

# Problems With and Solutions to Skull Formation in EBT Furnace for Tooling and Stainless Steel Production

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Bottom skull formation is a common problem in electric arc furnaces for high-alloy steel production. Skull formation creates a number of process problems: reduced furnace volume capacity, lower tapping weight hit ratio and lower steel yield. The formation mechanism of bottom skull in an 70-ton eccentric bottom tapping furnace for tool and stainless steel production in a steel plant in Korea has been investigated. The effect of bottom gas stirring and electromagnetic stirring (EMS) on the reduction of skull thickness has been compared. The results show that EMS is a more efficient way to reduce skull formation compared to gas stirring.

Bottom skull formation is a common problem in electric arc furnaces (EAFs) used for high-alloy steel production, especially when a high percentage of FeCr is charged into the furnace together with short tap-to-tap time. Skull formation creates a number of process problems such as reduced furnace volume capacity, lower tapping weight hit ratio, lower steel yield, reduced productivity, etc. It has been reported that electromagnetic stirring (EMS) could reduce skull formation for spout-tapping furnaces used for stainless steel production.<sup>1</sup> Electromagnetic stirrers installed underneath the furnace bottom generate a mixing effect on the entire bath, thus accelerating scrap melting and temperature homogenization, which is helpful for skull removal.

A new generation of electromagnetic stirrer for the electric arc furnace (ArcSave<sup>®</sup>) was installed recently on a 70-ton eccentric bottom tapping (EBT) furnace at SeAH's steel plant in Changwon, Korea. SeAH CSS was founded in 1966 in the city of Changwon. The Changwon plant produces 1.2 million tons of crude steel annually. SeAH CSS is the only seamless stainless steel pipe and tube manufacturer in Korea that uses integrated steel manufacturing

systems. The meltshop consists of an EAF, argon oxygen decarburization (AOD)/vacuum oxygen decarburization (VOD), ladle furnace and continuous casting/ingot casting. The EAF has a capacity of 70 tons with a 72-MVA transformer and is equipped with a lance manipulator consisting of four lances for injecting O<sub>2</sub>, alumina and carbon. In combination with electrical power, three oxy-fuel wall burners are used for chemical energy input. Basic furnace data is listed in Table 1. Serious skull formation is the biggest operational problem with this EAF. In 2012, bottom gas stirring, consisting of three porous plugs installed in the bottom hearth of the furnace, was tested with the aim of eliminating the bottom skull problem but was unfortunately unsuccessful. Similarly, porous plug maintenance is a major challenge due to the high frequency of clogging caused by bottom skulls. After nearly one year of testing, the porous plugs were removed from the furnace due to lack of positive effects. In 2018, with the same objective in mind, electromagnetic stirring technology was introduced to SeAH as a new potential solution to the bottom skull problem. This paper will summarize the test results obtained both during and after the hot commissioning

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Table 1

<i>Basic EAF Data, Steelmaking Team 3, SeAH</i>	
Furnace	Eccentric bottom tapping, 90% scrap
Tap weight	70 tons
Tap-to-tap time	65–75 minutes
Transformer	72 MVA
Equipment	Oxygen lances, wall and door
Production per year	180,000 tons

period. These results demonstrate that ArcSave is a more efficient way of reducing skull formation in the furnace compared to gas stirring. The effect of EMS on electrical energy, power-on time and gunning materials reduction is also discussed.

### Skull Formation

The skull formations on the bottom shell consisted of unmelted scrap, unmelted ferrochromium alloy and solidified slag. The skull thickness was sometimes up to 1,000 mm depending on the duration that the bottom shell had been in operation. A photo taken from the skull formed on the furnace bottom is presented in Fig. 1a. The skull was periodically removed by use of the refractory removal machine, as shown in Fig. 1a. After drilling the side of the bottom skull, the center of the skull was lifted by the crane, as presented in Fig. 1b. Such maintenance work of bottom skull removal is tough and time consuming.

