PHYSICAL AND MATHEMATICAL MODELLING OF STEELMAKING PROCESSES IN A VACUUM INDUCTION FURNACE

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Abstract

Vacuum metallurgy processes are now the primary processes of manufacturing new metallic materials. Requirements concerning product purity and accuracy in determining chemical composition constitute a huge challenge arising from the needs of new technologies. Examples include the required parameters of metal powders applied in 3D printing.

The subject of this paper is a kinetic model of the alloy steelmaking process, based upon the tank theory. Assumptions to this model enable the process to be simulated in real time. The method of determination of the equilibrium state at the metal-gas interface with the use of the *Equilibr* module from the FactSage® program is an essential component of the model. The computations were verified on the basis of laboratory heats made in a VIM 10-20 vacuum induction furnace.

Keywords: Vacuum induction furnace, process kinetic

1. INTRODUCTION

The development of modern metallic materials poses a significant challenge for contemporary materials engineering. Methods of engineering new types of materials are diversified, but they always lead to a stage where the manufacturing method should be developed and implemented in practice. As regards metallic materials, the biggest difficulty lies in obtaining the assumed chemical composition of metal. Very often, the required chemical composition contains elements which easily oxidise or have a high vapour pressure. Therefore, in many cases the only group of processes that enable this task to be accomplished are vacuum processes exclusively. Making a metallic alloy using a vacuum induction furnace always takes place at a certain distance from the system's equilibrium state, and therefore the method of controlling the steelmaking process has a very high impact on the ultimate correctness of the obtained chemical composition of the cast ingot. Due to growing market demand and the increasing complexity of metal alloys, a model was developed to simulate changes in the chemical composition of a metal bath during the melting process.

2. A MATHEMATICAL MODEL OF STEELMAKING IN A VACUUM INDUCTION FURNACE

The design of a kinetic model of the steelmaking process in a vacuum induction furnace requires a proper description of two key effects that occur in this reactor i.e. the process of metal bath mixing and the processes that occur at the metal-gas (vacuum) interface. The mixing process is significant for the characteristic of the homogenisation level of the melt disturbed by alloy additions introduced during melting. On the other hand, the description of processes occurring at the metal-gas interface should answer the question about the intensity of gas evacuation from the melt and the evaporation rate of alloy additions.

2.1. Metal bath mixing model

The concept of vacuum steel refining is based upon an assumption that it is necessary to apply a mixing model to describe the process kinetics, and this model should provide a solution within a time shorter than the actual refining time. The key task is to select the melt mixing model, and next, to incorporate the thermodynamic model allowing the local equilibrium at the metal-gas interface to be computed into the mixing model.

In the adopted solution, the selected melt mixing model is based upon the tank theory. It was assumed that the real reactor can be divided into so-called tanks, which have the following properties assigned [1]:

- The volume of a tank does not change over time.
- No concentration gradient occurs within a tank.
- The chemical composition of a tank changes stepwise at a predetermined time interval Δt.

The verification of the mixing model, based upon the described theory, requires defining the volumes of individual tanks and the values of mass transfer fluxes between the tanks. The quality of this verification is key to the accuracy of the mixing model forecast. **Figure 1** presents the assumed breakdown of the melt within the vacuum induction furnace into tanks [2, 3].

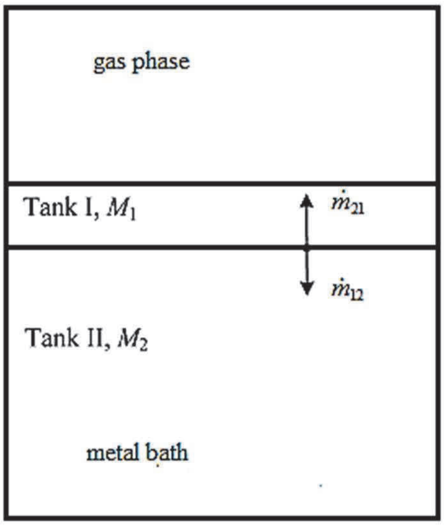

Figure 1 Division of a vacuum induction furnace into tanks

For the induction furnace, a very simple model structure can be assumed because the melt is stirred very intensively within the whole unit volume. The most important research problem is to answer the question about the intensity of the mass transfer between the surface layer of the melt and the surrounding vacuum. According to the hypothesis applicable in the theory of mass transport, it can be assumed than the equilibrium state exists in the thin layers adjacent to the interface, and, with all limitations, this equilibrium state can be determined on the basis of thermodynamic calculations.

