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Development of Scrap Charge Maximization Program Capable for Melt Prediction and Modification in Crucible Furnace

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ABSTRACT

The actual state analysis of an operational Crucible Furnace was used to develop a scrap melting charge maximization program for efficient charge balancing in this study. Operational model focused on the heat balance and material charge analysis and distribution during melting in the crucible furnace. Charge calculation and maximization model was then developed from the theoretical material balancing using the state analysis of the crucible furnace melting from CAD analysis of the furnace. These were combined to develop the conceptual framework of a working simulation model to handle the melting prediction and correction for crucible scrap melting with dynamic melt chemistry upon every charge. The conceptual framework design was converted into schematics design and the Microsoft Visual Studio (2012) integrated development environment (IDE) was used for appropriate model-simulation application development. The developed simulation application was validated using industrial crucible melting production data in cast iron foundry for seven operation heats for robust analysis. Statistical analysis result of the functionality of the program showed correlation value of 0.98 on the average was observed with average standard error and significance measurement of 0.06 and 0.00007, respectively for elemental comparison between real spark analysis and the program.

Keywords: Actual state analysis, Charge maximization, Material balancing, Heat balance, Theoretical modeling, Crucible furnace, Charge calculation

INTRODUCTION

Furnaces are equipment that are used to melt metal charge for casting or to heat materials to change their shape (example: rolling, forging) or properties (heat treatment). They can be classified according to the type of fuel used; oil-fired, gas-fired and coal-fired furnaces, or according to the mode of charging materials; batch, periodical and continuous furnaces, or according to the mode of heat transfer; radiation and convection [1]. Some of the more commonly used foundry melting furnaces include: crucible furnaces, the cupola furnace, induction furnaces, and electric arc furnaces. A crucible furnace is a melting unit that uses a refractory crucible which contains the metal charge. The charge is heated via conduction of heat through the walls of the crucible. The heating fuel is typically coke, oil, gas or electricity [2]. Crucible melting is commonly used where small batches of metal alloys are required. The capital outlay of the furnace makes it attractive to small foundries [3]. They are typically classified according to the method of removing the metal from the crucible tilting furnace, lift-out furnace and bail-out furnace.

The addition of Ferro-alloys of different grades for cast melt is possible from the total scrap meltdown in a crucible furnace. However, the degree at which the scrap mix can be optimized and which melting operation can be controlled and automated to achieve the right chemistry of the melt is limited [4]. This depends on the knowledge of the properties of the scrap, raw-materials in the charge mix, proper charge calculation and good scrap sorting and selection [5]. It is important to control the metallurgical reactions in steel making processes in order to obtain optimized cast melt with intended composition. The addition of slag formers for de-slagging process requires that elemental recovery

is incurred as a result of the complex reactions with the molten steel [6]. Hence, to obtain quality melt from the furnace, several metallurgical equations are taken into consideration before charging is done which is a function of the peculiarity of the furnace in use. This makes the use of computer simulations inevitable to achieve the right chemistry in real time and prevent production time lag leading to material and energy wastage [7]. This is quite important in the light of increasing demand on the final quality of steel products. It is quite difficult to achieve quality especially in Ferrous melting in the use of assorted scraps as different charge brings different calculation effort [8,9]. The use of crucible furnace is peculiar to getting it right in terms of a very effective charge optimization model [10].

The actual state analysis methodology provides the requirements on systems and application program design in the form of explicit models of system behavior and defines the state-based architecture of the control system. A dynamic charge maximization model and simulation program is developed in this research for a crucible furnace to achieve target melt composition for intended foundry user.

MATERIALS AND METHOD

Actual state analysis (furnace design)

The CAD assembly for the crucible furnace used for state analysis is presented in Figure 1. Parameters used for state analysis are therefore determined and used to form the basis of designing the melting support simulator. The mass flow analysis for burden charge into the crucible pot is shown in Figure 2. There is a melt chemistry dynamics at every charging of the scrap, ferroalloy and other additives from one heat to another. Scrap constitution vary in every melting sequence in that they are charged from assorted collection fields [9,11].

