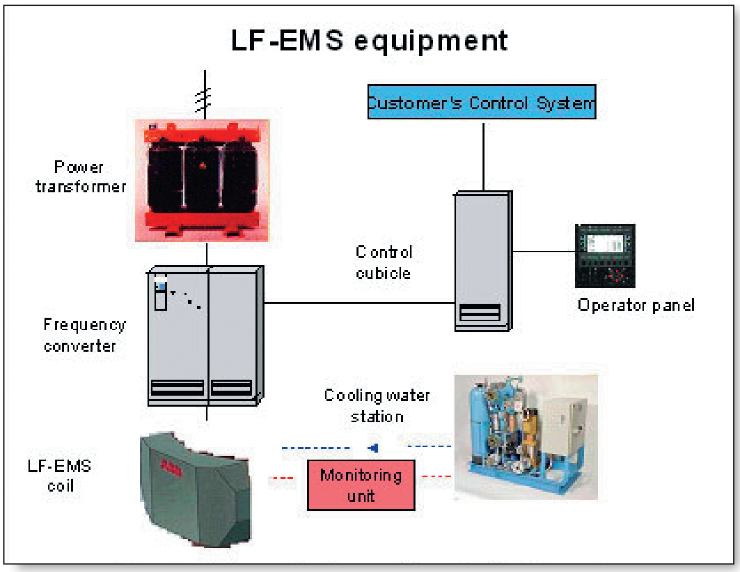

Fig.1 Schematic view of the LF-EMS system

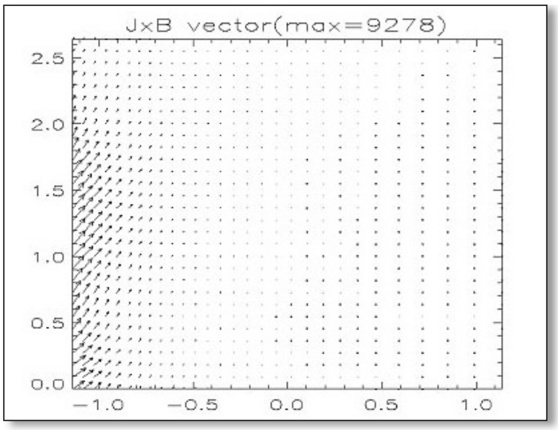

Fig.2 Calculated Lorenz force in the ladle

MAGNETIC FORCE AND FLUID DYNAMICS

The low-frequency magnetic field induces current in the melt. A Lorenz force is then formed as a result of the co-existence of the two fields:

$$\vec{F} = \vec{J} \times \vec{B} \qquad \textbf{[1]}$$

where: $\vec{J}$ is the induced current, $\vec{B}$ is the magnetic field and $\vec{F}$ is the Lorenz force.

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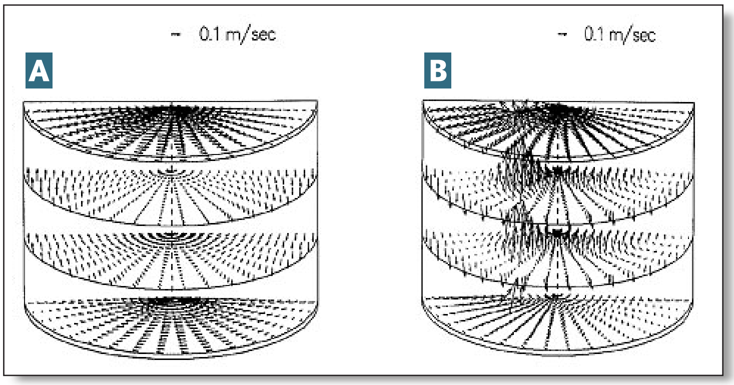
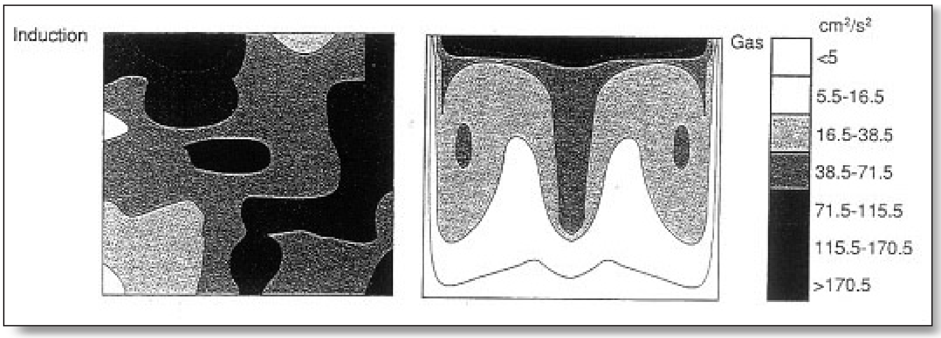
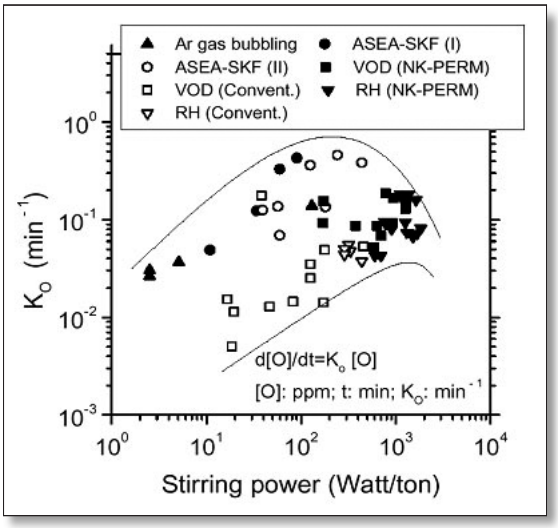


