

Intelligent Technologies for Electric Arc Furnace Optimization

Edward Wilson¹, Michael Kan², Anjan Mirle¹

1 – Neural Applications Corporation
2600 Crosspark Road, Coralville, IA 52241
319-626-5000, ewilson, amirle@neural.com
<http://www.neural.com>

2 – North Star Steel – Minnesota
612-731-5698, mike_kan@cargill.com
<http://www.northstarsteel.com>

ABSTRACT

With the Intelligent Arc Furnace™ (IAF®) controller, Neural Applications Corporation (NEURAL®) has already applied neural-network technology to optimize the electrical input for an EAF at more than 30 installations worldwide. The natural extension of this technology is development of an intelligent system for optimization and coordination of all major energy sources. Prototype development is currently underway at North Star Steel - Minnesota (NSS) for an intelligent system that can automatically and adaptively optimize each of the major energy inputs (arc, Oxygen, gas, Carbon).

As the cost of raw materials is often the largest cost in steelmaking, optimization of the charge material mix to obtain the required specification while minimizing material cost and melting cost is also important. Development of NEURAL's ScrapMaster system is also presented.

1. INTRODUCTION

Neural Applications Corporation supplies intelligent-software-based process control technologies to the metals processing industry worldwide, with special emphasis in electric furnace steelmaking.

NEURAL's Intelligent Arc Furnace controller, introduced over 6 years ago, and a scrap mix optimization system, introduced two decades ago, are providing a basis for the development of two new products:

(1) **Furnace Optimization** - The IAF uses a neural-

network electrode regulator to optimize electrical energy input for an AC EAF, optimizing electrical energy, electrode consumption, and throughput. Products presently available are the IAF 350 and ControlTech 2000. A prototype under development at NSS-MN will extend the optimization to include all major energy sources, including arc, Oxygen, gas and Carbon.

(2) **Scrap Optimization** - The scrap mix optimization system, originally a standard linear-programming optimization solution, has been upgraded to handle uncertainty in the material properties. Additionally, new functionality is under development that uses advanced identification technology to refine estimates of each type of scrap based on melt-in chemistry results.

This paper will describe the work presently underway in both of these areas.

2. FURNACE OPTIMIZATION

2.1 North Star Steel – Minnesota

North Star Steel has partnered with NEURAL in the development of the furnace optimization system. The prototype is being developed on the DC EAF at NSS-MN. Following is a brief overview of the NSS-MN meltshop.

North Star Steel Minnesota produces a wide variety of steel grades comprising about 25% rebar, 20% structural, 20% merchant and 35% special bar qualities. The melt shop is equipped with an 86 metric ton (95 short ton) Voest-Alpine DC-EAF, a ladle furnace and a 4-strand continuous caster.

The DC furnace anode design concept uses an array of thin sheets embedded in a monolithic magnesia refractory ramming mass. The first heat from the furnace was tapped in May 1994. The electric power from the 80 MVA transformer is carried by a 0.635 m (28 inch) diameter electrode. The furnace is fitted with a water-cooled oxygen lance with postcombustion capacity, a door burner and a sump burner. Typical tap-to-tap time is 60 min.

86 metric tons (95 short tons) of crude steel are tapped from the DC-EAF at a temperature of 1621-1632 degrees C (2950-2970 degrees F) in four to six minutes. The deoxidation, alloying and slag forming materials are added during tapping. The ladle is then transferred with the melt to the ladle furnace, where the refining

steelmaking practices (temperature and chemical composition adjustment, desulfurization, inclusion control) are carried out.