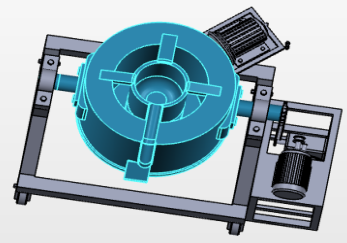

Figure 1: CAD for the crucible furnace arrangement

Determination of metal holding capacity of crucible

$$\rho(\frac{\pi d^2}{4})\mathrm{L} \quad (1)$$

Where;

ρ is the density cast iron, D is the diameter of the crucible=187.6 mm

L is the height of crucible=402.9 mm

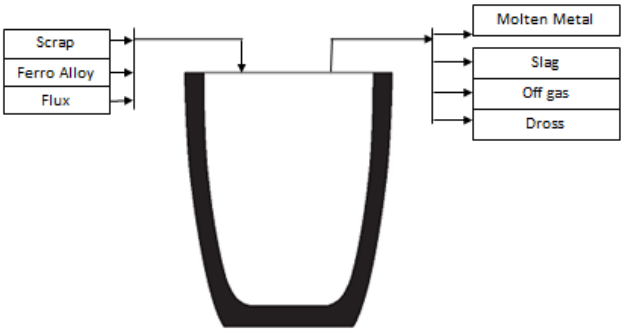

Figure 2: Material flow schematics of crucible furnace

Crucible furnace types are basically used to melt cast iron due to the refractoriness of the crucible as well as the melting point of the metal. Typical elemental composition analysis for cast iron scrap charge is presented in Table 1.

Table 1: Typical chemical composition of cast iron (1 kg)

Element	% Composition	Mass Present (kg)
Fe	90-92	0.9 M_{Fe}
Si	2.5	0.025 M_{Si}
Mn	2.0	0.02 M_{Mn}
P	0.8	0.008 M_{P}
S	0.8	0.008 M_{S}
C	2.0	0.02 M_{C}
Other	Other	Balance

Deterministic (mathematical) model for pit furnace mass flow optimization

The deterministic model approach used for the mathematical model takes the following into account:

i.Typical crucible furnace unit process step is as charge

ii.Slag formation is quite reduced to negligible {except for dross due to scrap dirt}

iii.Flux addition will not be necessary for slag removal; however dross removal could be done by skimming.

iv.Ferro-Alloys could be added for treatment to meet specified target

If various scrap Iron of different known Mass of M^1_x, M^2_y, and M^3_z are charged into the crucible. Each scrap contains the same constituent element although at varying percent composition [12].

Let the Mass of the Final Steel Melt=M_I

Considering a representative element:

If percentage compositions of Fe in the different scraps are Fe_x, Fe_y, Fe_z and target Fe in the final melt is Fe_I, therefore the Target Fe could be represented in mass according to which would be a sum total of the Mass of Fe_x, Fe_y, Fe_z. Hence, we say:

$$Fe_I = \frac{M_X.Fe_X + M_Y.Fe_Y + M_Z.Fe_Z}{(M_X + M_Y + M_Z)R^O} \quad (2)$$

Where, $M_I=(M_X+M_Y+M_Z).R^O$ and

R^O=Operational recovery based on scrap charge practice=[0.9-0.99]

If Ferro-alloy of known percentage composition of element B_A is to be added, mass of ferro alloy is calculated according to Seidu and Onigbajumo [12].

$$Fe_I^* = \frac{M_X.Fe_X + M_Y.Fe_Y + M_Z.Fe_Z + M_{FA}.B_A}{(M_X + M_Y + M_Z)R^O + M_{FA}} \quad (3)$$

Therefore,

$$M_{FA} = \frac{Fe_I^*(M_X + M_Y + M_Z)R^O - (M_X.Fe_x + M_y.Fe_y + M_z.Fe_z)}{(B_A - Fe_I^*)} \quad (4)$$

Where B_A is the percentage composition of the element B which its addition must influence the composition of a constituent element and hence the overall target.