The system of equations describing the mixing process in the induction furnace may be presented in accordance with the diagram in **Figure 1**, as follows:

$$dm_1^i(t) = -\frac{m_1^i(t)}{M_1}\dot{m}_{12}\Delta t + \frac{m_2^i(t)}{M_2}\dot{m}_{21}\Delta t$$

$$dm_2^i(t) = \frac{m_1^i(t)}{M_1}\dot{m}_{12}\Delta t - \frac{m_2^i(t)}{M_2}\dot{m}_{21}\Delta t \qquad (1)$$

where: M_i - the metal bath mass in tank “i”

$\dot{m}_{ij}$ - the value of mass flux from tank “i” to tank “j”

$m_j^i(t)$ - the value of component “i” mass in tank “j”

Δt - the value of the computing time interval

The system of equations (1) presented above is a typical system of the so-called two tank model (TTM). It is the basis to develop a hybrid model, which will enable changes in the chemical composition of the melt in the laboratory vacuum induction furnace to be simulated.

2.2. Hybrid model

The key solution to the hybrid model is to incorporate the term taking into account processes occurring at the melt-gas (vacuum) interface into the equation structure (1). The thermodynamic model is incorporated into the melt mixing model by modification of the first equation of the system of equations (1). Then, this equation ultimately assumes the form:

$$dm_1^{\mathrm{i}}(t) = -\frac{m_1^{\mathrm{i}}(t)}{M_1}\dot{m}_{12}\Delta t + \frac{m_2^{\mathrm{i}}(t)}{M_2}\dot{m}_{21}\Delta t + \Delta m_1^{\mathrm{i}}(t)_{\mathrm{eq}} \tag{2}$$

where $\Delta m_1^{\mathrm{i}}(t)_{\mathrm{eq}}$ - the change in the mass of component "i" in the first tank caused by the interfacial processes.

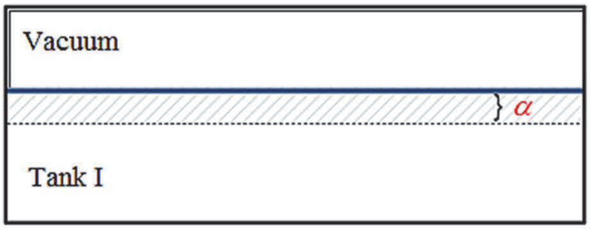

Figure 2 Diagram of the metal-slag interface with the marked boundary layer

The point of the proposed solution is explained by **Figure 2**, where the metal boundary layer achieving the equilibrium state in contact with the vacuum is marked. Correct defining of the thickness of this layer is the next step which is decisive to the accuracy of model calculations [4].

According to earlier research, the thickness of the metal layer that achieves the equilibrium state should be determined taking into account the time concerned. In the case of numerical calculations it is the computing time step Δt. The value of parameter α is determined from the relationship (3):

$$\alpha = \frac{\Delta \mathrm{t} \cdot \dot{\mathrm{m}}_{12}}{\mathrm{M}_{\mathrm{I}}} \times 100\% \tag{3}$$

where α - a factor determining what percentage of the first tank mass is transferred into the thermodynamic model [%].

Defining the thickness of the boundary layer, according to equation (3), allows a parameter such as the computing time step to be arbitrarily changed, without the need to verify the model once again.

