A phenomena-based model to investigate the possibility of scrap melting in an Open Slag Bath Furnace (OSBF) for green ironmaking

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Abstract:

This paper presents a phenomena-based model for investigating the possibility of scrap melting in an Open Slag Bath Furnace (OSBF) for green ironmaking. The goal of this study is to enhance the circularity of the steelmaking process by utilizing scrap as a green source of iron in OSBFs. The model takes into account the fundamental differences between OSBFs and traditional processes such as Electric Arc Furnaces (EAFs) and Basic Oxygen Furnaces (BOFs).

The model considers three primary regions where scrap heating and melting occur: the solid feed pile, slag, and hot metal. It accounts for factors such as the furnace geometry, scrap charging mechanism, and specific heat and mass transfer properties of the reactor. The model was validated using literature data and was used to investigate the heating and melting behavior of individual scrap particles under various process parameters.

The study finds that the scrap melting process in OSBFs involves three stages: shell formation, shell remelting, and subsequent melting of the parent scrap. The carbon content of the scrap and the liquid hot metal plays a critical role in determining the melting behavior. Depending on the carbon concentration and temperature, the melting process can be heat transfer controlled or mass transfer controlled.

The paper also examines the scrap feeding methods in OSBFs, including direct charging into the slag or charging through a feed pile. The model provides insights into the melting rate of scrap compared to Direct Reduced Iron (DRI) in OSBFs and highlights the role of carbon in this process.

Overall, this phenomena-based model contributes to the understanding of scrap melting behavior in OSBFs and provides valuable insights for optimizing the circularity and efficiency of green ironmaking processes. The findings of this study can inform the design and operation of OSBFs, paving the way for increased utilization of scrap as a sustainable feedstock in the steel industry.

INTRODUCTION

Tata Steel Nederland is committed to transitioning towards a clean, green, and circular steel, using direct reduction of iron ore followed by electrical melting. Within the vision of the company, use of scrap as a green source of iron plays a central role. Conventionally, Electric Arc Furnace (EAF) and Basic Oxygen Furnace (BOF) are the main processes where scrap addition can take place. Open Slag Bath Furnaces (OSBFs) are primarily considered to be operated using Direct Reduced Iron (DRI) and believed to have a promising performance, especially with low-grade ores.

While the use of scrap as an additional feed material in OSBFs has not been demonstrated on an industrial scale, it holds tremendous potential for enhancing the circularity of this process. However, the degree in which such furnaces can be used as scrap melting units is unclear (Cavaliere et al, 2022). Therefore, it is increasingly important to understand the scrap melting behaviour in OSBFs given their fundamental differences from EAFs and BOFs.

In the present study, a phenomena-based model was developed, considering the key differences between the OSBF and EAF and BOF. These differences include the geometry of the furnace, charging mechanism of scrap, and the reactor's specific heat and mass transfer properties. The model encompasses three primary regions where scrap heating and melting occur: the solid feed pile, slag, and hot metal. The model was validated and used to investigate the heating and melting behaviour of singular scrap particle under varying process parameters such as temperature, composition of hot metal, and size of the scrap.

SCRAP MELTING IN LIQUID HOT METAL

The scrap melting process involves three stages: shell formation, shell remelting, and subsequent melting of the parent scrap. Shell formation occurs due to flash absorption of heat by cold scrap particle upon contact with liquid bath. Key factors affecting the different stages of melting include coupled heat and mass transfer mechanisms and phase transformation (Wei et al, 2019). These factors are influenced by the chemical composition and temperatures of both the liquid hot metal and solid scrap particles. This melting phenomenon can be described as a dynamic moving boundary problem involving phase change otherwise known as Stefan problem (Chuang and Szekely, 1971).

The carbon content plays a critical role in determining the liquidus temperature and overall melting behaviour of scrap in liquid hot metal bath. When the scrap particle and the liquid bath have the same carbon concentration or the hot metal temperature is above liquidus temperature of scrap, the melting process is almost completely heat transfer controlled. In cases where the liquid hot metal carbon composition is higher than the scrap particle but its temperature is lower than the liquidus temperature of the scrap, diffusion melting comes to play. Carbon diffusion to the interface results in decrease in local liquidus temperature and enables the melting process. Therefore such melting condition is mass transfer controlled (Penz and Schenk, 2019).