Ⓐ **Fig.3 Calculated steel flow in (a) induction- and (b) gas-stirred ladles**



Ⓐ **Fig.4 Distribution of turbulent energy in the ladle**



Ⓐ **Fig.5 The effect of stirring power on the oxygen removal rate constant**

Figure 2 shows the calculated Lorenz force in the ladle. It is concentrated in the left side close to the coil and its direction may be upwards (as shown in the figure) or downwards by controlling the current phase difference. *Figure 3* compares the calculated flow in an induction-stirred and gas-stirred ladle.

It can be seen that LF-EMS gives a more homogeneously distributed steel velocity in the ladle and there is no significant difference between the velocities at the bottom and surface of the melt, as in the gas-stirred ladle. *Figure 4* shows the distribution of turbulent energy in the ladle. As with the Lorenz force the turbulent energy is more homogeneously distributed than in the gas-stirred ladle (lance or porous plug).

METALLURGICAL PERFORMANCE

Deoxidation and steel cleanliness LF-EMS generates controlled stirring in the melt and can keep the slag unbroken to minimise oxygen ingress and oxidation of aluminium and other elements. The homogeneously distributed stirring energy is favourable for the formation of larger inclusions and for their transport to the steel-slag and steel-refractory interfaces where they are captured. As a result the total oxygen content is about 20–30% lower than that of gas-stirred steel.

Figure 5 shows the effect of the stirring power on the oxygen removal rate constant for different processes. Excessively strong stirring is detrimental since the upward circulation of steel into the slag layer may expose an open surface or 'eye' to reoxidation, and the lining may be seriously eroded. It can be seen that a maximum deoxidising effect of LF-EMS (ASEA-SKF) is obtained by optimising the stirring power.

Figure 6 describes the deoxidising process. When a deoxidant such as aluminium is added to steel it reacts rapidly with the dissolved oxygen via the nucleation of small alumina inclusions. This lowers the dissolved oxygen content to an equilibrium value determined by both the deoxidant and the temperature. The total oxygen content does not decrease as fast as the dissolved oxygen content as the oxide inclusions need time to be removed from the steel by absorption into the slag.

These oxides increase in size mainly from collisions caused by velocity gradients. The separation of the oxides from the steel to the slag has been found to be enhanced by a buoyancy force which is initiated by density differences between the oxide and the steel, and by small eddies in the turbulent flow. The rate of separation of inclusions can be increased with the help of stirring, which causes inclusions to collide, as well as lifting the inclusions up to the top slag, where they can be assimilated.

LF-EMS can provide uniformly distributed turbulent energy (small eddies) in the bulk melt, which is beneficial to the collision of small inclusions, thereby increasing their size. An optimised flow speed on the melt surface ensures that the inclusions are easily absorbed by the slag

