The plasma heated ladle furnace for secondary metallurgical tasks at Dörrenberg Edelstahl GmbH

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Introduction

In steelmaking, secondary metallurgy refers to the treatment of molten steel between its being tapped from the primary melting furnace and solidification in the continuous casting or ingot mould. Today, most of the melt treatment steps involved are essentially carried out in the ladle, which has thus changed from a simple transfer or pouring means to a metallurgical treatment vessel. As a result, 'ladle metallurgy' has evolved into a fixed term. In recent years this technology has increasingly gained in importance; especially in EAF steelmaking, the shift of metallurgical processes from the electric arc furnace to the ladle has been permitting a much more effective use of the melting furnace. Moreover, the treatment of molten steel in the ladle can make secondary metallurgical work more precise and selective, consistent with today's ever more exacting demands on advanced materials (1).

Ladle metallurgy has its origins in vacuum technology. As early as in the 19th century, it was known that gases dissolved in the steel were responsible for diverse casting flaws. The first suggestions to apply a negative pressure to the molten steel go back to this period; at the same time, the use of argon as a bubbling gas was contemplated. However, it was not until around 1950 that such applications were first successfully realized on an industrial scale. Diverse process variants soon evolved from the technology, and a feature common to nearly all of them is that the vacuum treatment takes place in the ladle.

For the above reasons, it made sense to shift other metallurgical operations into the ladle as well, although at the overall level, the temperature loss associated with these steps began to make itself felt increasingly. This issue could be addressed, on the one hand, by raising the melting furnace tapping temperature; a much more elegant solution, on the other hand, is to provide the ladle treatment stand with a heating capability. To this end, both electrical and chemical heating methods were employed (2).

The basic tasks of secondary metallurgical work can be summarized thus:

- Melt homogenization
- Accurate addition of alloying elements, with minimization of melting loss
- Removal of oxygen, nitrogen and (if applicable) carbon
- De-sulphurization
- Active slag work
- Accurate adjustment of the optimum pouring temperature
- Refining to remove non-metallic melt contaminants
- Boosting productivity and cost effectiveness of the overall process

The technical development described above applies mainly to steelmaking in the common EAF to "mini mill" plant range, with annual outputs in the region of 100,000 – 400,000 metric tonnes. In this operating size bracket, the requisite plant technology is widely available. For substantially smaller plants, however, such as the increasingly widespread "micro mills" relying successfully on coreless induction furnaces as the main melting source – or, indeed, any other smaller steelmaking or foundry operations – the choice of affordable secondary metallurgical equipment is but limited at present.

Background situation at Dörrenberg Edelstahl GmbH

The name of Dörrenberg has been synonymous with iron and steel from the Oberbergisches Land region for more than 300 years. Established in 1860 as a forge and steelmaking company, Dörrenberg has continued to prevail against the competition thanks to its determined commitment to continuous improvement. Today, Dörrenberg Edelstahl is active in four mutually supplementary business segments, viz., high-grade steels, high-grade steel die casting, precision casting and surface technology. The company's products are shipped mainly to the mechanical engineering and equipment building, tool and mouldmaking, and automotive manufacturing industries. Its success is based mainly on its vast metallurgical expertise.
The steelmaking plant produces forging and remelting ingots in the 1.2 to 14.5 t weight range. Its focus is on cold and hot-work tool steels and high-speed steels. RSH grades with higher and lower carbon levels and low-alloyed engineering steels round out the product range. For scrap melting, the company uses an electric arc furnace with a tap weight of 9 – 11 t. In the past, all metallurgical work such as alloying and desulphurizing were carried out in this EAF unit. The melt was then tapped into an 11 t ladle and degasified in a vacuum degasification station. This system had been purpose-developed by Dörrenberg in 1986 for small ladles in cooperation with an equipment manufacturer. After a final gas bubbling refinement aimed at a controlled removal of inclusions, the ingots were cast.

However, steadily rising demands on ingot quality had become a growing challenge in recent years. Given the small melting capacity of 10 – 11 tonnes and the resulting fairly high cool-down rates, compliance with the prescribed temperatures and associated treatment times – in a process without heat input – turned out to be particularly difficult.