SCRAP FEEDING IN OSBF

The main feeding material in the OSBF is DRI that is charged through feeding ports above the furnace. In principle, a fraction of DRI can be replaced with scrap without changing the electrical input or other major changes in the process parameters (Belford et al, 2022). The current model aims at determining the melting behaviour of a single scrap particle when it is charged in an OSBF unit. It is particularly interesting to understand the role of carbon and the difference it makes in the melting rate of scrap compared to DRI in OSBF.

Scrap can be introduced into an OSBF through two primary routes: directly into the slag or via a feed pile consisting of a mixture of scrap and primary feeding material (i.e. DRI and fluxes). The feed pile, located above the slag layer, represents a confined system that floats on top of the hot metal layer due to its lower density. In the direct charging method, scrap particles pass through the slag layer before entering the liquid hot metal layer (Figure 1). Scrap particles charged via a feed pile undergo heating during their descent through the pile and subsequently sink to liquid hot metal. The scrap particle descends within hot metal due to the higher density of the scrap.

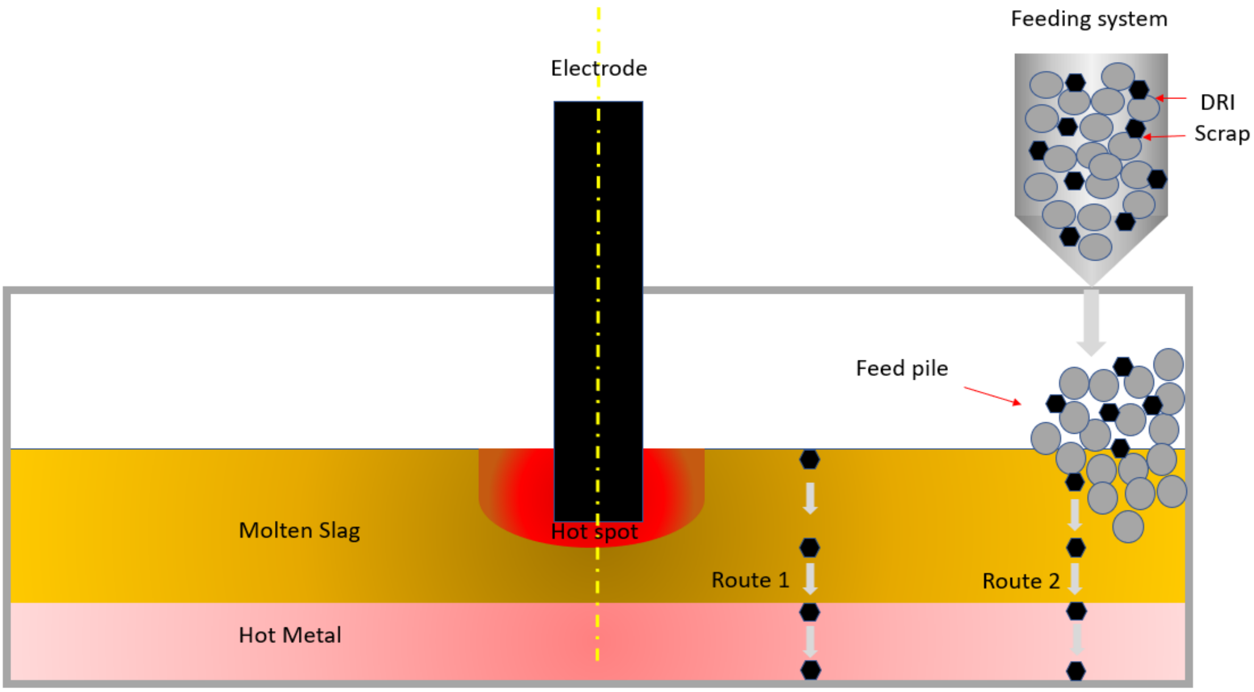


FIG 1. Schematic of an OSBF cross section. Left circles represents direct charging through slag; right circles show charging through feed pile.