The same analysis is repeated for the entire constituent element considered and the model is bundled to predict the composition of the final melt according to equation 5.

$$\%x^o = x_i^{(k+1)} \frac{(M_{st} \times x^i) + (M_{sc} \times x^n \times R^O)}{(M_{st} + SC) \times 100\%} \quad (5)$$

Mass flow simulation algorithm

To handle the dynamic material flow into the crucible furnace system for respective heats, a mass flow simulation model algorithm is presented in Figure 3.

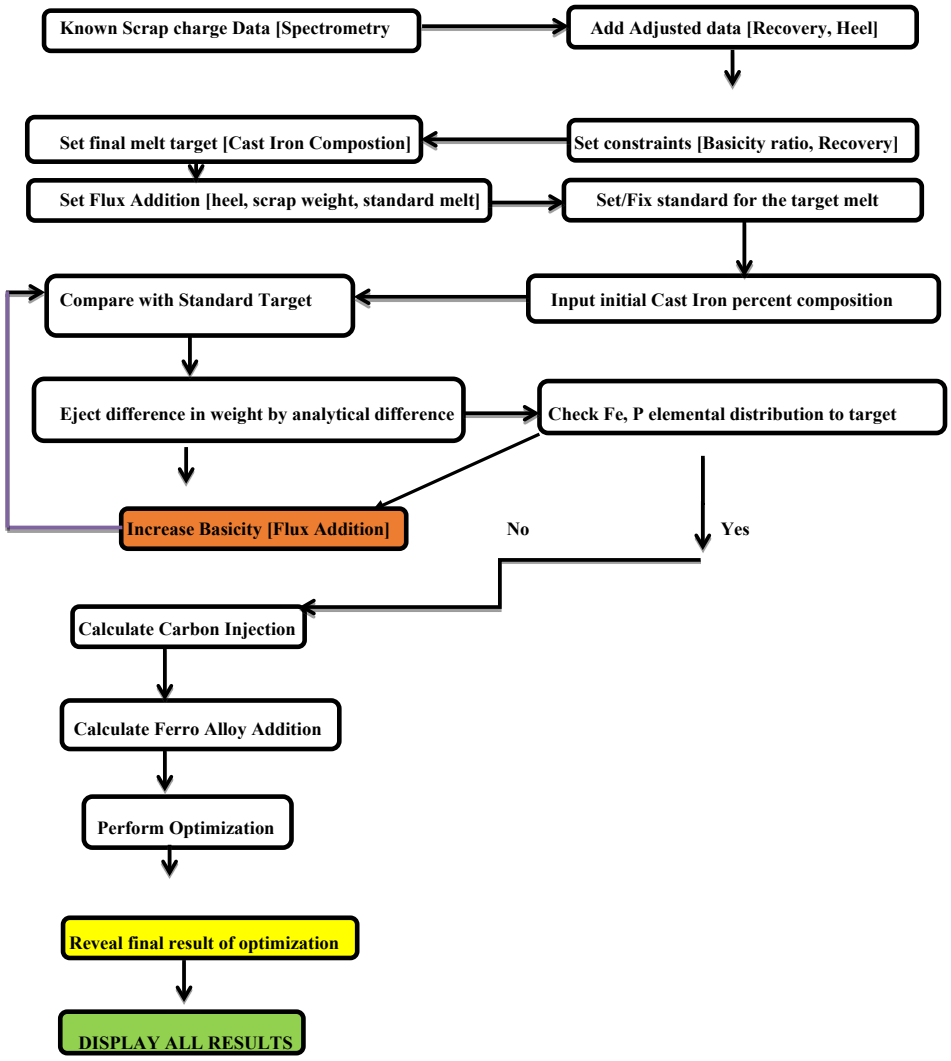

Figure 3: Melting simulation algorithm for material optimization obtained from the actual state analysis

RESULTS

Using the theoretical mass flow process model developed in this research analysis alongside the melting simulation algorithm presented in Figure 3, crucible furnace melting simulator was developed using virtual program with an integrated development environment (IDE).