### EMS Installation and Stirring Principles

The electromagnetic stirrer is placed underneath the furnace bottom, which is made of a non-magnetic (austenitic stainless steel) steel plate, as shown in Fig. 2. The low-frequency electrical current carried through the stirrer windings generates a traveling magnetic field, which penetrates the furnace bottom and in turn generates forces in the molten steel. Since the magnetic field penetrates the full depth of the melt, the melt flows in the same direction across the entire diameter of the furnace and through the full depth of the bath. After reaching the furnace wall, the melt has to flow back along the sides of the furnace. When the traveling field is reversed, the melt flows in the opposite direction. Since the stirrer is extended over the entire diameter of the furnace, good stirring forces are obtained over the whole bath.

The melt velocity distribution simulated by computational fluid dynamics (CFD) simulation for a 160-ton EBT furnace with a stirring direction from slag door to EBT is presented in Fig. 3. Fig. 3a shows the velocity distribution in the longitudinal cross-section, Fig. 3b shows the velocity distribution in the transverse cross-section, and Fig. 3c presents the velocity distribution of the melt surface. It can be seen from Fig. 3 that the whole melt bath is involved in the movement. The optimized average volume velocity of the melt is in the range of 0.2–0.4 m/second. Compared with bottom gas stirring, electromagnetic stirring creates mixing in the entire bath. This effect accelerates homogenization of both temperature and chemical composition of the steel. It should be pointed out

Figure 1

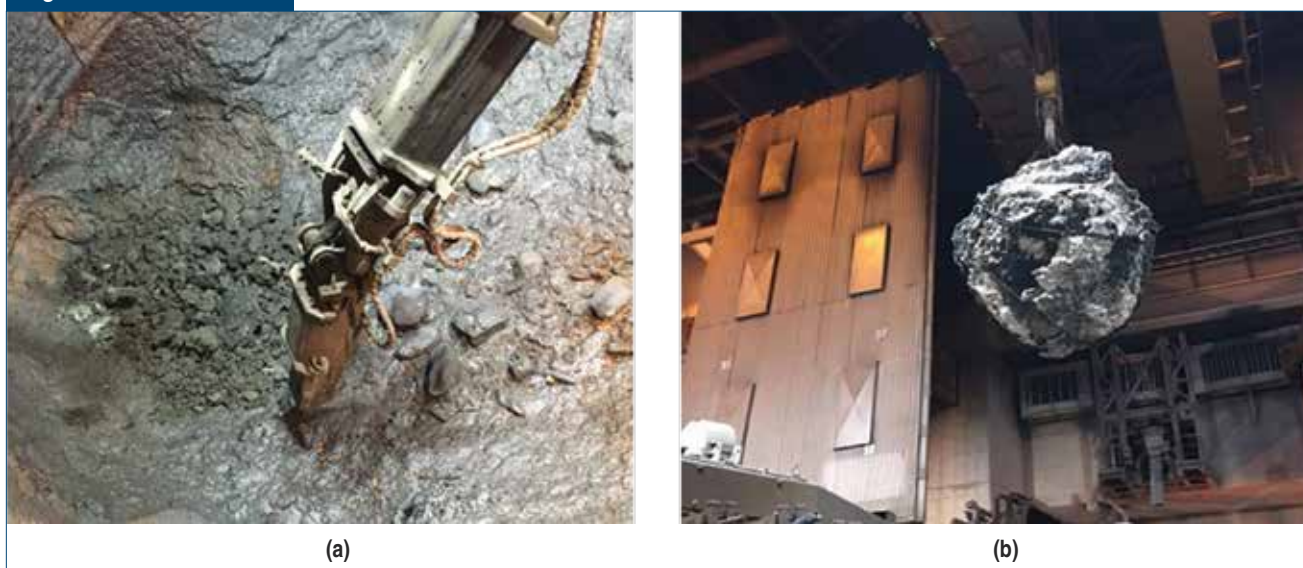


Photo of bottom skull taken from the SeAH electric arc furnace: bottom skull and removal machine in place (a) and part of the skull lifted by crane (b).

Figure 2



Arc furnace with ArcSave® stirrer mounted underneath the furnace bottom.