MODEL DESCRIPTION

The model consists of three main parts; solid feed pile, slag and hot metal. The scrap particles are assumed to absorb heat in the feed pile and slag in radial direction. Therefore, no mass transfer or chemical interaction is considered in these layers. The main factors influencing the degree of pre-heating in these layers are the residence time and temperature profile. Given that feed pile is at sub-solidus temperature it is expected that scrap does not undergo any significant chemical interaction within the feed pile.

In the slag layer, the chemical interactions and the role of mass transfer are excluded due to very limited knowledge on the kinetics of such interaction between scrap and the slag. It will be clarified later that the residence time in the slag layer is very short and as such the impact of chemical interaction is limited.

To simulate the scrap melting behaviour in the hot metal, the problem is reduced to a one dimensional heat and mass transfer problem. It is assumed that the heat flow within the solid is purely radial. The explicit finite difference method (FDM) with fixed grid is used as modelling approach and several assumptions are made:

- The physical properties of liquid melt and solid steel scrap are considered to be constant;
- The scrap is assumed to be uniformly exposed over all its surfaces;
- Internal diffusion of carbon in the scrap particle is not taken into account;
- Only heating phenomenon is considered between the scrap and slag/feed pile
- The carbon concentration of the shell is equal to liquid hot metal

Mathematical description

Feed pile

The movement of the pellets and scrap within the feed pile is a function of various parameters such as density of feed material and the melting rate at feed pile boundaries. In order to describe this complex phenomenon the problem is reduced to uniform descent of scrap within this layer.

Therefore, given a certain OSBF geometry, pile size and feeding rate one can estimate the descent velocity.

Another important factor in estimating the degree of pre-heating in the feed pile is the temperature profile. To estimate the temperature profile a one-dimensional linear gradient is assumed along the vertical axes where an interface temperature equivalent to the liquidus of DRI pellet is imposed at the bottom. The top temperature can be variable between ambient and the liquidus of DRI pellets.

Slag

To determine the residence time (*t*) in slag Stokes' law is used as represented in Equation 1.

(1) $$t = \frac{2R^2}{9}\,\frac{\rho_{particle} - \rho_{fluid}}{\mu l}\,g$$

where R is the radius of the particle [m], l is the slag thickness [m], ρ the density [kg/m^3], μ the viscosity [Pa·s]. For a small scrap particle (<20 mm) the terminal descent velocity is ~2.0 [m/s]. For a slag layer thickness of 1 m, a residence time of ~0.5 s can be estimated.

Only heat transfer is considered when the scrap particle travels solely through the slag layer. The temperature in the slag is considered to be constant and above the hot metal temperature since heating occurs in the slag via electrodes. Equation 2 describes the interface velocity or melting speed (v_{slag}) based on the heat transfer at the interface.

(2) $$v_{slag} = \frac{1}{\rho \Delta H_0}\,[k\frac{\partial T}{\partial x}\Big|_{interface} - h(T_b - T_m)]$$

where ΔH_0 is the standard enthalpy of melting, k the thermal conductivity [W/mK], T_b the bulk slag temperature [K], T_m liquidus temperature at interface [K] and h the heat transfer coefficient [w/m^{2}K].

Hot metal

For the scrap melting in the hot metal bath a combined heat and mass transfer is considered. The heat and carbon mass transfer equations are coupled in order to calculate the velocity of the interface. Equation 3 describes the interface velocity in hot metal (v_{HM}) based on heat and mass transfer at the interface.

(3) $$v_{HM} = \beta_0 \ln\left(\frac{C_i - C_{sc}}{C_b - C_{sc}}\right) = \frac{1}{\rho \Delta H_0}\,[[k\frac{\partial T}{\partial x}]_{interface} - h(T_b - T_m)]$$

in which, β_0 is the mass transfer coefficient at the interface [m/s], C_i the carbon concentration at the interface [wt%], C_{sc} the scrap carbon concentration [wt%], C_b the concentration in the hot metal [wt%]. Here T_b is the bulk temperature of hot metal.

