INDUCTION FURNACE VERSUS ELECTRIC ARC FURNACE IN STEELMAKING PROCESS; ADVANTAGES AND DISADVANTAGES

BY

KOBLENZER HARALD *

VUCINIC BOJAN **

SYNOPSIS

Available raw material and energy, socio-economic development, industrialization level, steel export versus import policy, required product mix from steel quality point of view and electrical network condition are just few of lot of variables needed to be considered in order to define Best Available Steelmaking Technology.

High demands from steel quality point of view, possibility to have controllable operational costs with different charge material together with strong year to year process control improvements are reasons for high application of electric arc furnaces.

Purpose of this study is to compare different steelmaking process routes highlighting advantages and disadvantages between them and to show developments over the past few years.

In addition, considering the transition period in World Wide steelmaking business few different process routes from different projects with induction and electric arc furnace application are described.

**Keywords**: Induction furnace, Electric arc furnace, steel quality, flexibility, operational cost

* Vice President DCM Process Technology, Danieli & C. Officine Meccaniche S.p.A, via Nazionale 41, Buttrio, Italy, 33042
** Senior Steelmaking Engineer, Danieli Changshu Metallurgical Equipment & Service Co. LTD. No. 19, Xing Gang Road, CEDZ Changshu, Jiangsu 215513
INTRODUCTION

Raw material availability and price, raw material purchasing strategy, market condition, geo-political and economy situation in states or regions, export and import policy, labour cost are just few variables which have to be considered before taking a correct decision regarding a steelmaking process route. Globally, the main two primary steelmaking furnaces are oxygen blowing converter and electric arc furnace (AOD converter from the author side is considered as secondary metallurgy equipment). Strong economy progress in China followed by strong industrialization, big infrastructure projects and high needs for steel together with low ore and coke prices resulted in much higher presence of integrated plants equipped with oxygen blowing converter. For example, in 2004 World Wide steelmaking production via electric arc furnace was 31.9% (from total crude steel production). During the 2005-2014 period, participation of steel production via electric arc furnace was increased, for example, in Italy for 12.3%, in USA for 7.5%, in Russia for 14.3%, but a due to strong increase of steelmaking production in China mainly with oxygen blowing converters, crude steel production with electric arc furnace at the end of 2015 was 25.1%. At same time, for example, the steelmaking situation in India was little bit different: about 56% of the total steel production in India is made using electric route. Out of this 56%, 22% of steel was made on electric arc furnace and rest by induction furnace (1).

In order to have a proper comparison between different equipment in steelmaking production, some variables have to be considered as fixed and can not be considered for BAT evaluation (local government policy, foundry vs. melts shop, etc...). Also, for proper evaluation between induction furnace and electric arc furnace, mini-mill steelmaking concept has to be considered in order to avoid talking about application of primary furnace in foundry or for process with non-continuous casting sequences. A recent example of the impact of local policy on steelmaking in China to replace induction furnaces with electric arc furnaces mainly to use available scrap for production of high quality steel grades instead of low quality grades only.

COMPARISON OF INDUCTION VERSUS ELECTRIC ARC FURNACE

When a foundry or a melt shop is choosing between induction and electric arc furnace, the main questions which have to be answered are:
- Available raw material (from material quality point of view and forecast regarding material availability).
- Raw material price – forecast.
- Product mix and impact on steel cleanness
- Operational costs.
- Required labour profile and their availability.
- Labour costs.
- Available area / footprint.
- Future melt shop expansion.
- Environmental regulations and cost.
- Investment and breakeven analysis
Steel chemistry – comparison:

The major difference between the compared melt processes is the ability to use different quality of charge material. It is well known that during melting in induction furnace all refining processes are limited, so the required steel chemistry per steel grade can be only achieved with a proper scrap selection which results in a limited product mix or higher production cost by using more expansive and cleaner scrap. For sure, a lot of trials and studies have been done in the past in order to improve refining part of process but results still are not comparable with results what can be achieved with EAF process.