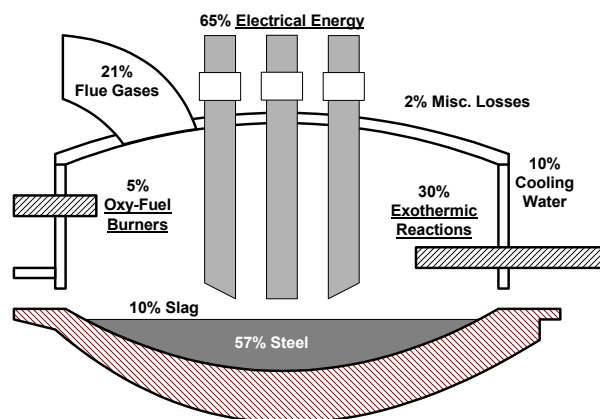
The heats are cast on the 4 strand machine with an 8 m (26 feet) bend section radius. The caster features mold electromagnetic stirring and the stream protection for better internal and surface quality of the billets. All produced grades are cast with mold oil lubrication.

2.2 Intelligent Arc Furnace Controller

The IAF uses a patented neural-network-based electric power regulator to continually adapt to changing operating conditions in order to optimize electric power input. It provides unprecedented supervisory closed loop control and regulation of the arc furnace melting and refining process. The IAF has also proven to be a valuable diagnostic tool for the steelmaker. Its data logging and reporting capabilities allow the furnace operator to view and review the furnace operation in great detail.

2.3 Total Energy Optimization

Currently, the primary source of thermal energy in EAFs is the electric arc (~65% of kWh), with additional energy input from Oxygen-fuel burners (~5%), and other exothermic reactions (~30%) that are supported by injecting Oxygen into the furnace. Presently, energy input setpoint profiles are developed based on the experience of furnace operators, and are non-optimal.



AC EAF, with energy flow indicated

Energy inputs are underlined: 65% Electrical; 30% exothermic reactions supported with blown Oxygen; 5% Oxygen-fuel burners. 57% of this energy input ends up in the steel. Energy losses: 21% is lost in the flue gas as sensible and chemically bound (latent) heat; 10% in the slag layer; 10% in cooling water; and

2% miscellaneous [10].

The basic goal of the research is to control and coordinate the energy inputs to reduce off-gas and cooling-water energy losses so that a greater portion of the energy input is transferred to the steel. Other factors such as production rate, furnace wear, and electrode consumption will also be considered in the cost function used for optimization. Due to the magnitude of the steelmaking process, even small-percentage improvements in efficiency will offer significant value to the steelmaker.

Due to the variability and complexity of the EAF process, accurate optimization must be based on actual operating data. Unfortunately, sensing capabilities are limited and often noisy, requiring significant pre-processing. The steelmaking process is continually changing, as the furnace wears, procedures change, and raw materials change. This requires the data-based optimization system to be adaptive. Fortunately, neural networks excel at nonlinear data processing and adaptation.

In Phase I, data-acquisition and analysis systems were developed and installed at the EAF at NSS - Minnesota to log, transmit, and process the large quantities of furnace data. Various intelligent technologies were investigated and evaluated considering the characteristics of this optimization application and the data collected. A web-browser-based production cost reporting system was developed.

In Phase II, a working prototype control system is being developed that extends and builds on the technologies developed in the IAF and in Phase I. A combination of neural-network, hill-climbing, and conventional-control technologies will be used to develop a total energy control system. This product will optimize a *user-specified* cost function that includes raw-material costs, energy costs, productivity (or furnace throughput), electrode consumption, and furnace life.

It will be possible to change the optimization objective on the fly – for example, if throughput needs to be increased temporarily at the expense of increased electrode consumption and energy costs, or if the cost of electricity is changed.

2.4 Related Research

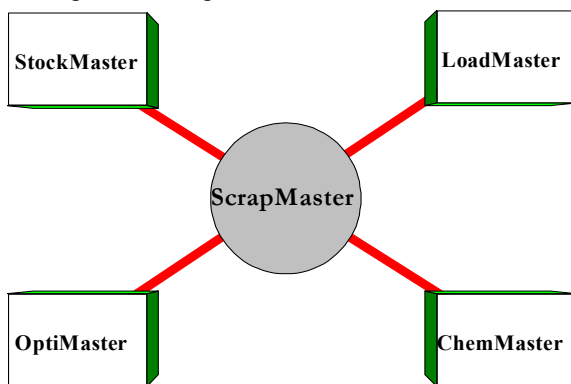
Much related research exists in the areas of postcombustion and furnace modeling, two areas that are central to our approach. This research is summarized briefly in Appendices A and B. There are several factors that complicate this research:

- (1) Combustion optimization will require better knowledge of combustion and postcombustion inside the furnace; however, measurement of off-gases is difficult. Accuracy is highly dependent on probe location, and probe survivability is questionable. In an effort to find an off-gas system that was being used in production for an extended period, we found that most off-gas analysis systems end up being removed after a period of initial testing. This is probably because the data provided does not warrant the expense and maintenance effort. As this article was submitted, a new off-gas probe was being installed at NSS-MN.
- (2) As in all iron and steelmaking processes, sensing of conditions inside the furnace is difficult, complicating development of a dynamic model.
- (3) Many factors affect the EAF process in unknown ways, effectively adding significant noise to any data that is used for modeling and optimization.
- (4) The EAF process is highly complex, requiring any attempt at physical modeling to use many approximations. Given the limitations in (2) and (3) above, it is difficult to validate these approximations and models.

NEURAL is developing models to predict performance throughout the heat (dynamic) as well as the overall heat performance (heat-wise). Both types of models will be used in optimization, and both types will be tied directly to the actual operating data.

3. SCRAP OPTIMIZATION

Handling scrap is one of the most important functions of an electric arc furnace meltshop. Using the wrong grades of scrap will result in higher raw material costs and difficulty in meeting product chemistries. To help convert scrap from a problem into a profit center, NEURAL has developed the ScrapMaster.



3.1 ScrapMaster Overview

The ScrapMaster is a group of four modules designed to automate the scrap planning and tracking functions in the meltshop. These modules interact with each other to optimize the purchase, use, and tracking of raw materials. A mill can select the modules that it needs to solve its specific problems while also retaining the ability to expand the system as needs develop. The modules in the ScrapMaster are:

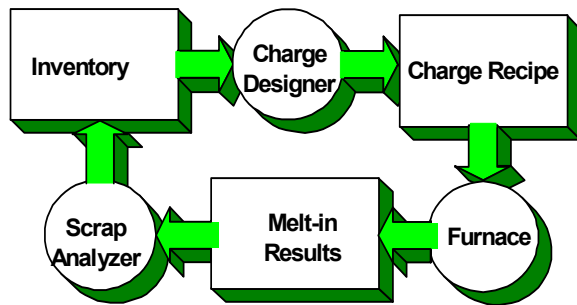
- StockMaster
 - Inventory Control — Tracks scrap material inventory from the point at which it has been ordered, through the scrap yard, and on to the furnace.
- OptiMaster
 - Optimum Charge Design — Develops a least-cost charge mixture using the available raw materials.
 - Material Requirements Calculator — Determines the optimum mixture of raw materials to purchase based upon the heat schedule and the prices and properties of the scrap
 - Heat Scheduler — Produces a schedule of heats based upon customer orders taking into account factors such as elemental carry-over and caster changes.
- LoadMaster
 - Recipe Tracking — Transmits charge design recipes to the crane operator and records the actual materials and quantities used.
- ChemMaster
 - Intelligent Scrap Composition Analysis — Intelligently analyzes the results from the furnace melt-in to identify the actual properties of the scrap materials used.

3.2 ChemMaster

The ChemMaster, presently under development, analyzes the results of the heat melt-in and determines if a specific lot of scrap has an anomalous makeup.

Optimum charge designs are developed based upon the anticipated properties of the scrap. If this information is not valid, the scrap charge designs will not produce least-cost heats that meet the melt chemistry requirements for the desired grade. To close this feedback loop, the

intelligent scrap analysis module (ChemMaster) dissects the melt-in results and correlates this data with the actual material charged to determine if all of the materials used in the heat matched the predicted characteristics.



