Optimization of Steelmaking Production for API Grades Through EAF and Conventional Caster Route

ArcelorMittal Lázaro Cárdenas Flat Carbon Steel Producing Division is a unique conventional slab producer with electric arc furnace (EAF) production based on 100% direct reduced iron. Through continuous practice and equipment improvement in the past decade, it has become a leading slab producer for API applications. The steelmaking route via EAF + ladle metallurgy furnace + RH degasser with special know-how guarantees extremely low S, low P, low N, low H as well as low residual elements. Established casting practices and machine maintenance procedure ensure slab internal and centerline quality with excellent steel cleanliness required by API applications. This paper summarizes the continued technical efforts.

It is well known that the world steel slab market has become much more demanding nowadays in terms of steel quality for specialized applications that require tight controls of elements such as phosphorus, nitrogen, hydrogen, sulfur and other tramp elements, as well as the Ti/N ratio in some cases. For as-cast semi-products, the surface and internal quality as well as shape and dimension of slabs must also meet very tough requirements. ArcelorMittal Lázaro Cárdenas Flat Carbon Steel Producing Division is a unique conventional slab producer of five million tons annually with electric arc furnace (EAF) operation based on 100% direct reduced iron (DRI) feed. Through continuous practice and equipment improvement in the past decade, it has moved gradually up the value chain from a low-end slab supplier to become a leading slab producer of heavy-gauge API grades for the toughest environment applications and advanced high-strength steel (AHSS) grades, including the third generation, for the U.S. automotive industry via ArcelorMittal-Nippon Steel’s joint venture in Calvert, Ala.

Fig. 1 shows the normal production route for the API, AHSS and other tough high-strength, low-alloy (HSLA) grades. The steelmaking shop receives DRI directly from Midrex and HYL units next door and charges into four 250-ton EAFs. In a normal case, 270 tons of DRI is applied for the production of one heat of 220 tons of steel. Due to the lower %P, N, S and tramp elements (Cu, Ni, Cr, V, Nb, etc.) contained in this alternative iron unit against scrap charge, the steel’s chemical specification can be properly controlled from the start of the production route. Under normal conditions, the %S in the DRI is 0.002%, while %P is about 0.045%, and the N can be as low as 8 ppm.

After EAF melting, the liquid steel is tapped into a 220-ton ladle and moved to one of the three ladle metallurgy furnaces (LMFs) followed by RH or vacuum tank degasser (VTD) treatment. The heat then is sent to one of the two 2-strand conventional slab casters. In order to guarantee the best centerline quality, caster No. 2 underwent a major revamp to be equipped with dynamic soft reduction (DSR). Since most of the new grades are designed with more and more alloy content, the slabs have become much more crack-sensitive. Hence, for a slab supplier, Lázaro Cárdenas has installed a slab slow cooling facility to enable a variety of slow cooling practices.

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The steelmaking route via EAF + LMF + RH with special know-how guarantees extremely low S, low P, low N, low H, as well as low residual elements, which are typically high for EAF operations with scrap charge. Established casting practices and machine maintenance procedures ensure slab internal and centerline quality with excellent steel cleanliness required by API applications. This paper summarizes the continued efforts through technical improvement. This trend will continue, as Lázaro Cárdenas Flat Carbon operation has signed a contract with Primetals Technologies to start up a new 2.5-million-ton-per-year hot rolling mill in 2020. This is expected to put more pressure on steelmaking operations to produce quality slabs to feed the advanced rolling mill. In the meantime, it has to produce more value-added grades for ArcelorMittal Flat Carbon Americas internally and for the external slab market.

Steelmaking and Casting

How to Reach Extremely Low Levels of Tramp Elements

— The adverse effects of harmful tramp elements for rolling operations and final properties of flat products cannot be underestimated. Elements such as Cu, S, P, Cr and Ni can be brought into steel from the scrap supplies, which is the reason most of the EAF operations with scrap charge cannot make highly demanding steel grades. Luckily, these residual elements are well under control at Lázaro Cárdenas because of its 100% DRI charge. Table 1 shows the tramp elements typically obtained in the steel grades using 100% DRI, which is almost unimaginable for scrap-charged EAF operations.

Some of these tramp elements can also be brought in from ferroalloys or artificial slag-conditioning agents. Care must be taken when balancing the raw material cost and tramp element contaminations. Because these elements cannot be removed once they appear in the steel, the only way to reduce them is the reduction of their intake. In any case, at Lázaro Cárdenas the level of tramp elements in steel can match or even exceed those of integrated steel plants with blast furnace (BF) + basic oxygen furnace (BOF) operations.