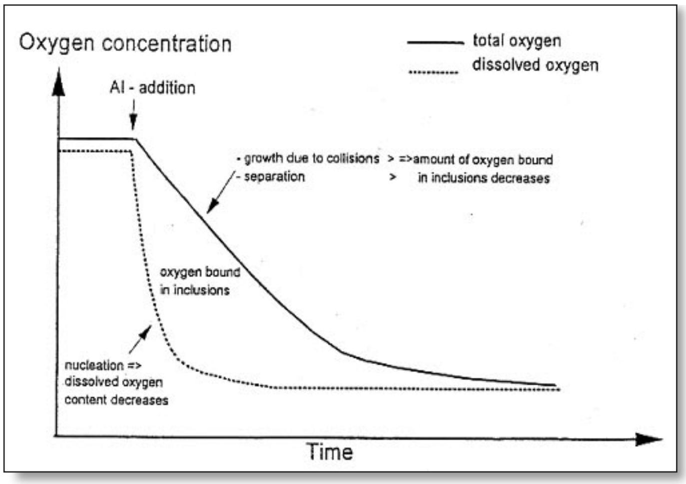


Fig.6 **The principle of the deoxidising process**

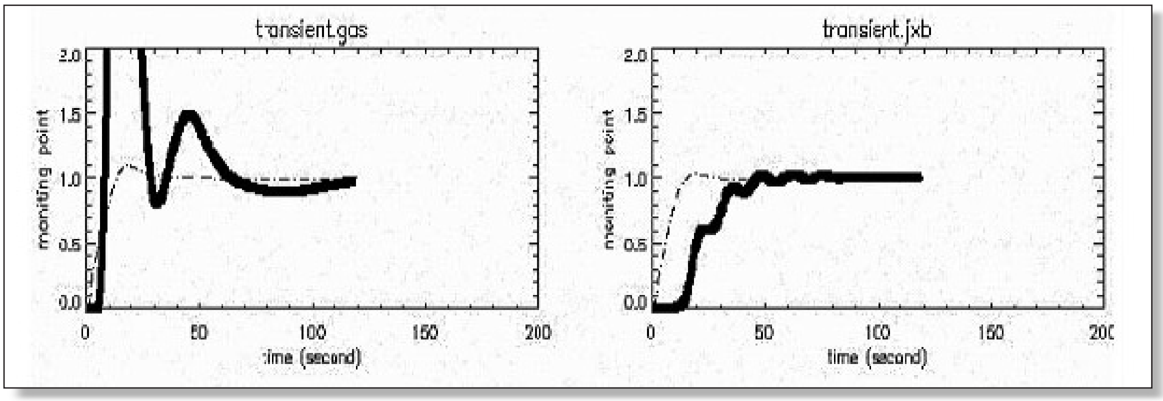


Fig.7 **The calculated mixing time of (a) gas-stirred and (b) induction ladles**

layer. The stronger the deoxidising elements used, the more important becomes the issue of avoiding exposure to the furnace atmosphere to minimise reoxidation and aid removal of inclusions.

In light of the above, induction stirring offers the best possibilities for clean steel production and it has been estimated that induction stirring will result annually in 0.2% fewer rejects for internal steel quality as compared to gas stirring.

Alloying and analysis control Because of the ability of LF-EMS to produce a controlled 'eye' and efficient bottom stirring energy, the melting and homogenisation of alloys is rapid. *Figure 7* shows the calculated mixing time in gas-stirred and induction-stirred ladles. It can be clearly seen that induction stirring gives much better mixing than gas stirring. LF-EMS is an excellent tool for production of highly alloyed steels because of the high active arc power for melting of alloys and the rapid mixing time because of induction stirring. *Figure 8* shows an example of alloy additions at Ellwood Uddeholm Steel Company in the production of a 45t AISI H-13 tool steel heat. 80kg of FeCr/tonne steel was added into the EMS ladle and homogeneity was achieved less than 15 minutes after the start of the FeCr addition. Note the low superheat after the FeCr addition.

The operational experiences from a large number of installations with induction and gas stirring show that the rate of oxidation of deoxidising elements is generally lower for induction stirring than for gas stirring (see *Figure 9*). Differences in aluminium oxidation rates between gas stirring and induction stirring of 2–5ppm/min have been reported. This means that the corresponding amount of aluminium added can be saved. Also, this difference can increase if there is contact between the steel and the furnace atmosphere during treatment caused by leakages through a roof that does not seal perfectly against the ladle rim.

For low carbon grades, excessive carbon pick-up from electrodes during arc heating can be detrimental. *Figure 10* shows the results of the carbon yield in induction- and argon gas-stirred ladles, indicating that gas-stirred heats have a carbon yield considerably over 100% and of greater variability compared to induction-stirred ones. ▷