By using pattern recognition and cross-correlation techniques, the ChemMaster is able to identify material that may potentially be out of specification more quickly than has been previously possible. To accomplish this, the ScrapMaster maintains a database of the results of the melt-in of each heat. This data can be received automatically from the NEURAL IAF, the mill's Level 2 system, or it can be manually entered.

The NEURAL ChemMaster can automatically correct the stored chemistry information based upon the results of previous heats that have used the same materials. This allows for the more accurate design of charges, particularly in the area of residual control.

Any major changes made in the chemistry information for a lot of scrap are reported. A major change is defined as more than ten percent of the concentration of the element in the material. Scrap materials that cause significant variations in the melting energy requirements will also be reported.

4. SUMMARY

Two major research efforts aimed at optimizing EAF steelmaking have been presented. A furnace optimization system that will coordinate and control all major energy sources for an EAF is presently under development at North Star Steel –Minnesota. A scrap optimization system has extensions beyond the standard Linear Programming solution to scrap optimization including (1) the ability to account for variability in scrap properties, and (2) the ability to provide on-line updates of scrap-property estimates based on previous melt-in chemistry measurements.

ACKNOWLEDGEMENTS

The authors are grateful to North Star Steel Co. for their cooperation and support of this research. We would like to thank Dane Meredith, Carl Czarnik, Randy Stillings, Gary Loewenberg, Jeff Gartner, Jack Shinnick, Gary Wettern, Tom Curry, Dave Steidtmann, Harold Olden, Tony Hickl, Wendy Winge, and Mike Coleman for their valuable suggestions and assistance.

REFERENCES

- 1 H.D. Goodfellow: "Future trends in design of EAF fume systems," 5th European electric steel congress Proceedings, 1995, p610-616.
- 2 E.J. Evenson, H.D. Goodfellow and J. Guerard: "Energy optimization and continuous fume analysis at CO-STEEL LASCO – The expert furnace system optimization process (EFSOP)," Electric Furnace Conference Proceedings, vol. 55(1997), Iron and Steel Society, p435-454.
- 3 N.G. Kournetas, A. McLean, I. Sommerville, M. Thomson, J. Guerard: "Effects of post combustion, validated by steel mill demonstration," Electric Furnace Conference Proceedings, vol. 55(1997), Iron and Steel Society, p373-380.
- 4 G. Daughtridge, P. Mathur: "Recent developments in post-combustion technology at Nucor Plymouth," Electric Furnace Conference Proceedings, vol. 52(1994), Iron and Steel Society, p135-138.
- 5 B. Sarma, P.C. Mathur, R.J. Selines: "Heat transfer rates and mechanisms in EAF post-combustion," Electric Furnace Conference Proceedings, vol. 54(1996), p519-537.
- 6 D. Kocsics, P. Mathur, D. Engle: "Results of oxygen injection in the EAF with Praxair Coherent Jet Injectors – a novel technology," Electric Furnace Conference Proceedings, vol. 55(1997), Iron and Steel Society, p305-314.
- 7 Nicolas Perrin, Michel Devaux, Karl-Heiz Klein, Jan-Erwin Schindler: "Industrial use of ALARC-PC™ post-combustion technology worldwide," 5th European electric steel congress Proceedings, 1995, p99-109.
- 8 Frank Sloopman, Marc Buffenoir: "Effect of post-

combustion on the heat balance of an electric arc furnace," 5th European electric steel congress Proceedings, 1995, p630-633.