Developed mass flow simulation interface (TROS CastMELT)

The mass flow simulation interface (MFSI) for the program was designed using the Visual Basic IDE with version control for graphic user interface (GUI) integration. Plates 1-4 shows the graphic user interface construction across the program.

Plate 1: 1st MFI - (standard input, scrap weight input, heel, basicity, recovery and A - Sample spectrometric analysis input)

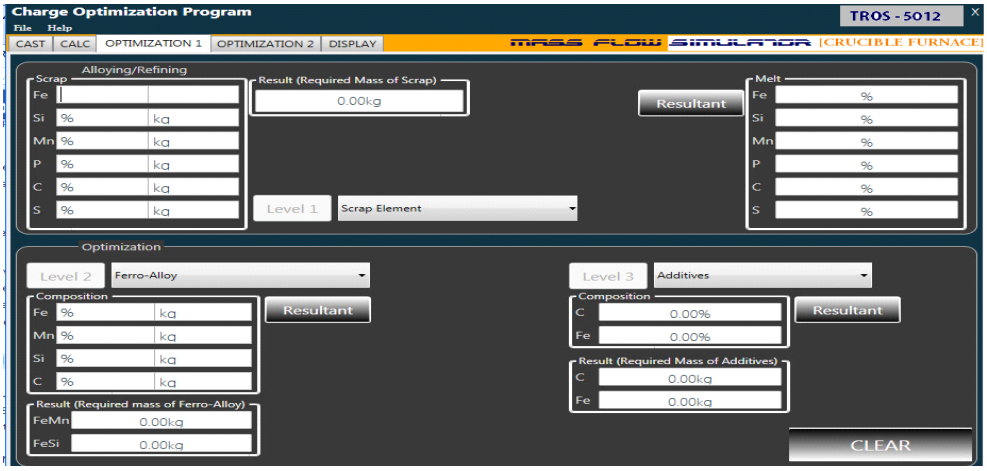

Plate 2: 2nd MFI - (scrap optimization, Ferro-alloy addition and other additives resultant effects)

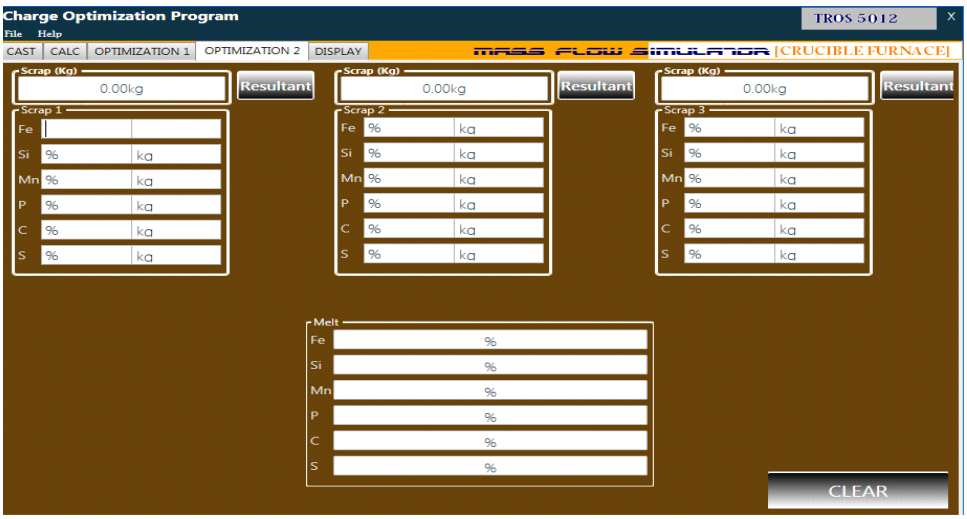

Plate 3: 3rd MFI - (scrap charge iteration and resultant effect of addition)