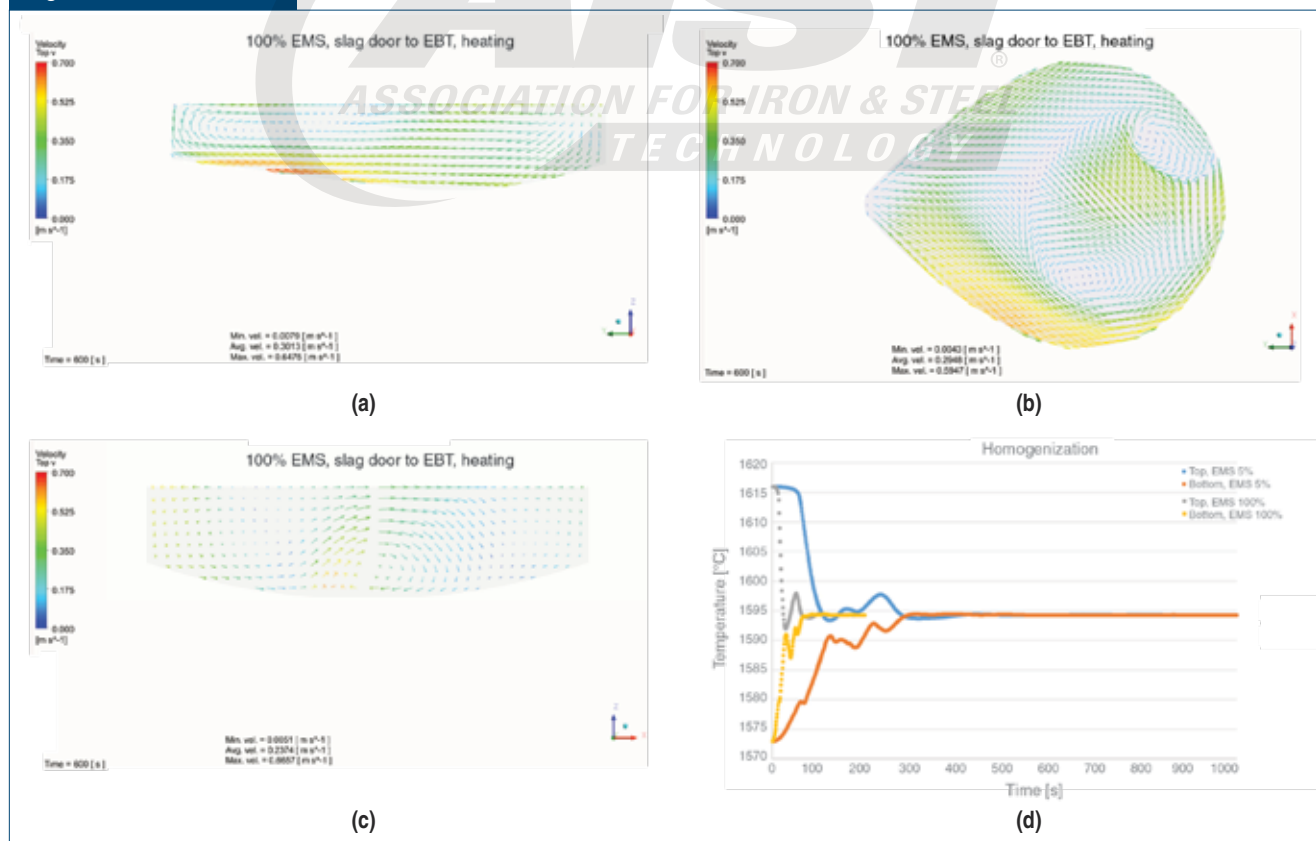
that the magnetic force acts not only in a horizontal but also a vertical direction, which results in a more efficient mixing effect on the entire bath. EMS offers the added benefit of having no physical contact with the steel melt, which results in very low maintenance requirements.

Liquid bath temperature homogenization was calculated with the following assumptions:

- For the non-stirred bath, the bottom temperature is assumed to be 1,560°C while the surface temperature is 1,620°C. Then the temperature distribution (homogenization time difference) is compared with and without EMS stirring.
- For the non-stirred bath, natural stirring was simulated with a case of 5% of maximum EMS force as a reference.