- 9 Manfred Reinhardt, Dieter W. Reiber: "Practice of ALARC-PCTM post-combustion at Von Roll Ltd., Gerlafingen," 5th European electric steel congress Proceedings, 1995, p117-125.
- 10 Frank A. Vonesh, Nicolas G. Perrin: "Post-combustion for the electric arc furnace," Iron and Steel Engineer, June 1995, p30-32.
- 11 D.S. Gregory, D.K. Ferguson, F. Sloodman, et al: "Results of ALARC-PCTM post-combustion at Cascade steel rolling mills," Iron and Steelmaking, May 1996, p49-56.
- 12 A.C. Deneys, K.D. Peaslee: "Post combustion in the EAF – A steady state simulation model," Electric Furnace Conference Proceedings, vol. 55(1997), Iron and Steel Society, p417-428.
- 13 Jeremy A.T. Jones, James F. Oliver: "A review of post-combustion in the EAF, a theoretical and technical evaluation," 5th European electric steel congress Proceedings, 1995, p83-97.
- 14 S.A. Matson, W.F. Ramirez : "The dynamic modeling of an electric arc furnace," Electric Furnace Conference Proceedings, vol. 55(1997), Iron and Steel Society, p675-688.
- 15 C. Hayman, S. Agarwal, L. Heyd, I. Gordon, S. Granstorm: "A dynamic model for the optimization of the electric steelmaking process," Electric Furnace Conference Proceedings, vol. 55(1997), Iron and Steel Society, p409-416.
- 16 K.E. Sewald: "Fourth hole energy/scrap preheat thermal model," Electric Furnace Conference Proceedings, vol. 44(1985), Iron and Steel Society, p243-250.

APPENDIX A

Review of related research in Post-Combustion

Goodfellow [1-2] has developed an expert system for modeling post-combustion (PC) using off-gas probe data. A proprietary Direct Evacuation Simulation model evaluates the furnace exhaust gas composition, heat load and flow rates on a minute by minute basis based on thermochemical mass and energy balance. Energy sources

were identified in electrical power, oil in scrap, iron oxidation, carbon injection, oxy fuel burners, electrode consumption and carbon in scrap, while energy consumed were in steel melting, sensible heat, chemical heat, W/C panels, slag loss, electrical losses and water evaporation. The investigation comprised of analyzing off-gas composition for CO, CO₂, H₂ and O₂ for different heats at Co-Steel, Lasco. It was observed that the CO and H₂ concentration peaks occurred early in the heat while there is still scrap in the furnace. As a method to effective post-combustion, the net oxygen input to the furnace was increased by changing the *burner ratio* from 3:1 to 8:1 [3]. This resulted in a shift in the CO concentration measurement on the off-gas probe to lower levels from the base line operation. Energy consumption reduced to 35 kWh/t and the power-on-time reduced by 4 minutes per heat.

On the other hand Mathur and others [4-5] at PraxairTM conducted post-combustion experiments both through sidewall burners and through lance. In the investigation with burners, the oxygen ratio was enriched after the normal cycle. The results did not show expected benefits and was abandoned. The second trials were with a consumable hand held post-combustion oxygen lance inserted through the slag door and used in conjunction with normal manipulated lance through a "Piggy-back" mounting. The PC lance was directed into the slag close to the steel bath. Off-gas analysis was through a "Severe Service Sampling System." They have characterized this approach wherein post-combustion oxygen is introduced in the lower part of the furnace to be of 'foamy slag post-combustion' type as opposed to the other method 'free space post-combustion' (also referred to as 'free board' approach) in which oxygen is introduced in the upper part of the furnace. Certain heat transfer analysis was conducted assuming a one-gas, two-sink radiation model, incorporating radiative heat transfer to determine the heat transfer efficiency between the foamy and the free-board approaches during the scrap melting and the flat-bath conditions. Further, the heat transfer between slag and metal was analyzed assuming circulating metal droplets. In their analysis, free-board approach contributes significantly during the scrap-melting with reduced effect during flat-bath conditions. Though it is reasoned that some of the PC oxygen may be leaving the furnace unreacted in free space method, no such experimental data is reported in the literature. The two methods are projected to bring in post-combustion efficiency at 28% in case of free-board while with foamy-slag it is 70%, the difference being attributed to the degree of contribution from the radiative and convective heat transfers. As an advancement, perhaps incorporating a balance of the two

approaches, a commercially designed system consisting of wall-mounted injector nozzle delivering laser-like oxygen jet mounted at about the same height as burner position is proposed as a replacement for normal lances and burners accomplishing lancing/decarburization, post combustion and burner operations in one single integrated system [6]. To estimate the loss to iron oxidation in slag, because of increased oxygen into the process, slag samples were analyzed. They were observed to be less than 5%.