SIMULATION RESULTS

First the results of the model were validated against a set of literature data. Then a parametric study was done of the melting behaviour of a singular piece of scrap when it is charged in an OSBF unit. The influence of important process parameters was studied using the model.

Model validation

Published experimental data were used to validate the model for scrap melting in hot metal. Xi et al (2020) studied the melting characteristics of singular round and square bars in hot metal (Figure 2a). The validation showed that the model is able to predict the experiments reasonably well. When simultaneous heat and mass transfer is considered, a deviation of 23-33% was obtained in predictions of final melting time across various carbon concentrations in the hot metal (Figure 2b). Furthermore the model is capable of predicting the decrease in melting time as a function of carbon in the bath which follows the theory of scrap melting discussed earlier.

(a) (b)

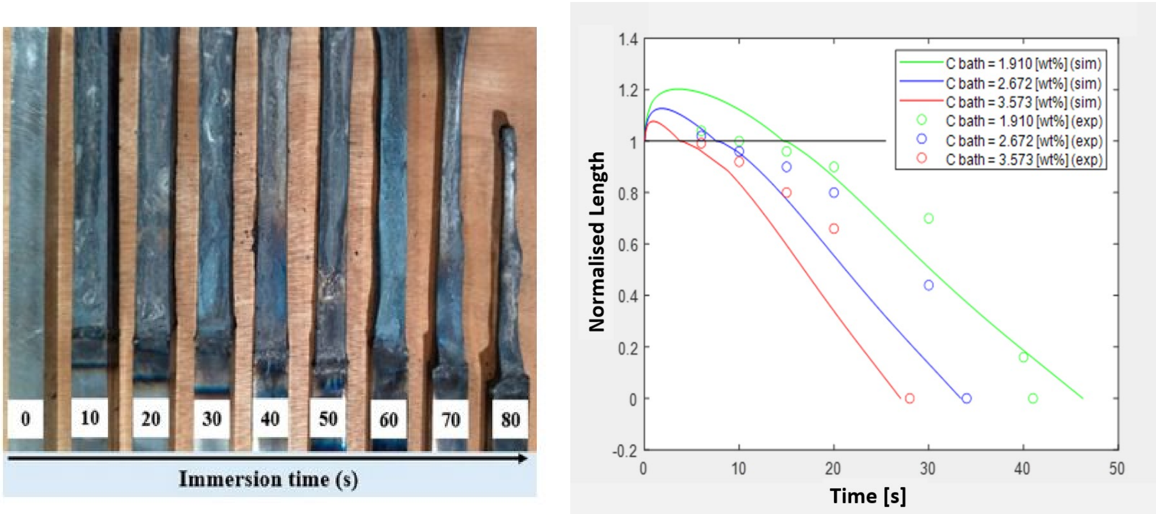


FIG 2 – (a) An image of the scrap samples after several seconds from submersion in hot metal (b) Validation of model using experimental data from Xi et al (2020).

There is some discrepancy in predicting the initial shell formation phase between the model and the experiments. This is partly due to the numerical approach and partly due to the inaccuracy in the acquired experimental measurements for the shell thickness. Such inaccuracies can arise as the freshly formed shell is removed during the extraction of the solid bar from the hot metal.

Parametric study

In this section a parametric study was conducted using the operational condition in Table 1 for a concept OSBF unit. The aim of the study is to understand the influence of the following process parameters: carbon concentration in hot metal, hot metal temperature, scrap size and pre-heating temperature on melting behaviour of scrap. The base case for the scrap size throughout the study was small particles. The large particles were used to demonstrate the influence of size in melting behaviour.