3. EXPERIMENTAL SETUP

Tests allowing the defined kinetic model of the vacuum steel refining process to be verified, were conducted in a vacuum induction furnace with a crucible capacity of 10 kg, **Figure 3**. This unit is equipped with a vacuum chamber enabling the steel refined to be cast in a vacuum. It is also possible to take metal samples, and to add alloy additions without the need to unseal the vacuum chamber. The furnace equipment enables the operating parameters to be fully recorded in the form of a text file. The furnace applied for the tests is presented in **Figure 3**.

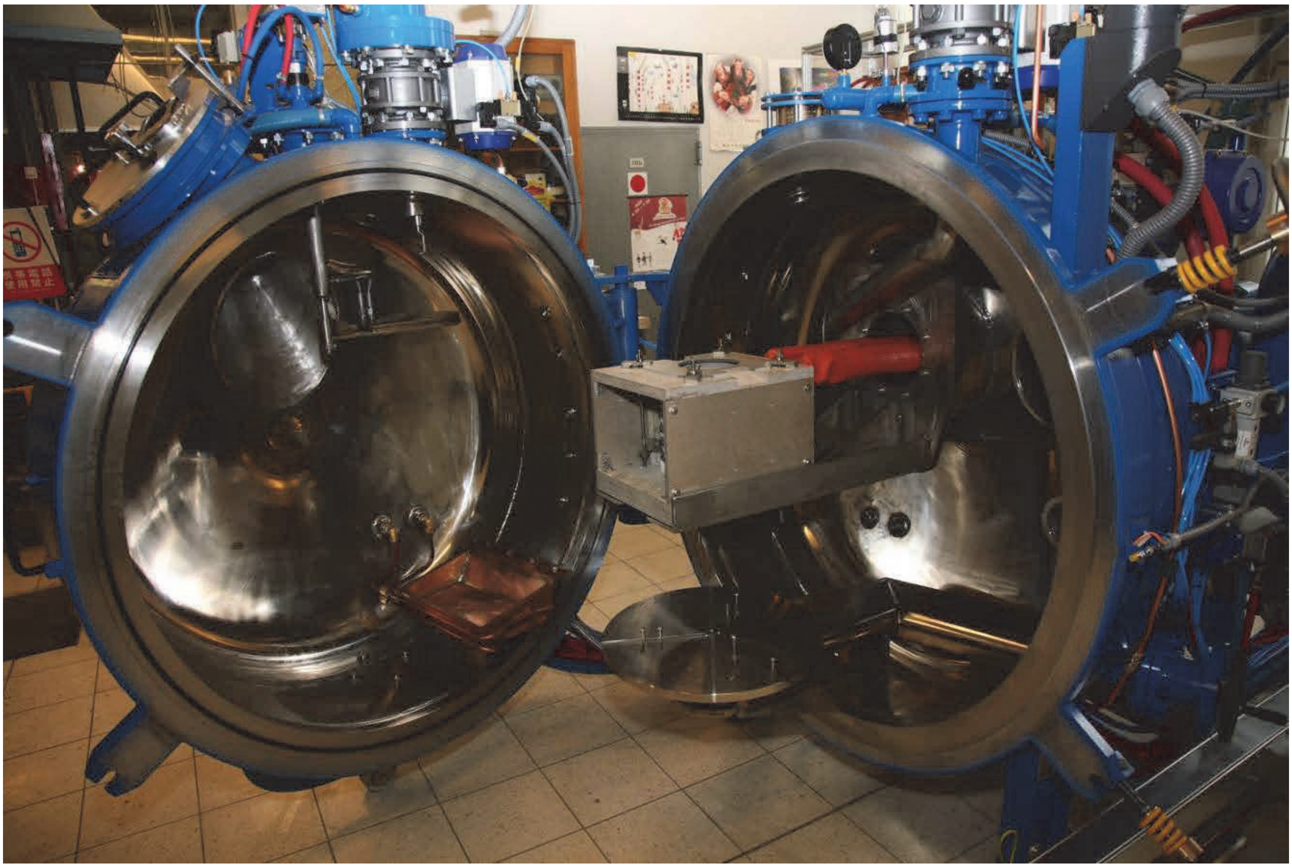

Figure 3 The laboratory vacuum furnace with a capacity of 10 kg

4. EXPERIMENTAL RESULTS

Making steel with a complex chemical composition is a task that requires extensive experience in the operation of a laboratory vacuum furnace. The number of factors that may disturb the assumed steelmaking process, and the limited possibilities for intervention into its course, determine the methodology of experiments [5].