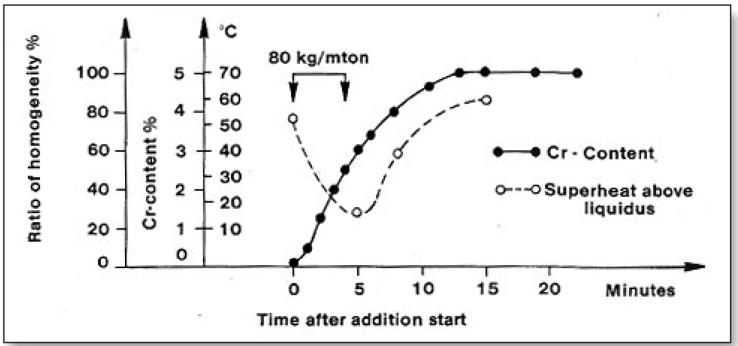


Fig.8 **Alloying and temperature control in an induction-stirred ladle**

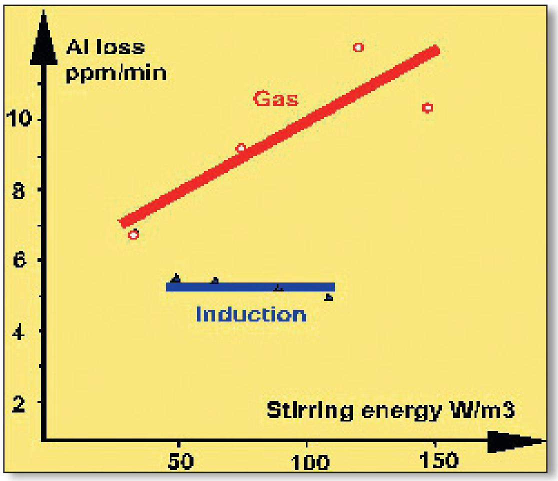


Fig.9 Aluminium loss during stirring

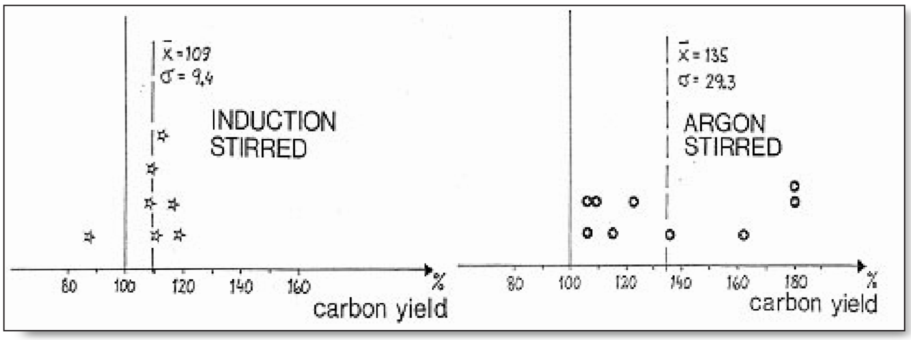


Fig.10 Carbon yield over total ladle furnace treatment

This relates to the longer arc length and greater exposure to air during gas stirring. By implication electrode consumption is lower with LF-EMS.

Desulphurisation Good desulphurisation requires good mixing of the slag and melt. Experience shows that the most complete desulphurisation is obtained with a combination of induction stirring, gas stirring and arc heating working in a complementary manner. Gas stirring is used when there is a need for an intensified interaction between slag and steel to maximise the desulphurisation reactions. This is followed by a period of smooth induction stirring to let the CaS inclusions float out of the steel.

PLANT OPERATIONS

Temperature control Efficient and controllable reheating cycles are important in order to minimise secondary effects like lining wear and unexpected composition changes of the melt, as well as minimise energy use and heating times. The arc length and slag thickness are both important factors in energy transfer to the melt; the longer the arc the thicker the slag layer needs to be. Due to the relatively calm slag layer, LF-EMS can use a short arc to heat the melt, which ensures a higher electrical efficiency of the arc energy transfer to the bath. A 50–70% higher efficiency has been measured, which is of great importance to short, efficient reheating cycles.

Induction stirring makes it possible to operate with shorter arcs (lower voltage) without unacceptable carbon pickup. Heating is normally made with a cos fi of 0.7–0.71 with induction stirring, and with a cos fi of 0.78–0.81 using porous plugs. This advantage makes it possible to run on a higher power with induction stirring compared to gas stirring for the same refractory wear index. A higher power will give a shorter heating time, which will minimise the risk of dissolution of atomic nitrogen from the arc zones when heating Al-killed steel. From our ABB LF installations we have learned that running on high power and waiting gives a lower nitrogen level and a better ladle life than running continuously on a lower power.

Buffer between steelplant and caster Shorter heating times mean fewer delays and hence potential for greater output. When combined with argon gas stirring, LF-EMS is also beneficial, because it opens the porous plug due to its good temperature homogenisation.

THIN SLAB CASTING

Thin slab casting is increasingly becoming a viable alternative to conventional slab casting. Increased emphasis, however, has to be placed on temperature control and homogeneity, steel cleanness (low oxygen content) and low nitrogen content to guarantee product quality. LF-EMS is ideally suited to this process because of its excellent control of these parameters. This has been proved in steel plants operating with both LF-EMS in the ladle furnace and thin slab casting.

CONCLUSIONS

LF-EMS has excellent performance with respect to deoxidation, temperature control, chemistry analysis control, alloy yield and the production of clean steel. In order to improve the desulphurisation performance LF-EMS can be complemented by argon gas stirring. LF-EMS is also an important tool for reliable and economic thin slab casting. **MS**

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