How to Reach Extremely Low Levels of P — Slabs from Lázaro Cárdenas contain low P to achieve better mechanical properties. There are three key points at Lázaro Cárdenas to maintain this extremely low P:

- The proper control of the raw materials quality for steelmaking is mandatory and the selection starts from iron ore going into the pelletizing plant. Choosing a good blend from a local mine that contains very low P in the ore is the first step. This is the main reason why API steel grades are produced with 100% DRI. There is no another option in terms of P in this case.
- The second point is good running foaming slag with the correct slag chemistry and oxidation state at the early stage of the meltdown. Low temperature and high oxygen potential create the right condition for removing P further.
- The third key is to prevent P reversion from carryover slag into the ladle. This is achieved by maintaining good taphole condition and by using a slag vision camera to minimize slag carryover amount. When the tapping time is at about 6 minutes, the slag carryover is minimal, as shown in Fig. 2.
With the ferroalloy additions going higher and higher in newly developed steel grades, the potential of P contamination increases drastically. Any intake of P into the steel after the EAF can hardly be removed because of the unfavorable thermodynamic conditions. Therefore, a good alloy purchasing and monitoring program is necessary to ensure these elements are within specifications from different suppliers. In the case of extremely high-alloy and high-demanding grades, the best quality alloys must be added. An example is the use of a large quantity of electrolytic Mn as an assurance to achieve the best final properties in the products.

An example of P change through the steelmaking process is given in Fig. 3. The final P in the sample from the mold can be in the 50 to 60 ppm range or even in the lower 40s in some cases. Fig. 4 shows the %P histogram in a highly alloyed API grade made in the first half of 2017. The average P in these 516 heats is 78 ppm. It should be noted that the customer specification for upper limit of P is 150 ppm.

**How to Reach Extremely Low Levels of N** — As mentioned earlier, one of the main advantages in the steelmaking shop is the usage of 100% DRI with high %C (2.30–2.70%). It is very important to have very low nitrogen content at meltdown. The previous study in the shop showed that the higher the %C in the DRI, the lower the nitrogen content in liquid steel at meltdown. For example, with 2.80%C in the DRI, the nitrogen content at meltdown was typically only between 10 and 20 ppm. The CO formation when using high-carbon DRI promotes the vigorous CO bubble generation throughout the process without the necessity to use carbonaceous materials for the foaming slag. This CO gas helps to protect the metal bath from the air infiltration, providing a barrier between the steel and the atmosphere. The vigorous CO formation can take place even before the EAF power-on, preventing nitrogen absorption at the early stage of the EAF operation.

In the meantime, CO bubbles can take the nitrogen out of the steel bath and release nitrogen into the atmosphere. However, starting from the EAF, special care must be taken to maintain N in the lowest range. One of the key steps is preventing N₂ reversion at tap. During EAF tapping, the taphole must be well maintained to ensure a tight steel stream, which can help minimize the N pickup from the atmosphere.

At the LMF, quick production of fluid basic slag can reduce N pickup and achieve better desulfurization at the same time. The aforementioned alloy quality monitoring program will help with low N as well. Ar
bubbling is a must for a number of purposes during LMF processing. Too much Ar flow can create an open eye and expose the liquid steel to allow N pick-up. Due to good solubility of N in steel, RH or VTD removal of N at low N level becomes difficult.

N reversion can also occur at the caster. With submerged-ladle exchange practice and good tundish furniture design, exposing of the liquid steel to the atmosphere is well under control at Lázaro Cárdenas.

An example of N change through the steelmaking process is given in Fig. 5. The final N in the sample from the mold can be in the 30 to 40 ppm range or even in the lower 20s in some cases. Fig. 6 shows the %N histogram in a highly alloyed API grade made in the first half of 2017. The average N in these 516 heats is 41 ppm. It should be noted that the customer specification for upper limit of N is 80 ppm.

How to Reach Extremely Low Levels of S — For API grades, the fracture toughness is a critical requirement. It has long been recognized that the presence of sulfur, which forms elongated manganese sulfide stringers, is highly detrimental to toughness. Depending on the toughness requirements for a particular project, the sulfur level will be restricted accordingly.

In EAF processing, the high oxygen potential is unfavorable for S removal. Therefore, the key in low-tap %S of course will rely on raw material feed of DRI, which can be better controlled compared with scrap-charged EAF operations. The control of %S in the fluxes used is another key factor to promote the lowest %S in the EAF process.