Figure 4 presents the full documentation of an example of heat containing alloying constituents shown in **Table 1**. The objective of the described experiment was to achieve the equilibrium state of the melt-vacuum system, and next to add the assumed mass of the alloy addition in the form of FeMn.

One of the most important parameters controlling the process is the ability to control the pressure in a wide range, combined with the option of purging the chamber with argon. The stable course of the experiment is ensured thanks to maintaining increased argon pressure until the charge is fully molten. After the charge has been fully molten the operation of intensive melt de-gasifying is carried out for about 10 min. Due to a low chamber pressure of 1 mbar, the process of carbon oxidation with oxygen contained in the metal starts within the melt. This process occurs primarily at the surface, and its speed depends on the melt stirring intensity. In accordance with the assumptions presented in Section 2, the carbon content decline was computed using the experimental heat input data. The simulation results are presented in **Figure 5**.

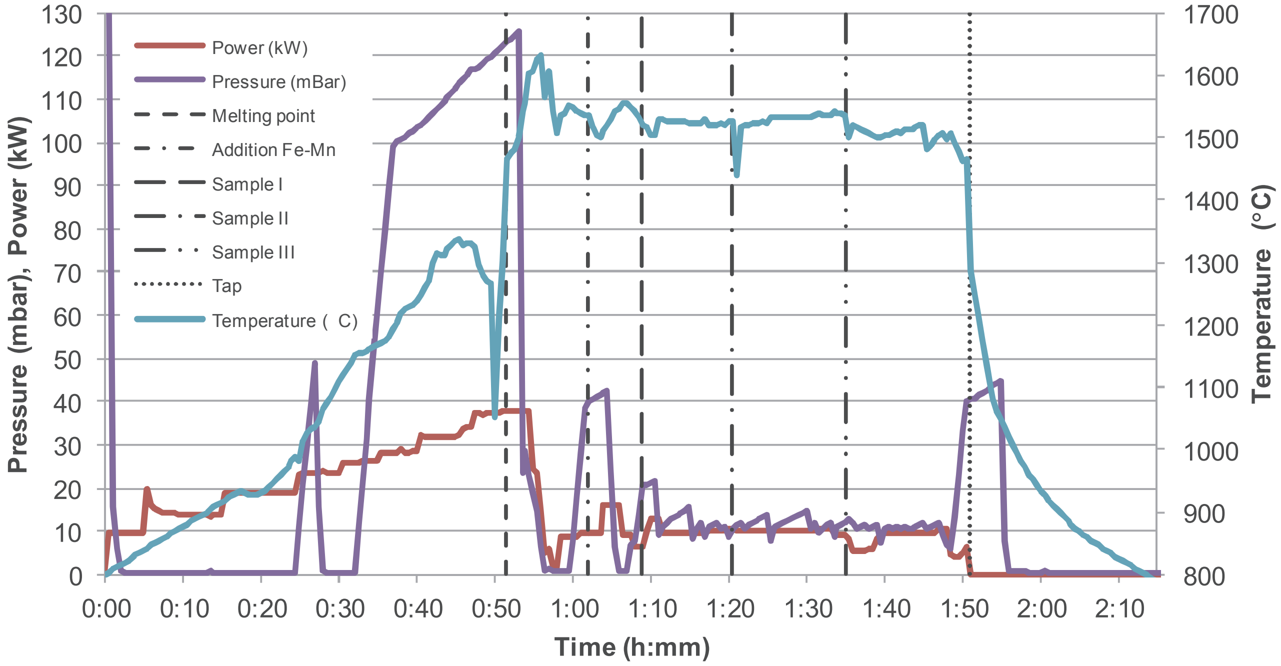

Figure 4 The steelmaking process in the laboratory vacuum furnace with a crucible capacity of 10 kg