Thanks to the possibility to use slag builders and oxygen, during the electric arc furnace process is possible to reach low phosphorous and low / controlled carbon content at the end of the refining period. In the figure 1 is reported the phosphorous content at the end of primary melting process for rebar and high quality grades via electric and induction furnace processes and in the figure 2 is reported phosphorous and carbon content after tapping for 80 heats in an induction furnace melt shop sequence.

Figure 1: Phosphorous content after primary steelmaking process

Figure 2: Carbon and phosphorous content after tapping from induction furnace (rebar steel grade)
As can be seen from figures 1 and 2 phosphorous content during mainy rebar grades production via induction furnaces is in a range of 0.02-0.03% with carbon content in range of 0.18-0.22%.

Sulphur removal during EAF process is limited not due to lack of refining capability but mainly due to the presence of high oxygen content and higher oxides content in the slag. During the induction furnace process due to low slag basicity and low slag volume sulphur removal is not present.

Due to the lack of refining capability with induction steelmaking process, induction furnaces are mainly present in rebar production with required carbon content in range of 0.20%-0.25% and with required phosphorous content of max 0.035%. Application of induction furnace in production of high quality grades is not standard yet, except for stainless steel grades with stainless steel scrap melting for small heat sizes, for high alloyed steel production (small heat size) or for ferro alloys melting process.

- Electrical energy consumption – comparison:

Compared with EAF, induction furnaces have the following characteristics (2):
- High and relatively narrow melting vessel (low d / h ratio).
- Low crucible wall thickness.
- Low slag temperature.
- Powerful bath motion.

There are two main challenges for induction furnace units:
- Availability of raw materials.
- Electrical energy consumption

Shredded scrap as type of charged material is considered to be the best input material due to its high density and lower melting losses. However, this type of scrap has some tramp elements such as aluminium, copper, nickel, zinc, chromium, etc...Aluminium, zinc and chromium could be removed completely or partially by oxygen which is one limitation more for their application in induction furnace process (3).

Electrical energy consumption for scrap melting process via induction furnace is higher compared with EAF process. In figure 3 is reported electrical energy consumption for induction furnace process (reference plant IF-A) versus electric energy consumption for two different scrap melting processes via electric arc furnace (EAF-A; EAF-B).

As can been seen from figure 3, electrical energy consumption for induction furnace mainly is in range of 550-650kWh/t. During EAF process electrical energy consumption is less.

Thanks to the possibility to use oxygen and fuel during EAF process, electrical energy consumption is less compared with consumption during IF process. Electric arc furnace can be designed for different scrap charging methods, different operational practice and with application of advanced process control which has strong impact on reduction of electrical energy consumption.

Reduction of electric energy consumption during IF scrap melting process is limited mainly by the operational practice and by the type of applied scrap (shdredded scrap is for example benificial scrap from an electrical energy consumption point of view).
Lots of operational practices are implemented in order to reduce electrical consumption. Below are listed some of practices useful to control the ratio between power on and power off and to reduce overall energy consumption:

- Initial scrap charging by bucket.
- Power on control during de-slagging operation.
- Ensuring full crucible before tapping.
- Minimum holding time.
- Proper scheduling of furnace.
- Scrap quality.

Proper scheduling of furnace is reported on figure 4 (IF-B). Three induction furnaces are in cycle in order to provide tap to tap time per each ladle in 45 to 50 minutes. Time between end of power on versus power on start for the next heat is in range of 10 to 15 minutes including tapping. On this way, proper refractory thermal conditions will ensure less energy consumption.

Another example of operation practice and its impact on energy balance on induction furnace process is reported on figure 5(5).

As can be seen in the figure 5, in case of cold induction furnace (cold start up) total energy losses are increasing mainly due to accumulated energy through the refractory. Also, by keeping cover in open position, total energy losses are higher as well.
From a productivity point of view electric arc furnace has advantageous compared with induction furnace. Thanks to the latest improvements, the process is controlled from an energy and mass balance point of view. With sampling and temperature measurements during power on time together with applied additional tools in operation it is possible to minimize power-off time and to reduce consumption of electrical and chemical energy. Compared with IF’s instead of application of two or three furnaces very high productivity with short tap to tap time (less than 40 minutes) can be achieved with one electric arc furnace.