For the LMF, the oxygen activity at the beginning of the process must be low to reach the best conditions for sulfur removal. Hence, slag treatment is mandatory to reach extremely low oxygen potential. The indication of oxygen activity in the slag is the FeO+MnO content. The lower the % (FeO+MnO) in the initial slag, the higher the sulfur capacity $L_s$. Therefore, in the LMF process upon ladle arrival, the slag is immediately treated using Al shots, CaC$_2$, alumina or CaF$_2$. Table 2 shows the typical slag composition for these API steel grades. This slag system has very high sulfur capacity and good fluidity at the same time for de-S kinetic conditions and inclusion absorption.

Another key to quick removal of S is the strong mixing between slag and steel at the initial stage of desulfurization. At Lázaro Cárdenas, Ar gas is blown into the ladle with two porous plugs at a flow rate of 30 m$^3$/hour in each plug to achieve good mixing and slag emulsification.

### Table 2

<table>
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<th>Ladle Metallurgy Furnace (LMF) Slag Chemistry for API Steel Grades</th>
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However, it’s very important to control the Ar flow-rate once the chemical composition has been adjusted in order to avoid steel reoxidation. After the last ferro-alloys addition at the LMF, an intense Ar bubbling must be maintained for a short time to promote good mixing and inclusion agglomeration. After the final Al adjustment, the Ar flowrate is decreased to the minimum at the Ca injection stage. It is very important to carry out Ca injection as sulfur in the steel is lower than 0.005% for better sulfur removal effect⁴ and to maintain an adequate composition of the slag. After Ca injection, 5–7 minutes of Ar rinsing is carried out by a gentle bubbling for inclusion removal to achieve the best clean steel level.

Fig. 7 gives an example of %S change through the steelmaking process. The final %S in the sample from the mold can be in the 10 to 20 ppm range or even below 10 ppm in many cases. Fig. 8 shows the %S histogram in a highly alloyed API grade made in the first half of 2017. The average %S in these 145 heats is 17 ppm.

How to Reach Extremely Low Levels of H — With the RH or VTD process, hydrogen can be removed easily under deep vacuum. According to kinetic calculations, the effect of the vacuum time on hydrogen removal efficiency based on the incoming hydrogen in steel is given in Fig. 9. To guarantee the maximum 2.5 ppm hydrogen requirement for heavy-gauge API steels, a minimum of 15 minutes on high vacuum (<1.0 torr) is applied as standard practice in anticipating occasional incoming 6 ppm H.

However, it is still desirable to have very low incoming H in steel to give more operation flexibility at the RH or VTD. Previous studies have shown that a good way to minimize hydrogen at the EAF is to minimize the quantity of carryover slag.⁵ Fig. 10

Example of %S by process step.

Histogram of S in a high-alloy API grade.

Effect of degas time and initial H on H removal.

Tapping time, taphole diameter and final H.
shows the correlation between the tapping time, the taphole diameter and the final H in the steel. It shows clearly the advantage with a tapping time slower than 6 minutes. With all the efforts, the final H in tundish becomes extremely low, which is averaged at 1.2 ppm in 24 heats of a special API grade, as an example given in Fig. 11.

How to Reach Extremely Low Levels of Inclusions — API grades also require excellent steel cleanliness and smaller inclusion size to achieve best performance for sour gas applications and to pass the toughest ultrasonic testing (UT) at the welding zone, as well as the inclusion modification per Ca treatment to reduce MnS stringers in the rolled plates and to generate liquid CaO-Al₂O₃ inclusions to reduce nozzle clogging at the caster. It is well known that all the steps from the LMF to the caster are important to make superclean steel not only in the liquid steel, but also in as-cast slabs.

As mentioned earlier, at the LMF, a gentle Ar bubbling of a mandatory 5 to 7 minutes is undertaken in practices for all API grades after Ca treatment. The key here is to accurately control the Ar flow rate into the ladle to make sure there is no open eye while maintaining the stirring. So a solid program of porous plug and Ar feeding pipe maintenance is needed for consistent results.

The final RH/VTD process step becomes even more important for steel cleanliness in modern steelmaking and it is decided that, for all API grades, this step cannot be skipped; even the steel incoming H can meet the specification.

At the caster, the key is to prevent steel reoxidation. Therefore, a number of practices are put into place to shorten the tundish mixing time at ladle exchange, avoid steel/slag mixing in tundish as much as possible, cover the open eye around ladle shroud and improve tundish furniture design.

With these practices implemented at all process steps, the total oxygen in the pin samples from the mold can be below 20 ppm, which is a world-class level for Ca-treated steels. An example is given in Fig. 12, showing the total oxygen variation in the last heat of a cast sequence of API grade. The automated inclusion analysis was also made with ASCAT® on lollipop samples from the mold taken with 100 tons of steel left in the ladle from the same heat.