Following a thorough study of the requirements for a reproducible process, it soon emerged that there would be manifold advantages in adding a ladle furnace to the EAF and vacuum degasification plant. One such advantage would be that the charge weight could be increased by installing a new 15 t ladle. The additional melt requirement could be supplied from the induction furnaces in the adjoining steel casthouse; their output would simply be subjected to secondary metallurgical work together with the molten steel from the electric arc furnace. This solution was consistently put into practice. An additional objective of revamping the steel mill was to gain the ability to melt steels with less than 0.05% carbon. To this end, it was necessary to heat the melt with minimum carburization. Especially this last-mentioned requirement prompted the owner to opt for a plasma-heated ladle furnace.

The plasma-heated ladle furnace: system description

In the following sections we shall be examining the main characteristics of the plasma-heated ladle furnace system and its advantages over a conventional ladle furnace with three-phase arc heating (3 – 7).

Mechanical plant structure:

Mechanically speaking, the plasma-heated ladle furnace consists of two electrode support arms attached to a rotary motion control system. Each support arm has a water-cooled electrode holder with a clamping device for the graphite electrode. Both electrode holders can be raised and lowered by means of an electric motor which acts on a spindle integrated into the support arm; this is done to position the electrodes above the bath for heating and to retract them from the lid again afterwards. The purpose of the motion control system is to swivel the support arms from their operating position into their park or maintenance position so that the ladle can be inserted or removed using the overhead crane. In addition, the motion control system drives the cable for lifting the lid which seals off the ladle during the heating cycle. Each of the hollow electrodes has a gas inlet port through which plasma-forming argon gas is supplied.
Electrical equipment concept:

The plasma-heated ladle furnace is electrically connected to the plant's 3-phase a.c. grid via a transformer (30 kV/3.3 kV). On the load side it operates on a single phase supply. However, a power factor correction and phase balancing station has been provided to distribute the single-phase load over the three grid phases and to correct the reactive power factor generated by the system at four operating points (cos phi > 0.95). The power input is modulated via a control transformer featuring a load-switchable tap changer on its primary side. In addition, the system features a power choke to stabilize the arc and to keep the load circuit short-circuit-proof. All system functions are monitored and controlled by a PLC using proven technology to ensure the system's reliable operation and largely automatic performance. The furnace has two graphite electrodes which, in electrical terms, run on a single-phase, i.e., there exists only one circuit powering both arcs. Thus, if we analyze a single a.c. phase, the current is supplied via one of the two electrodes, flows through the first arc, then passes through the melt and the second arc before returning via the other electrode. This straightforward electrical arrangement is a precondition, along with the stable arc behaviour described below, for a stable – and, above all, contactless – interaction between the melt and the electrodes. Both arc voltages are measured continuously, and the electrode positions are readjusted to keep these two voltages identical at all times. Thus, the lengths of the two arcs are kept automatically the same.

Plasma generation:

As a rule, argon is used as a plasma gas; it has established itself as the standard bubbling and stirring gas in steelmaking applications due to its absolutely inert behaviour towards steel. Since argon has a low ionization threshold compared to air or nitrogen, it vastly improves the re-ignition properties of the arc and causes it to operate in a particularly stable manner. As a result, argon arcs are much less susceptible to extinction and can be more effectively controlled than conventional electrode heating systems – this is important if one intends to prevent systematic short circuits and hence, physical contact between the graphite electrode and the melt. Needless to say, a plasma-heated furnace can also be run on other gases such as, e.g., nitrogen. It can even operate without additional plasma gas, i.e., in the manner of a conventional ladle furnace. However, both of these modes tend to give rise to an instable arc and the controllability of the system becomes similar to that of a conventional electric-arc furnace. Moreover, it has been shown in practice that a systematic contact between the electrodes and the melt needs to be ensured under these conditions if a stable operation is to be maintained.

The argon supply for the arc is ensured by a suitable plasma gas station. For a precise flow control, this station is fitted with temperature and pressure-compensated flow controllers.

Typical plant operation:

The operation of the plasma-heated ladle furnace is almost fully automatic, based on preset parameters. As soon as the ladle is in its operating position, the operator presses the start button. The motion control system is swung over the ladle, the ladle is closed by lowering the lid, and the electrodes, already energized, are lowered towards the melt.

From the position of the last ignition point the electrodes descend at a reduced speed, with the result that the arc will be ignited before the electrode gets immersed in the metal. Once ignition has occurred, the electrodes are automatically pulled up again and the arc voltage is adjusted in line with the settings made during commissioning of the plant. Thereafter, the system adjusts its heating power to the preselected setpoint or, in "high power" mode, to the maximum acceptable current level. The operator can adjust the heating power by switching to another power stage. This causes the electrode to move to the optimum discrete position determined for that stage in the commissioning process. Only some allowance for electrode wear may be made by moving the electrodes that little extra distance. Thanks to this technology, the furnace runs at its maximum efficiency at all times.