The temperature homogenization curves are presented in Fig. 3d. The homogenization time is calculated at the point when the max temperature difference is less than 5°C. The temperature homogenization time with 5% EMS is 305 seconds and it is only 58 seconds with 100% EMS. The results show that

Figure 3



Melt flow velocity vectors and temperature homogenization time simulated in an eccentric bottom tapping (EBT) furnace: Velocity distribution in the longitudinal cross-section (a), velocity distribution in the transverse cross-section (b), velocity distribution of the melt surface (c), and temperature homogenization curves (d).



bath temperature homogenization time with 100% EMS is only 19% of the time without EMS. The quick homogenization of temperature increases arc heat transfer efficiency and also the scrap melting rate.

During the spring of 2018, the EMS was installed at Steelmaking Plant 3 at SeAH's Changwon site. To accommodate this installation, a new stainless steel lower furnace shell was installed, and the installation process went smoothly during the 9-day shutdown. EMS stirring features fully automatic control by way of a stirring profile that can be customized to match the needs of different EAF process steps such as scrap heating, homogenization, melting of alloys, decarburization, deslagging and tapping. The EMS operation is characterized by low running cost, high reliability, high safety and high reproducibility. The EMS control profile used by SeAH is presented in Fig. 4. The stirring direction will be changed according to the plus or minus value of the frequency.

## Results and Discussion

The main advantage of stirring molten steel in the EAF process is the acceleration of heat and mass transfer process. To compare the effect of ArcSave on the EAF process, process data was collected for four months without stirring as a reference (in the first quarter of 2018) and six months with ArcSave to measure performance. The effect of EMS on bath temperature homogenization, energy and electrode consumption, power-on time, and refractory consumption will be discussed in this section.

**Bath Homogenization and Temperature Difference** — The bulk turbulent flow induced by EMS stirring brings a thorough mixing of the whole melt, resulting in very good temperature and composition homogenization. The temperature distribution without/with EMS has been measured at two positions in the furnace: one from the furnace door and the other from the EBT area, as shown in Fig. 5. The temperature difference is in the range of 9–39°C with EMS off, and in the range of 0–10°C with EMS on.

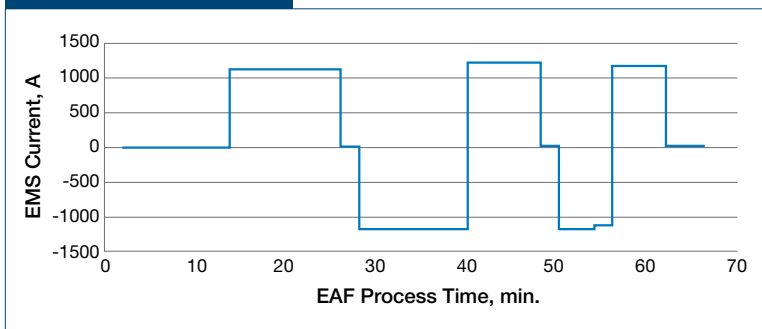
Good melt bath homogeneity is important from a metallurgical standpoint. It allows for reliable determination of bath composition, accurate prediction of final tapping carbon control and exact tap temperature measurement. Bath homogenization after using EMS therefore makes

it possible to obtain an exact tapping temperature for different steel grades, which is very important to reduce variation in target tapping temperature and enable smoother downstream ladle furnace (LF)/VOD operation.

**Scrap Melting and Scrap Handling**<sup>4</sup> — The forced convection induced by electromagnetic stirring enhances the melting of larger scrap pieces and bundles and makes scrap stratification less significant. CFD simulation results show that the melt velocity is increased by a factor of 10 with ArcSave compared to only natural convection in the melt bath.<sup>2</sup> This strong convection inside the melt contributes to a homogenous temperature distribution and high scrap melting rate. In addition, it is also found that ArcSave has stabilized the arc with reduced electrode current swings by melting of big scrap bundles faster and reducing scrap cave-ins.<sup>3</sup>