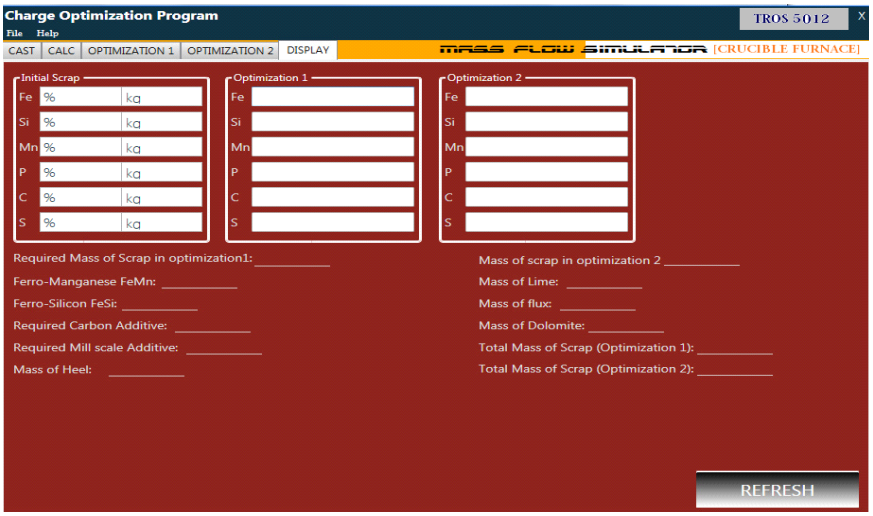

Plate 4: 4th MFI - (display of overall results from 1st - 3rdMFI for all process analysis)

Mass flow interface program functions

The graphic user interface construction is based on the developed algorithm which takes care of the dynamics in the elemental constitution of the charges as well as the integration of the unit melting process/operation involved in obtaining molten metal.

The 1st MFI (Plate 1) is the input interface on the charge calculation program where initial charge data are input by the user.

Standard/target setter

this is the upper portion of the interface where the user will set up the program according to the prevailing target standard of final melt for the major elemnents in the produced cast Iron.

i and f scrap

are scrap input tabs which allow the user input the initial mass of scrap - 'I' and the final mass of scrap - 'F' into the program. The i-scrap module is calculated according to the available operational recovery practice which will be set in the Recovery tab before the F-scrap.

Melt

this portion of the interface is also set by the user according to the initial spectrometric test result (percentage) obtained from the metal analysis when the whole scrap has fully turn into melt. The program automatically converts this into weight composition of the constituent element.

The 2nd MFI (Plate 2) allows the User to to perform optimization by calculating the amount of Scrap, ferro-silicon, ferro-manganese, carbon and mill scale (optional). It enable the user to input necessary value of scrap, ferro-alloy elemental percentage compositions derived from scrap analysis and manufacturers quote, respectively.

The 3rd WTI (Plate 3) allows the User perform scrap iteration by inputing scrap percentage compositions of different scrap available or selected from the scrap yard. The program calculates the resultant effect of such addition in the overall melt and the new melt composition is revealed. The user can either alter the percentage compositions or the Mass of scrap intended to charge and such additions are calculated as the program reveals such iteration according to the relation.

The 4th MFI (Plate 4) displays the overall results of all the various results obtained from flux addition, Optimization, ferro-alloy addtion, scrap iterations and total mass of scrap charged to obtain the Target melt.

DISCUSSION

The compatibility and adaptation of the simulation melting tool for charge calculation and analysis in in a small sized foundry producing custom Cast Iron products was verified using the Nigerian Foundries Limited (NFL) plant, South-West Nigeria. NFL operates two 500 kg, 1 and 2 tons capacity furnaces. Confirmation could not be made on how the foundry engineers were carrying out charge manipulation and correction due to close door operation and secrecy. The melting was carried out in a 2 ton melting capacity for seven (7) heats. Figures 4-7 shows the scatter plot analysis comparing the final melt chemistry of Carbon, Silicon, Manganese and Chromium upon the addition of alloys and the predicted chemistry between the experimental results and simulation program.