Upon completion of the heating cycle, the electrodes are withdrawn from the furnace and the lid is raised. Thereafter, the entire heating system is swung away sideways so that the ladle can be removed by crane. Fig. 2 shows the plasma-heated ladle furnace in operation.
Ladle metallurgy:
For final adjustment of the melt analysis, alloying elements can be added into the plasma-heated ladle furnace. The heating lid possesses a charging orifice connected to a dosing system for this purpose. Manual or wire-fed alloying is only carried out with the system de-energized and locked out. In the power range provided, such alloying work is unproblematic. It is also possible to add slag formers through the charging orifice; the slag thus obtained can then be kept hot, e.g., for a de-sulphurizing treatment. Here the melt-slag reaction is assisted specifically by argon bubbling of the ladle through a bubbling plug in the ladle bottom, which promotes a continuous exchange of substances between the slag and the melt. Temperature measurements and melt samples can likewise be taken through the charging orifice with the system de-energized.

Prevention of carburization:
In metallurgical terms, steel carburizes only through direct graphite-to-melt contact. Diverse studies show that carburization from the gas phase – e.g., by sublimated electrode graphite – takes place so slowly as to remain undetectable by analytical equipment. On the other hand, if the electrodes get immersed repeatedly in the bath or if melt splatter in the arc area becomes so intense that steel keeps running down the electrodes, some carburization of the melt will be inevitable. This is precisely where the plasma-heated ladle furnace has its main benefits. With a stable arc running on a single-phase supply, any active electrode-to-bath contact is avoided; in conjunction with distributed argon bubbling, this allows the melt to be heated without carburization of the metal. This characteristic of the plasma process quite significantly expands its application range when compared with three-phase arc heating, since it greatly facilitates the holding and superheating of steels of very low carbon contents.

Specification

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Ladle load:</td>
<td>min. 7 t, max. 15 t</td>
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<tr>
<td>Heating rate at 15 t charge weight</td>
<td>max. 3 K/min.</td>
</tr>
<tr>
<td>Bath temperature</td>
<td>max. 1780 °C</td>
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<tr>
<td>Plasma furnace heating output</td>
<td>max. 1600 kW</td>
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<tr>
<td>Connected load</td>
<td>2150 kVA</td>
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<td>Number of plasma electrodes / arcs</td>
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<td>Electrode material</td>
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<td>Electrode diameter</td>
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<tr>
<td>Electrode current</td>
<td>max. 8 kA</td>
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<tr>
<td>Arc voltage range</td>
<td>70-100 V</td>
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<tr>
<td>Plasma gas</td>
<td>argon</td>
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<tr>
<td>Cooling water demand</td>
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</table>

Comparison between the classic EAF process and the new secondary metallurgy process at Dörrenberg Edelstahl GmbH

By way of example, let us consider the melting process for a 1.2344 hot-work steel (X40CrMoV5-1).

Arc furnace:
1. A 10.5 t load of suitable scrap is charged into the furnace; at the same time, 150 kg of lime is added. This charge is then melted down and superheated to 1600 °C, for which a time of 2h20min. is required.
2. Approx. 300 kg of melting slag is removed and a melt sample is taken for analysis.
3. Slag former (100 kg) is blown onto the charge; at the same time, approx. 100 – 300 kg of alloying element carriers are added. This is followed by superheating to 1700°C within 20 minutes. During this period, the alloying elements are dissolved and the melt is desulfurized.
4. A melt sample is taken for analysis. If the specified sulphur content is reached, the charge is deslagged and superheated to 1750°C, then tapped into the ladle preheated to 1150°C. If the specified sulphur content is not reached, the slag is changed and the melt is then held at 1700°C for further desulfurization.
5. During tapping into the ladle (1750°C), around 8.0 kg of slag former are added.
6. This is followed by a vacuum treatment of the melt in the ladle. Duration: approx. 20 min., start temperature: 1660°C, end temperature: 1550°C.
7. Argon bubbling under atmospheric conditions is performed for a duration of 10 minutes. Thereafter, the melt is cast into ingots at 1530°C.