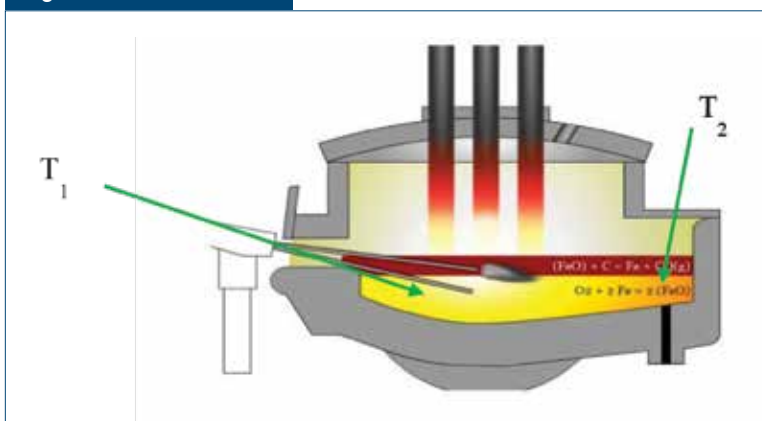
The major benefit of fast scrap melting is the reduction in scrap handling costs at SeAH. Before EMS was used, the internal rejected ingot had to be cut into

Figure 4



Dynamic EMS current profile for tool steel melting at SeAH.

Figure 5



Bath temperature measurements from the slag door and EBT area. The average temperature difference in two positions is less than 9°C with EMS. Furnace illustration from Materials Engineering NEDUET Karachi.

smaller pieces (less than 250 kg) before being charged in the furnace, otherwise it's difficult to melt in the furnace within one heat. Using ArcSave, the rejected ingot (up to 4 tons) could be directly charged into the furnace without any melting problem. Less scrap handling work means less labor cost, less natural gas consumption and higher metallic yield. The scrap handling cost is reduced 70–80% after EMS installation.

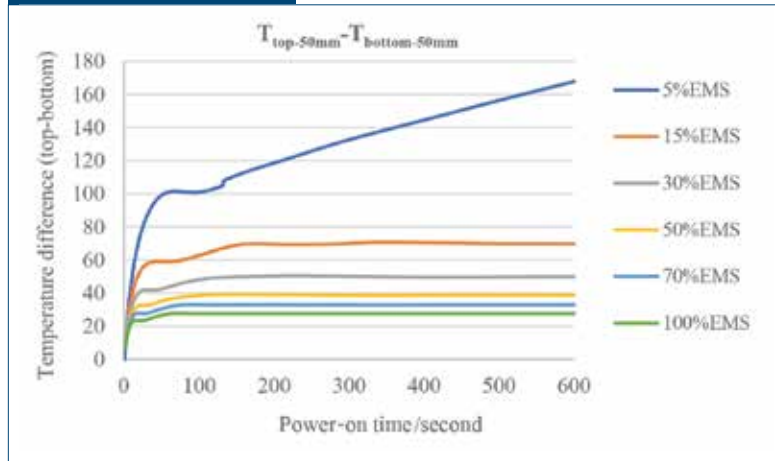
#### Arc Heating Efficiency and Energy Saving —

Temperature gradients in the flat bath during scrap melting in conventional AC arc furnace have been reported in the range of 50–70°C<sup>4,5</sup> without stirring. Practical limitations make measurement of the temperature on the bottom of the bath difficult to perform, especially during the arc power-on time. To estimate the bath temperature distribution during power-on time, a CFD simulation was performed studying the effect of stirring on temperature distribution during arc heating in a 160-ton EBT furnace with a total active power input of 70 MW. The arc power distribution in the furnace was assumed as three parts:

- $P_{con}$ : 55% to the melt by convection. This part of the power input can be described as a function of the distance to the electrode.
- $P_{rad}$ : 20% to the melt by radiation, which can be considered to homogeneously distribute into the melt.
- $P_{los}$ : 25% power loss to the wall, roof and electrodes.