- **Man power – comparison**

From manpower / workforce point of view electric arc furnace is more beneficial. For advanced EAF with automatic sampling, automatic EBT refiling and tapping system, the number of operators could be reduced to a maximum of three including crane driver on the charging platform. By using automatic scrap charging system (bucket process) it is possible to have crane driver in pulpit as well together with furnace operator. In case of medium frequency induction furnace, due to overlapping from process point of view between two furnaces and the needs to have continuous charging during melting process number of operators and chargers is higher.

- **Environment - comparison**

During best available technology evaluation it is not enough to make comparison from investment point of view only. Healthy and safety conditions together with pollution control must be considered as well. As we can see on photo #1 induction furnace has to have housing for dust and fume collection. At same time, from environmental point of view EAF is equipped with quenching tower, cyclone and
filter (fines de-dusting) together with possibility to install heat exchangers, for example.

Photo 1: Induction and electric arc furnaces in operation

For example only, on the next picture is reported tapping from EAF versus tapping from IF.

Photo 2: Tapping from electric arc and from induction furnace

- Operational cost – comparison

Main differences from operational cost point of view between EAF and IF are:
- Electrode consumption during EAF (different for different charge mix and depending on type of electrode cooling system – could be less than 1.4kg/t for example for scrap bucket process)
- Slag builders consumption during EAF process (higher operational cost but benefits from steel quality and from EAF refractory life time)
- Oxygen and fuel consumption during EAF process (required for steel quality and to reduce electrical energy – to replace electrical with chemical energy).
- Higher electrical energy consumption for induction furnace process (in range of 550÷600kwh/t compared with 340÷420 kWh/t for electric arc furnace for scrap based process for different charging practices).
• Electrical network – comparison

Impact of type of steelmaking process on electrical network is different for different type of applied equipment and process. Flicker formation is directly influenced by:
- Designed process cycle (bucket process or continuous scrap charging system with or without preheating or flat bath condition).
- EAF power system (alternating or direct current – AC or DC furnace)
  Type of furnace (AC or DC furnace) together with charged material and way how material is charged are described in flicker formation with dedicated coefficients which are different for different material and type of charging:
  a) The biggest impact on flicker formation has presence of heavy melted scrap with bucket charging process.
  b) Application of light scrap will reduce flicker formation.
  c) Flat bath process will reduce flicker formation.
  d) Application of DC furnace as result has less flicker formation compared with application of AC EAF with same process and same charge material.
- Application of compensating equipment to reduce flicker (e.g. SVC).

PROCESS AND PRODUCTION FLEXIBILITY

Having proper flexibility from process and production point of view means to be able to manage running costs based on:
- Possibility to produce different steel grades.
- To be present on the market with high quality product with competitive price:
  o Low running costs.
  o High productivity.
- Possibility to use different charging mix.

• Process flexibility:

EAF process is confirmed process for different charge material including:
- Different type of scrap,
- Continuous scrap charging system:
  o Scrap preheating
  o Continuous charging of shredded scrap
- HBI; DRI or pig iron
- Hot metal

Application of material such as pig iron will reduce electrical energy consumption by having presence of higher chemical reactions in the system. The same is with hot metal where oxidation of carbon, silicon together with high enthalpy already present in system with hot metal will reduce electrical energy consumption.

In the figure 6 is reported impact of different charge mixes on electrical energy consumption of EAF (6).

As can be seen from figure 6 the lowest electrical energy consumption is with application of hot metal but at same time due to presence of carbon and silicon for example, oxygen consumption is highest. Also, on the same figure we can see
different electrical energy and oxygen consumption for different application of solid charge mix.

Figure 6: Average electrical energy and oxygen consumption for different charge mixes

In figure 7 is reported the average oxygen and electrical energy consumption during EAF process with different hot metal participation in charge mix.