Table 1 – The operational conditions of the concept OSBF process

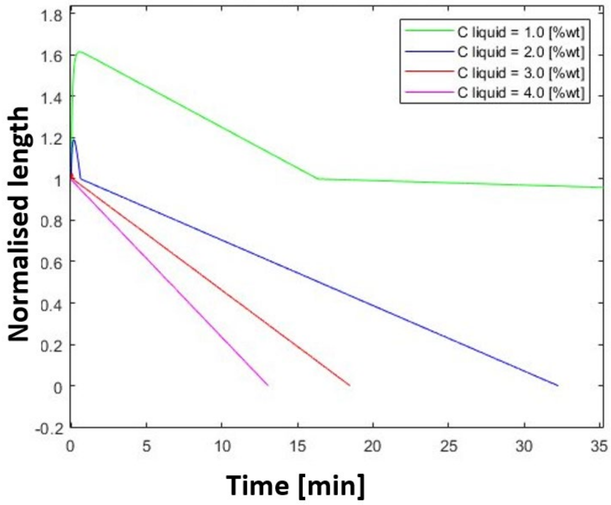
Process parameter	Value	Unit
Average Hot metal temperature	1475	°C
Hot metal carbon concentration	4.0	wt%
Average Slag temperature	1575	°C
Scrap temperature	25	°C
Scrap carbon concentration	0.1	wt%
Scrap Shape	Sphere	-
Scrap typical diameter	20 (small particle), 140 (large particle)	mm
Scrap liquidus temperature	1509	°C
Average feed pile temperature	875	°C

Carbon concentration in hot metal

In Figure 3, the melting time of small scrap particles is depicted for hot metal carbon concentration values between 1 and 4wt%. The liquidus temperature of the scrap particle (1509°C) is higher than the liquid hot metal temperature (1475°C) and the hot metal has a higher carbon concentration (> 1.0wt%) compared to the scrap particle carbon concentration (0.1wt%). Under such conditions the melting rate is controlled by mass transfer. Consequently, the carbon content has a significant influence on the total melting time of the scrap particle: with higher carbon content, the melting rate is higher.

For small scrap increase in carbon from 1.0wt% to 2.0wt% results in ~15 times faster melting. Whereas for an increase from 3.0wt% to 4.0wt% the melting rate increases by 30%. Therefore, the influence of carbon is more significant at lower carbon levels.

(a)



(b)

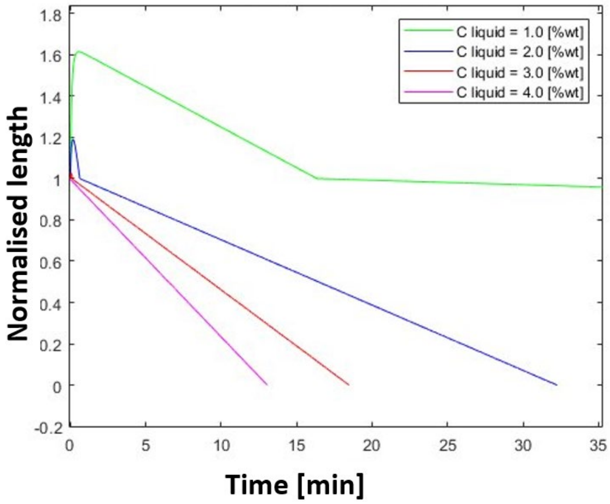


FIG 3 – (a) The influence of carbon concentration in hot metal on melting behaviour of small scrap particle (b) Magnification of the early stage of the melting

Hot metal temperature

Based on the data from Table 1, at temperatures below 1509°C the melting is mass transfer controlled. As depicted in Figure 4, the temperature of hot metal has a significant influence on the total melting time. The melting time is reduced by ~56% when using 1600°C hot metal temperature compared to 1500°C. While increasing the temperature from 1400°C to 1500°C results in ~72% reduction in melting time. This behaviour indicates that increasing temperature in mass transfer controlled regime has more significant impact on melting than in the heat transfer controlled regime. While a unit change in temperature results in more improvements in melting time in mass transfer controlled regime, the melting at heat transfer controlled regime occurs at higher rates.