The average temperature gradient between the bottom layer (50 mm up from bottom) and the surface layer (50 mm down from the surface) during arc power-on time has been calculated in an EBT furnace for several cases applying different EMS stirring powers (5%, 15%, 30%, 50%, 70% and 100% EMS force) and the results are presented in Fig. 6. It can be seen that the average temperature gradient with 5% EMS force (the case for without stirring) increases with power-on time and reaches 168°C after 10 minutes of power-on time. The temperature gradient decreases as stirring force increases. With 100% EMS force, the average temperature gradient is only 28°C and is almost constant as power-on time increases. This means that stirring reduces melt surface superheat and that the heat from the arc zone is quickly transmitted to the bulk melt. The reduction in surface superheat temperature reduces heat losses to the furnace wall and roof during power-on period, and thereby lowers electricity consumption. At the same time, electromagnetic

Figure 6



The average temperature gradient between furnace bottom layer (50 mm up from bottom) and surface layer (50 mm down from the surface) during power-on time in a 160-ton EBT furnace.

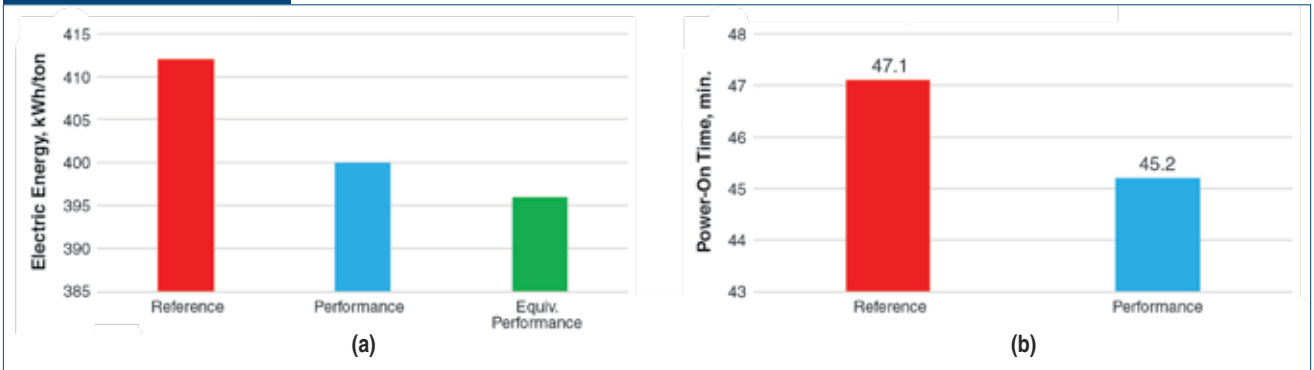
stirring increases scrap melting and decarburization rates, therefore saving the furnace process time, which also contributes to heat loss reduction. The relative increase in bath bottom temperature during power-on time also contributes to bottom skull melting during the process.

During the SeAH EMS test, the average electrical energy savings is some 3% together with a 7% reduction in injected oxygen. The equivalent energy saving is around 4% by compensation of injected O<sub>2</sub> consumption, as presented in Fig. 7. Power-on time is reduced by 4–5%. The stable arcing, less superheat and less electrical power consumption also result in lower electrode consumption in the range of 3–4%.

**Skull Reduction and Operational Benefits —** As discussed in the previous section, one of the main objectives of installing ArcSave at SeAH was to solve the bottom skull problem. The skull thickness was measured by using a laser distance meter and change in thickness with EMS has been compared to that of the reference test without EMS. A general illustration of the skull profile in the furnace is presented in Fig. 8. The skull thickness was reduced from 700–1,000 mm without EMS to 200 mm with EMS. The reduction in skull thickness is to some extent dependent on the EMS running power. For the current case, a 1,400-amp EMS current is more efficient for reducing skull formation.

The mechanism for skull removal with EMS could be the relative temperature increase in the bath bottom and the convection flow in the bath. The high melting point temperature and high density of FeCr means that it tends to rest on the bottom of the furnace, where the melt is cooler, thus dissolving can be problematic without a stirrer. It was also found that

Figure 7



Effect of ArcSave on electric energy consumption (a) and power-on time (b) reduction.