Fig. 13 is the oxide inclusions ternary CaO-MgO-Al₂O₃ diagram, with the average chemistry showing on the top left corner and the red diamond on the ternary diagram, which is inside the liquid range circled by the red line. It should be mentioned that the red dot is the average of all inclusions and the inclusions in the size range from 2.5 to 5 mm (green dots) are heavily concentrated inside the red line. This indicates that the majority of the inclusions in this size range are liquid, achieving the purpose of Ca treatment. Fig. 14 shows a sulfide inclusion ternary diagram of Ca-Mn-S. The sulfides are almost all CaS, also reaching the goal of inclusion modification. Steel cleanliness in the liquid steel is only the first step, while the accumulation of inclusions/Ar bubbles in the as-cast slab is equally important for API steel grades. Hence, mold flow control through the optimized flow control system and casting practices become the key to improve the situation without mold electromagnetic stirring (EMS) at Lázaro Cárdenas.

How to Reach Best Centerline Quality of As-Cast Slabs — The DSR segments were combined with improved secondary cooling control for the No. 2 Caster, which applies the correct amount of thickness reduction at the right moment of slab final solidification point depending on casting speed and superheat. This not only reduces potential centerline porosity, but also reduces centerline segregation as well as large-sized precipitates such as TiN, Nb(CN) and MnS.
Although DSR can take care of slab centerline with speed variations, it is still desirable to cast slabs at a constant speed with close-to-constant superheat. This requires excellent coordination among all process steps from the DRI units to the casters and a good shop scheduling program and ladle management system. With these combined efforts, the centerline quality of API grades can be guaranteed. Table 1 shows an example of the internal quality obtained in the slab produced after electrolytic macroetching, while Fig. 15 shows the statistics based on Mannesmann-Demag centerline rating on longitudinal samples of a special API grade.

### Slab Slow Cooling and Handling

The integrity of the slabs must be sound enough to allow heavy load when being placed at the bottom of a slab stack and long-distance travel to reach customers.

### Table 1

<table>
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<tr>
<th>Slab</th>
<th>Central segregation</th>
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in addition to the appearance of slabs, including straightness, shape and dimensions. Issues such as surface cracking, internal cracking, centerline soundness and slab dimension can be dealt with at the caster by optimizing casting practices and mold cooling. However, with new alloy designs for highly demanding applications, some API steel grades become more crack-prone after casting. Therefore, a slab slow-cooling program was developed that includes slab stack cooling and box cooling to allow slabs to cool more uniformly to reduce thermal stress and residual stress.

A variety of combinations of number of slabs per stack, box insulation thickness, stacking timing and casting practices, etc., were monitored by thermocouples to understand the slab cooling behaviors of different steel grades. This study helped to develop optimized slow cooling practices to speed up the slow cooling without compromising slab integrity in order to reduce inventory and improve logistics.

After slow cooling, the handling and transportation of slabs become critical. At Lázaro Cárdenas, a workable practice was developed that involves trucking, crane moving, boating of slabs at varied transition points for gentle handle and loading of slabs to reduce any potential damages to any slabs in the slab stack. As such, all slabs can reach the hands of customers in the best form for rolling.

Conclusions

API and AHSS steel grades demand very low %P, S, N and H, as well as clean steel for inclusion size, number and correct modification. Usage of 100% DRI in EAF operations has been a very important advantage for ArcelorMittal Lázaro Cárdenas to successfully produce these steel grades along with a very low tramp element content of Cu + Ni + Cr + Sn less than 0.05%. However, many efforts have been tailor-made for this unique production route in terms of equipment investment and technique/practice improvements. The steelmaking route via EAF + LMF + RH with special know-how guarantees extremely low S, low P, low N, low H, as well as low residual elements, which are typically high for EAF operations with scrap charge. In continuous casting, the DSR segments combined with improved secondary cooling control for the No. 2 Caster applies the correct amount of thickness reduction at the right moment of slab final solidification point, depending on casting speed and superheat. This not only reduces potential centerline porosity but also reduces centerline segregation so that large-sized precipitates such as TiN, Nb(CN) and MnS can be minimized.

Details of how to achieve the best quality steels are summarized in the paper. It is obvious that a strategic general view must be carefully given in handling each element mentioned at every process step with the consideration of overall shop operation and cost control. Sometimes, a condition that favors removing one element is not always good for other elements. One key aspect before the order is given to production is the proper selection and balancing of raw materials at each process step. Then, timing restriction and temperature control of every step need to be carefully planned in anticipating unexpected problems based on daily operation conditions. Maintenance of all equipment involved is very important in keeping the completion of each step on time.

All the care and know-how mentioned above enable Lázaro Cárdenas to successfully achieve the production of API steel slabs that meet the toughest requirements of its customers.

References