Optimal hot metal participation in the charge mix for given EAF geometry is up to 40%\(^{(4)}\). With hot metal participation up to 35-40%, productivity will increase by keeping same electrical power input. Having more than 40% of hot metal, furnace geometry has to be design in order to be able to apply higher oxygen flow rate and to control violent reactions during main carbon removal period.

Figure 7: Average consumptions and EAF productivity for different hot metal participation.

Compared with induction furnace during electric arc furnace process with same charge mix is possible to apply different practices based on required final steel quality (mainly, phosphorous content) and based on aimed running cost. By increasing chemical energy input the overall thermal efficiency decreases (thermal efficiency is expressed as ratio between steel enthalpy and total energy input) – reported in figure 8 \(^{(7)}\).
Increasing of chemical energy is mainly achieved by the increasing of fuel and carbon input. In order to limit iron losses and to have an under control charge material yield, it is necessary to balance oxygen and carbon addition. However, it is difficult to avoid a residual loss of yield even at high ratio between carbon and oxygen addition, mainly due to faster iron oxide generation compared with reduction kinetics by injected carbon. The best control of needed amount of injected carbon for slag reduction and a proper slag foaming is by application of arc stability measurements.

Low or high applied “chemical energy input practice” has to be developed based on real transformation costs. As it is already described above, high chemical input practice has influence on higher yield losses. On the other hand, low applied chemical input practice requires higher electrical power input which will have as consequence higher refractory wearing index for same furnace geometry. Also, higher power input means higher applied arc voltage and a needed better control on slag foaming by carbon injection. With a proper slag foaming practice and a proper arc covering, harmonics in electrical system are reduced as well.

**Figure 8: Effect of chemical energy input on energy efficiency**

- Production flexibility:

  “While the technology is key to the mini-mill concept, the concept of the mini-mills is more closely tied to a business strategy and management philosophy then it is to technology” (8)

  Apart of equipment design (primary furnace secondary metallurgy station, continuous casting machine), layout is key parameter in order to have high efficient mini-mill shop from high level and repeatable productivity point of view.

  On the next figure (figure 9) is demonstrated compact layout with induction furnace as primary melting unit (melt shop – A).

  Secondary metallurgy is in line with induction furnaces in order to provide high melt shop flexibility. Observed problems during production mainly are related to the:
  - Difficulties with proper scrap selection from final carbon and phosphorous content point of view
  - Higher steel temperature losses between end of induction furnace process versus ladle metallurgy station mainly due to exposed steel stream...
  - Slag quality prior to the ladle furnace process
Figure 9: Melt shop layout with induction furnace as primary melting unit.

![Image of induction furnace melt shop layout]

Mini-mill concept with EAF as primary unit is reported on figure 10. Electric arc furnace is in line with secondary metallurgy station. Instead of three primary units (as we have at induction furnace melt shop) one melting unit is present only. Designed productivity of primary melting unit is according to required melt shop productivity considering all needed power off operations.

Figure 10: Mini-mill concept with EAF as primary unit.

![Image of mini-mill concept with EAF]

From layout point of view both melt shops have high flexibility. The main difference between them is the impact of the primary furnace on melt shop productivity. In case of an EAF process, the equipment is designed to reach aimed hourly productivity and in case of the induction furnace, the melt shop process overlapping between two or more induction furnaces in operation and chemistry composition before tapping have a strong impact on overall melt shop productivity.

- Quality control:

Due to absence of refining metallurgical process during induction furnace melting, a proper scrap selection from carbon, phosphorous and residual elements point of view is needed. Steelmaking process via electric arc furnace is more flexible due to the possibility to generate proper slag from basicity and Fe-oxides content point of view, to control temperature and to use different charge mixes. In figure 11 is reported a histogram of nitrogen distribution for scrap based process together with nitrogen reduction by using pig iron. 

(6)
As it is reported in the figure 11 expected average nitrogen content before tapping from EAF for scrap based process is in range of 50-70ppm. By using pig iron for example, nitrogen content before tapping could be reduced.