the skull formation problem is more serious when the ferrochrome addition is higher and the tap-to-tap time shorter. The buildup of unmelted ferrochrome on the furnace bottom is the main reason for skull formation. Argyropoulos and Guthrie have modeled the effect of temperature and bath agitation on the dissolution time of spherical ferrochrome particles in the steel bath.<sup>6</sup> It was reported that the dissolution time for 20-cm ferrochrome was approximately 950 seconds at 1,570°C, 90 seconds at 1,600°C, and 50 seconds at 1,620°C.<sup>6</sup> As presented in Fig. 6, the bottom bath temperature with EMS was increased by about 50–100°C during power-on time. The relative increase in bath bottom temperature reduces dissolution time for the ferrochrome addition in the melting process. It was also reported that at a fixed steel bath temperature (1,600°C) the bath stirring at a slip velocity of 0.3 m/second will reduce the ferrochrome dissolution time to only one fourth of that without stirring (only natural convection) case.<sup>6</sup> This means that both temperature homogenization and the forced convection of the melt will help with dissolution of both FeCr and big pieces of scrap. The positive effect of EMS on

skull removal has also been proven in a spout tapping furnace for stainless steel production.<sup>1</sup>

The reduction of skull thickness in the SeAH furnace brings the following operational benefits:

- Easier scrap bucket charging.
- Better melt bath level control.
- Increased charge or tap ton per heat.
- Higher tap weight hit ratio.
- Less maintenance work on the furnace refractory.
- Higher scrap and ferroalloy yield.
- Consistent furnace operation.
- Higher steel productivity.

**Bath Surface Temperature Reduction and Refractory Savings** — Twenty months of EMS operation at SeAH demonstrate that stirring in the melt bath has reduced furnace repairing refractory consumption by some 45% for hot repairing and 9% for cold repairing compared to the absence of EMS. The reduction in bath surface temperature by EMS stirring during power-on is probably the main contribution to this

Figure 8

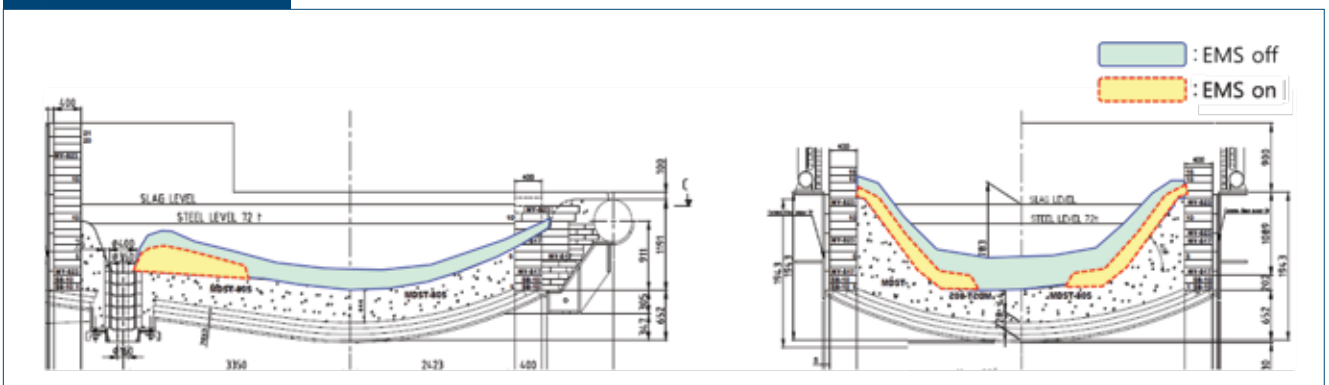
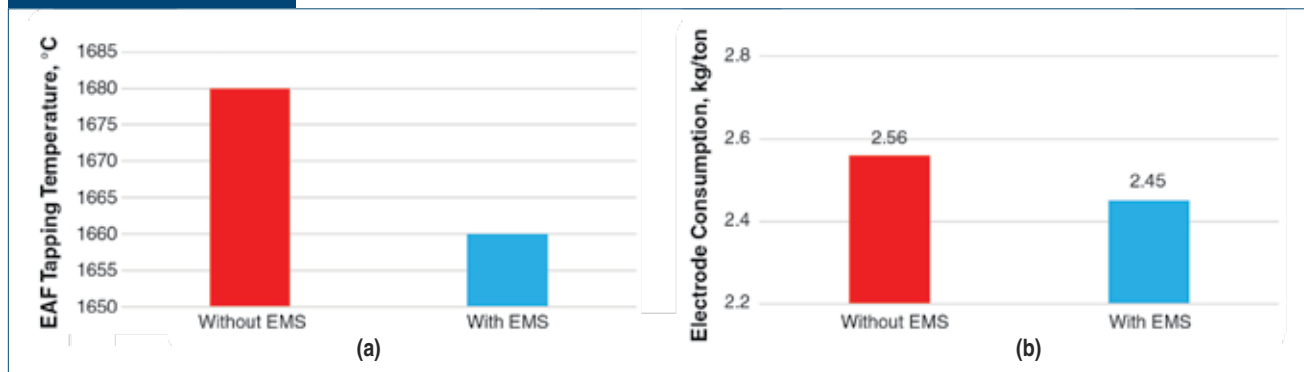