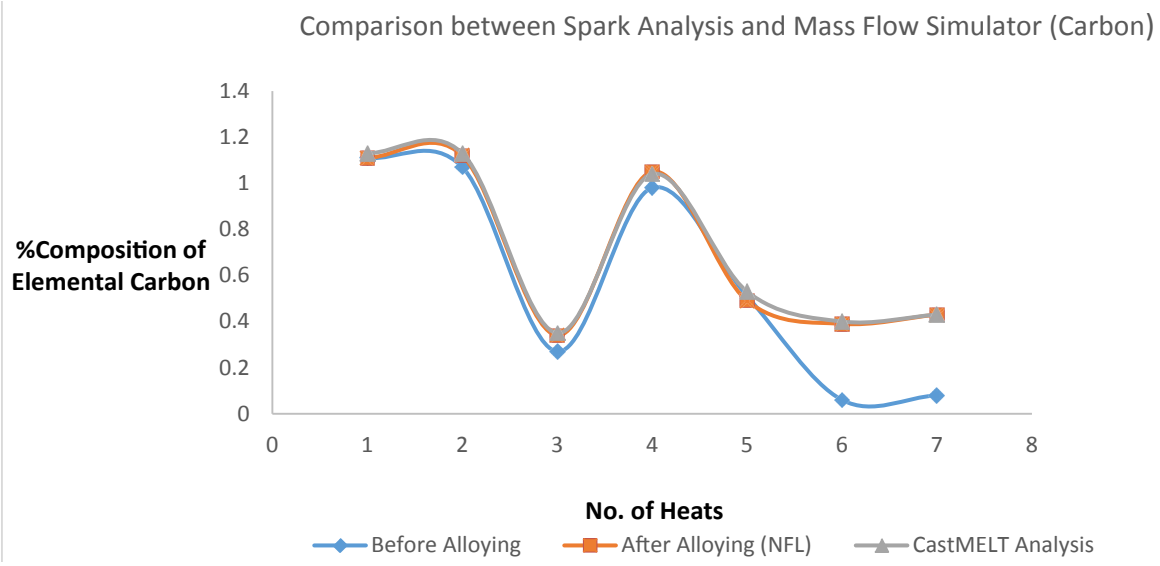

Figure 4: Correlation scatter plot comparing spectrometric analysis (NFL) after alloy addition with mass flow simulator for carbon composition