Another proprietary technology reported for post-combustion is the PC-ALARC™ system from Air Liquide [7-11]. The apparatus consists of a continuous off-gas analysis system, and counter-current oxygen injection into the furnace atmosphere through special injectors located in the upper part of the water-cooled panels. It is claimed that the limitation of post-combustion comes from reactions at gas/liquid or the gas/solid interfaces. In particular conditions for post combustion are not favorable when high speed jets of O₂ or CO₂ impinge the liquid bath, which promotes mainly oxidation or decarburization. Therefore burners or supersonic lances are considered ineffective for post-combustion. Post combustion when introduced in the slag layer may alter the slag properties, adversely affecting slag viscosity and surface tension resulting in poor foamy slag with lower heat transfer efficiency. Gregory et al [11] have further investigated the changes to electrical arc system from the use of post-combustion by considering the active and reactive energy profiles, power factor, arc stability and harmonics. They observed improved electrical characteristics and significant contribution of energy into scrap from post-combustion. The increased thermal energy to the scrap, results in a more consistent, faster feed of scrap into the arc flare, reducing the number and magnitude of cave-ins. Contrastingly, in this investigation the CO analyzer was fitted at the exit of the baghouse fan in order to study the emissions at the baghouse. The temperature in the baghouse reduced by about 7°F since CO had combusted and a reduction in the CO concentration by about 15%.

Deneys and Peaslee [12] have developed a steady-state model to describe post-combustion. Arc furnace melting is treated to be a single reactor problem with four zones – melting, foamy slag, post combustion and duct zones. Each zone is identified with appropriate time independent input and output variables and solved using Pyrosim™ simulation software which can calculate multi-component multi-phase equilibria and energy requirements. Post-combustion is considered to occur from air ingress through the slag door and gaps in the ductwork. The model has been used for investigating different variations

to the process such as normal and enhanced oxygen lancing, scrap pre-heating and post-combustion.

An excellent review of post-combustion is given by Jones [13]. The principles applicable to BOF, bath smelting and EAF are compared and analyzed. While considering post combustion, the author suggests a proper evaluation to the possible effects on heat load on shell, loss of electrodes, Fe loss to slag, post combustion in free-board or in slag, heat transfer efficiency etc.

APPENDIX B

Review of related research in Furnace Modeling

Models describing the melting of steel from the time of scrap charging to the end of heat are not many in literature. Most available models consider macroscopic calculations wherein, the amounts of oxygen, flux, carbon and energy required to melt a given charge composition to the final carbon content are predicted. Such calculations often use thermodynamic calculations to predict the outputs. More recently, Matson and Ramirez [13] have proposed a dynamic melting model for the arc furnace. It is assumed that the scrap is made up of a certain number of spheres of specified average radius and the heat transfer to one sphere is modeled first and then scaled up for all other spheres. This accounts for the melting of scrap. To account for the bath, slag and gas phases, two control volumes one for the metal bath and the other for the free-board gas are defined, with a slag resistance between the two to limit the mixing. The two volumes exchange gaseous compounds by convection and by concentration gradient flux. A set of six and two independent chemical reactions are associated with the bath and gas control volumes respectively. Assuming that at high temperature steel-melting reactions are not kinetics limited but mass transfer limited, a set of simultaneous equations describing the mass conservation of reactants and products is set up which are solved numerically at discrete time intervals. The model is used for studying the effect of using excess oxygen in the burner and of injecting carbon continuously instead of adding it all at the beginning of the heat. The simulation predicts a decrease in CO release from the furnace.

Other approaches to modeling the melting problem are in [14-15]. Macroscopic enthalpy balance for the metal, gas, slag and water panels form the basis of these calculations.

Updated results will be presented at the conference and made available on NEURAL's web site at <http://www.neural.com>