Illustration of bottom skull changes: thickness was reduced from 700–1,000 mm (no EMS) to 100–200 mm (with EMS).

Figure 9



Effect of ArcSave on EAF tapping temperature for stainless steel (a) and electrode consumption (b) reduction.

refractory savings, since most critical damage to the refractory occurs in the slagline area, especially in the hot spots. Another factor that lowers refractory wear is the reduced tapping temperature after EMS. The average tapping temperature for stainless steel grades was reduced from 1,680°C to 1,660°C, while for tooling steel it was reduced from 1,630 to 1,610°C, as presented in Fig. 9. One should keep in mind that the 20–30°C reduction in tapping temperature as measured in the EAF could be separated as two parts: the first part of some 15°C tap temperature reduction will not affect ladle furnace arrival temperature. The elimination of thermal stratification in the melt bath apparently reduces the tapping temperature. In the case of an unstirred bath where, in general, the steel is hotter near the surface, the measured temperatures are frequently not representative of average bath temperature. The second part of 5–15°C will be the absolute tapping temperature reduction in the tapping ladle. The 20–30°C tapping temperature reduction will definitely reduce refractory wear. The third way in which EMS stirring contributes to refractory savings is by reducing skull formation. Fewer problems with the bottom skull will result in less bottom maintenance work and a consistent bath level control. It can be concluded that EMS has a positive effect on the furnace wall refractory lining and has reduced furnace refractory maintenance costs.

**Process Reliability and Safety** — Safety and reliability are always of great importance for EAF operation. The positive effect of EMS on the EAF process as discussed in the previous sections has a significant impact on improving process reliability. The fast meltdown of big scrap and ferrochromium provides a quick homogenization of the melt bath on both chemical composition and temperature, which ensures the targeted steel tapping weight and temperature. Stirring in the melt bath decreases carbon boiling out.

Homogenous temperature in the entire bath provides for smooth tapping and reduces tapping delays. In addition, elimination of thermal stratification in the melt bath clearly reduces tapping temperature. It was found that the tapping temperature with EMS could be reduced by 15–20°C without changing the LF arrival temperature. In the case of unstirred heats where, in general, the steel is hotter near the surface of the bath, the measured temperatures are frequently not representative of average of bath temperature.

### Conclusion

EMS stirring improves heat and mass transfer in the EAF process and reduces energy and electrode consumption while increasing operational reliability and safety. The hot test results show that EMS enhances scrap and ferrochromium melting and efficiently reduces furnace skull formation. The steel

Table 2

Process Improvements After EMS Installation at SeAH	
Items	Improvements
Electric energy reduction	–3–4%
Electrode reduction*	–3–4%
Power on time reduction	–4–5%
Bath temperature homogenization	≤10°C
Tapping temperature reduction	–20–30°C
Hot gunning materials reduction	–40–50%
Wall refractory reduction	–6–10%
Tapped liquid steel per heat	+3–5 tons
Scrap handling cost reduction	–70–80%
Productivity increase	+5–7%



temperature in the bath is more homogenous and target tapping temperature is controlled more accurately, which smooths downstream VOD operations. Short tap-to-tap time and consistent furnace operation also give increased productivity. The process benefits obtained from the EMS are presented in Table 2.

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