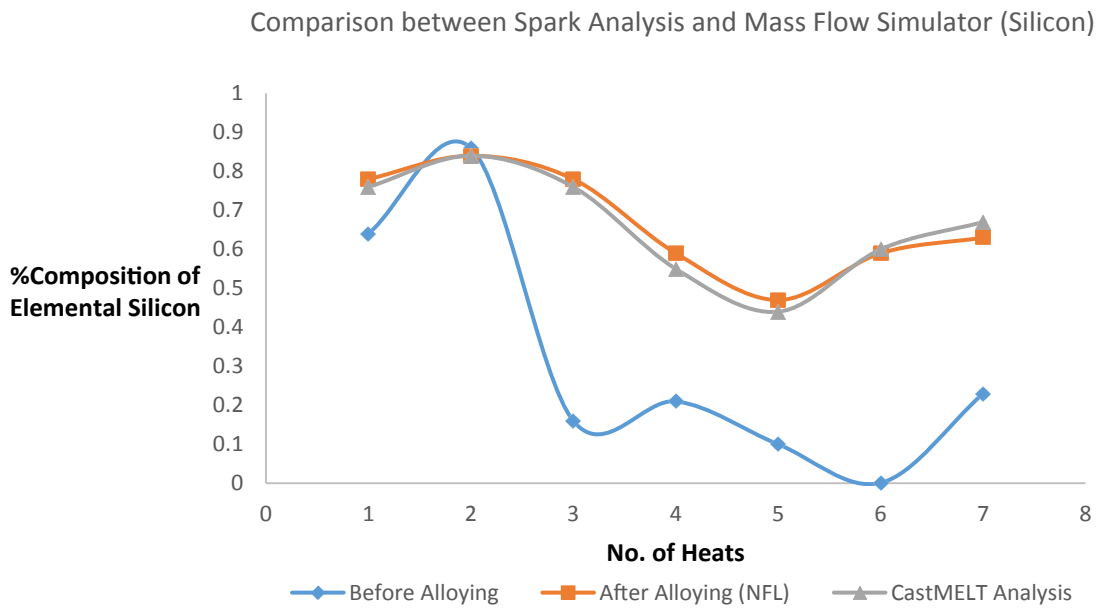

Figure 5: Correlation scatter plot comparing spectrometric analysis (NFL) after alloy addition with mass flow simulator for silicon composition

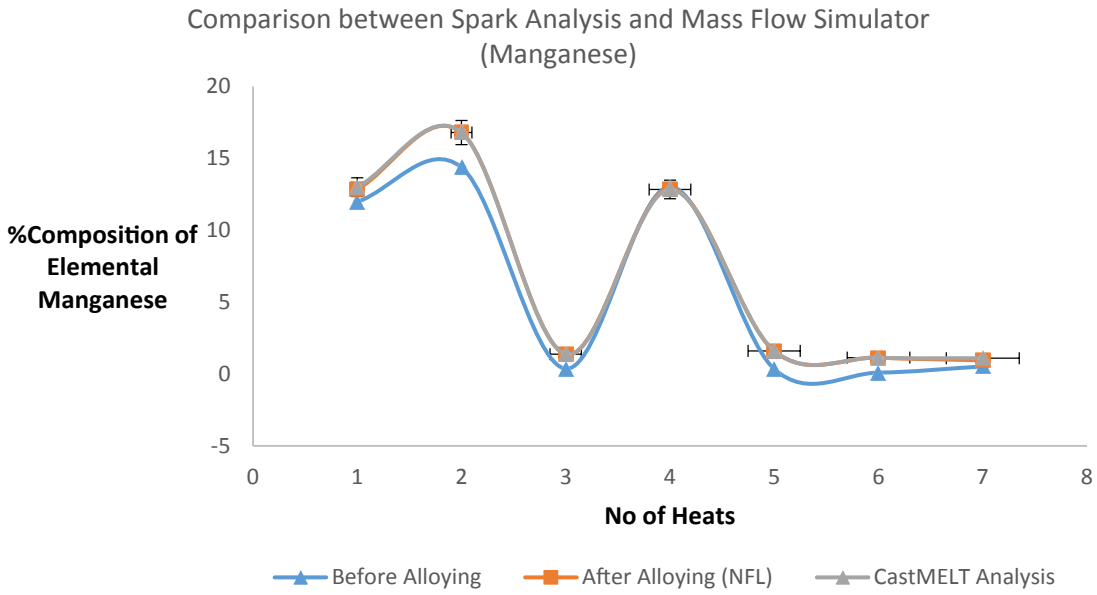

Figure 6: Correlation scatter plot comparing spectrometric analysis (NFL) after alloy addition with mass flow simulator for manganese composition