Figure 11: Nitrogen distribution for scrap based process (left graph) and nitrogen reduction by using pig iron for EAF process (right graph).

Existing tendency to employ more electric motors and copper holding electronic elements in the cars will cause higher copper content in recycled scrap. Thanks to possibility to use electrical and chemical energy together during EAF process, it is possible to make different combination of solid and liquid charge mixes. The next figure (Figure 12) shows copper content before steel tapping for process with 80-85% of hot metal (rest part is mainly recycled scrap) versus process with 100% DRI in charge mix (average: 14% cold DRI and 86% hot DRI) versus process with 100% of scrap.

Figure 12: Copper content before tapping from EAF for three different charge mixes
ELECTRIC ARC FURNACE– PROCES CONTROL IMPROVEMENTS

As a metallurgical equipment the electric arc furnace has been improved a lot in order to have high production level and high flexibility from application of different raw material point of view. At the beginning, the EAF has been designed for scrap melting process only, but nowadays is possible to use different raw material. The electric energy requirement of an EAF-based melt shop is largely connected to the melting process and even limited improvements in this field translate into considerable yearly savings for the steel maker.

The electrode regulation system is the technology at the heart of the EAF and plays a very important role in the melting process, as it manages more than 50% of the process power input via the electric arcs. Typically, the system is a servo-hydraulic positioner, which controls the arc length acting on the position of each column. Primary voltage and current acquisition is performed on a small time scale (few microseconds) to allow a proper response to the fast-changing operating conditions inside the furnace. The most used control strategies are based on arc impedance voltage (V) or current (I); the choice between them usually considers different factors:

- Desired maximum active power transferred to the melt.
- Melting process progress.
- Needed control stability.
- Tolerance on transformer technical limits.
- EAF practice.

Electrode lowering movement is controlled by the counter pressure exerted by the hydraulic system.

The real-time fast voltage and current data acquisition and processing also allows the arc status evaluation, which is crucial to ensure a proper foamy slag practice. A proprietary and robust transfer function, based on Fast Fourier Transform of the electric signals, is typically used to qualify the arcs coverage (ACI, Arc Coverage Index) and thus control both chemical and electrical process set-points.

Synergy of tools such as off gas analyzer and mathematical model together with electrode regulation system gives full (automatic) process control during electric arc steelmaking process. Based on continuous online reading of CO, CO\textsubscript{2}, H\textsubscript{2}O and off gas temperature, mass and energy balance are continuously monitored. Automatic process control confirmed already in practice is actually closed loop between mathematical model, real off gas analysis, electrode regulation system and chemical package in order to have safe production and low running costs due to optimized consumptions, high steel quality and high material yield.

Safety improvement, power off reduction, transformation cost control can be improved more by implementation of additional tools such are robots, automatic tapping system, semi-automatic or fully-automatic systems for EBT cleaning and opening, slag door cleaning, sampling, etc…

CONCLUSION

One of the first applications of induction furnace in steelmaking area, for example in India, was for stainless steel scrap melting. During last 30 years this process has been improved from melting control and heat size point of view. In order
to make a good decision regarding application of induction furnace in steelmaking process, proper feasibility study has to be done mainly from:

- Market requirements point of view (required steel quality, quantity, business orientation: local supply or export, etc…).
- Scrap availability (local versus eventually imported scrap).
- Availability of additional material which could be considered for steelmaking process.
- Safety policy
- Environmental policy.
- Required productivity versus optimized melt shop design from type of equipment and layout point of view.

Application of induction furnace as unit for ferroalloy smelting is proven process and strong source for energy saving and reduction of running cost especially during production of stainless steel or high alloy steel grades.

Electric arc furnace compared with oxygen blowing converter or induction furnace is most developed unit for steelmaking process. The flexibility of electric arc furnace in using different material for the steelmaking process, capability to produce high quality grades (including stainless steel), different charging practices, strong environmental control, reduced and optimized electrical energy consumption and fully advanced process control are key factors usually considered during Best Available Technology evaluation.

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