Secondary metallurgical process:
1. The charge is melted down in the conventional manner, as above. Upon removal of the sample for analysis and a check of the melt composition, the steel is tapped into the ladle after deslagging at 1700°C. At the same time, silicon and carbon carriers are added for deoxidation and reduction of alloying elements from the slag carryover.
2. The ladle is transferred to the treatment stand. The temperature of the steel melt is now at 1610°C. For desulphurization, 240 kg of synthetic lime-aluminate slag is added. From a metallurgical viewpoint this slag quantity is not always necessary, but the slag height of approx. 10 cm results in enclosure of the arcs, which is beneficial to the heating performance and reduces noise emissions.
3. Heating is continued at 1500 kW for approx. 30 minutes. After 7 minutes, the heating process is briefly interrupted to take a sample for analysis as well as a temperature reading. It should be noted here that a significant portion of the heat input is absorbed by the refractory lining of the ladle, given that its preheat temperature is limited to 1150°C.
4. Alloying is performed and the melt is heated to the vacuum treatment baseline temperature of 1630°C. The vacuum treatment is then performed for a duration of 25 minutes; the final temperature is 1540°C.
5. A sample is taken for analysis and argon bubbling is carried out for at least 10 minutes. This is followed by casting of the ingots at 1530°C.

The improvement of the production process resulting from the integration of the plasma ladle furnace is evident from a number of aspects in the above comparison:

- The EAF tapping temperature could be reduced by 50 K in the above-described case; the average reduction amounts to 30 K overall. Lining maintenance needs have dropped substantially.
- The tap-to-tap cycle time is 30 minutes shorter on average. This is due chiefly to the fact that the desulphurization treatment has been shifted from the electric arc furnace to the ladle. It should be noted that this time gain is greater with metallurgical more demanding steels than with standard grades.
- The vacuum treatment time has been extended without problems. The necessary treatment times are met in every case.
- While one heat is being treated in the plasma ladle furnace, melting of the next scrap charge can already be started in the electric arc furnace.

The very low carburization associated with heating in the plasma ladle furnace makes it possible to obtain steels with both a low carbon (< 0.05%) and low sulphur (< 0.003%) specification. For example, after refining the steel in the electric arc furnace to, say, 0.016% C, the charge is tapped into the ladle and then heated for 50 minutes. During this time the metal is alloyed and desulphurized. If one allows for a 0.016% increase in carbon due to the added alloy carriers (e.g., FeCr) and a further 0.008% carburization attributable to the carbon-containing refractory ladle lining which occur over the 75 minutes of secondary metallurgical work (including the vacuum treatment), an aggregate carbon increase by approx. 0.024% results from these factors alone. From the final carbon content of 0.04%, it is evident that no further carburization is caused by the heating process itself. The final sulphur content achieved is 0.001%.
A no less important benefit lies in the process reliability gained. Without the ladle heating option, minor equipment malfunctions or variations in the temperature of the preheated treatment ladle could be compensated only by shortening the vacuum treatment or the gas bubbling cycle, given that the necessary pouring temperature had to be maintained at any rate. With a plasma-heated ladle furnace, the melt can be heated anytime, even for longer periods where necessary. The service life of the ladle has not been affected by the integration of the plasma-heated ladle furnace. Prior to its installation, only one vacuum treatment with subsequent argon bubbling was carried out in the ladle before the steel was poured; the same refractory lining and a similar alloying program were used. Now, the substantially longer steel dwell time in the ladle and specifically the melt heating process have no negative effect on the service life of the refractory ladle lining. This is due, among other factors, to the use of only two electrodes (instead of three in the conventional 3-phase ladle furnace) which results in a greater distance between the electrode and the ladle wall. This makes for lower local temperature loads.

**Conclusion**

The secondary metallurgical tasks first mentioned above proved fully achievable with the integration of a plasma-heated ladle furnace at Dörrenberg Edelstahl GmbH. The expected benefits in terms of overall process improvement were successfully obtained. Especially with fairly small ladles, the plasma technology offers decisive advantages over the conventional three-phase electric arc ladle furnace, so that this technology has great appeal to smaller mills making special steels but also to the increasingly widespread number of "micro mills" using a coreless induction furnace as the main melting source. Another outstanding technical feature of the plasma heated ladle furnace is that it eliminates the time-related carburization effect that is an inevitable characteristic of conventional ladle furnaces.

**Literature**