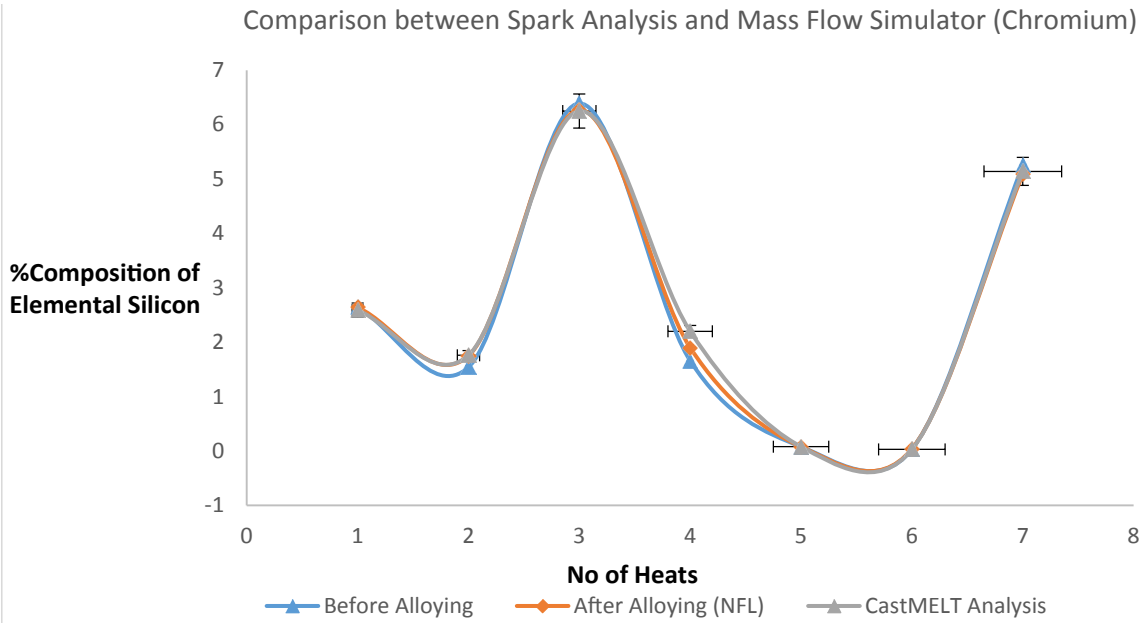

Figure 7: Correlation scatter plot comparing spectrometric analysis (NFL) after alloy addition with mass flow simulator for chromium composition

The correlation between the results obtained from the use of scrap melting simulation program and experimental real time melting were presented in Figures 5-7. The various changes in elemental constitution of the melt are revealed in the variation in percentage composition of the elements due to differential in scrap chemistry considered across the heats. This dynamics involved in mass analysis of melt from one heat to another necessitate the use of a computational program for performance of the model for unlimited runs.

The scatter plot analysis shows a correlation value of 0.99, 0.98, 0.999 and 0.998 for Carbon, Silicon, Manganese and Chromium, respectively. The validation analysis of the mass flow simulator program for prediction and charge calculation purpose is evidenced in the high value of R-squared, Standard Error, Pearson correlation and Significance value of (0.934, 0.06, 0.97, 0.0003) for Carbon prediction, (0.962, 0.06, 0.98, 0.00009) for Silicon prediction,

(0.999, 0.048, 0.999, 9E-11) for Manganese Prediction, and (0.997, 0.076, 0.999, 6E-7) for Chromium Prediction respectively. An overall confidence performance level above 99 % was observed using the developed simulation program as a charge calculation tool.

CONCLUSION

Actual state analysis of a CAD crucible furnace was adapted to develop deterministic and dynamic mathematical model with schematics framework and algorithm for charge maximization with the graphite crucible pot as the melting system. Based on process material balance analysis, the mass flow simulator program was also developed using the Microsoft visual studio programming language. Upon validation of the simulation functionality, correlation value of 0.98 on the average was observed with average standard error and significance measurement of 0.06 and 0.00007, respectively for elemental comparison between real spark analysis and the program. The program is adjudged as a tool which can replace manual and spreadsheet calculation for charge analysis especially for experimental scrap melting purpose in the foundry workshop. It can also make melt corrections and final chemistry prediction for which there are no tools in the local foundry which is employed for such purpose. The mass flow simulation program could be used to create unlimited charge compositions for the users with a wide degree of scrap manipulations and alloy additions without any workshop trial and error operation saving the managers a great deal of time and cost of operation.

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