After stabilising the carbon content, a portion of FeMn was added to the bath. The developed kinetic model was applied to check if in conditions of the conducted process the Mn content in steel changed. The simulation result showed no significant changes in the Mn content. It should be emphasised that the experiment was carried out for about 60 min, and manganese is usually a fast evaporating steel alloying component. Theoretical predictions concerning the Mn behaviour during the experiment were confirmed by the analysis of the taken samples. The chemical constitutions of metal samples are presented in **Table 1**. Theoretical analysis of the system containing manganese leads to a conclusion that in this case the mass of the gaseous phase staying in equilibrium with the melt has a key influence on the thermodynamic equilibrium state. **Figure 6** presents hypothetical metal bath equilibrium states for two different argon amounts versus pressure.

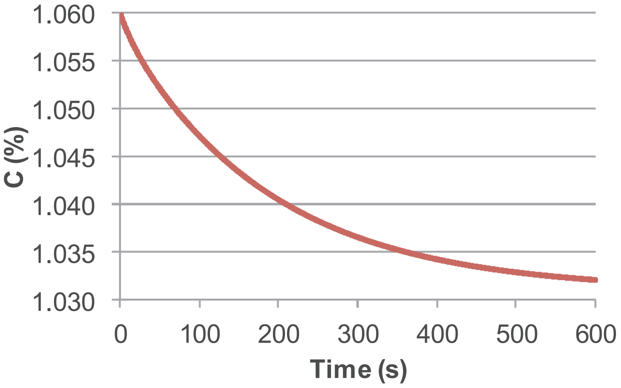

Figure 5 Change in the carbon content in the metal bath forecast by the kinetic model of the process, p = 1 mbar, T =1520 °C

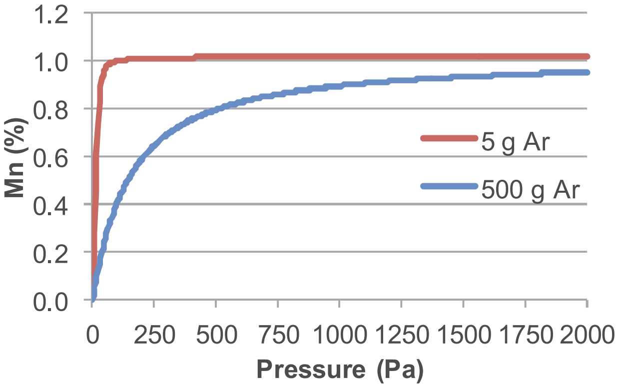

Figure 6 Change in the manganese content in the melt forecast by the kinetic model of the process. Charge mass: 10,000 g, argon mass: 5 g (ca. 2.5 mbar in the vacuum chamber at V = 1.4 m^3), 500 g (ca. 25 mbar in the vacuum chamber at V = 1.4 m^3)

Table 1 The chemical composition of metal samples taken and the composition of the finished ingot

	C (%)	Si (%)	Mn (%)	Cr (%)
Sample 1	1.03	0.277	1.010	2.18
Sample 2	1.01	0.275	1.060	2.17
Sample 3	1.01	0.281	1.010	2.16
Ingot	1.01	0.276	0.913	2.20

5. CONCLUSION

The formulated kinetic model of alloy steel making in the vacuum induction furnace allows changes in contents of the primary alloying elements to be predicted during the melting process. The conducted experiments allow us to draw the following conclusions:

1) A correctly defined kinetic model of the steelmaking process in a vacuum induction furnace should include both the effect of intensity of melt mixing and the processes occurring at the metal-gaseous phase (vacuum) interface.
2) The melt mixing intensity in the induction furnace allows us to restrict the tank model to a simple TTM (two tank model) structure.
3) The gaseous phase mass and chemical composition control and information on the course of pressure changes during the process are key to the correctness of the kinematic model predictions.
4) For a laboratory furnace with a small crucible capacity, the stability of the chemical composition of the alloy additions introduced is very important, regardless of the material grain-size distribution.

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