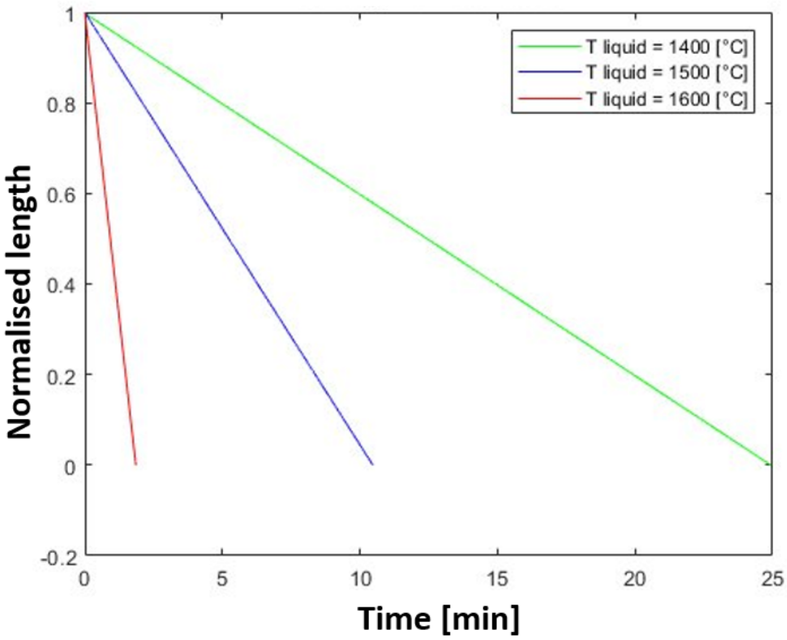


FIG 4 – The influence of hot metal temperature on melting behaviour of small scrap (From right to left 1400°C, 1500°C and 1600°C).

Scrap size

Figure 5 shows the total melting time for different feed pile heights for small (20 mm diameter) and large (140 mm diameter) scrap particles. The large scrap particle has ~ 8 times longer melting time compared to small scrap particle. This is a result of larger surface-to-volume ratio for small particles.

A higher feed pile height does not have a significant influence on the total melting time for the scrap particles. There is only 3% difference in total melting time between directly charged big scrap particle and those charged in the feed pile. For small scrap particles the difference is insignificant. This is because the majority of the heating and melting occurs in the molten hot metal after scrap particle is detached from the feed pile.

Even though, feed pile height does not have a significant influence on the total melting time, it reduces the initial shell formation phase for large scrap particles. The reason that such phenomenon is not observed for small particles is the large surface-to-volume ratio of small particles, which in turn results in very short or no shell formation phase.

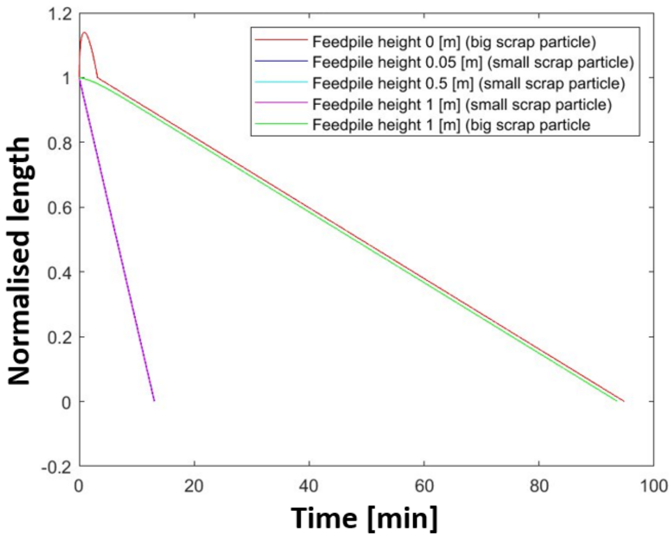


FIG 5 – The influence of scrap size for different feed pile height on melting behaviour of scrap

Preheating temperature

As explained in the previous section the preheating in the feed pile has no significant influence on the total melting time of small scrap. This holds for preheating of scrap before entering the OSBF as well. However, since the feed pile height had some influence on the shell formation phase of large scrap particles, the influence of the preheating temperature on large particles was studied separately.

(a) (b)

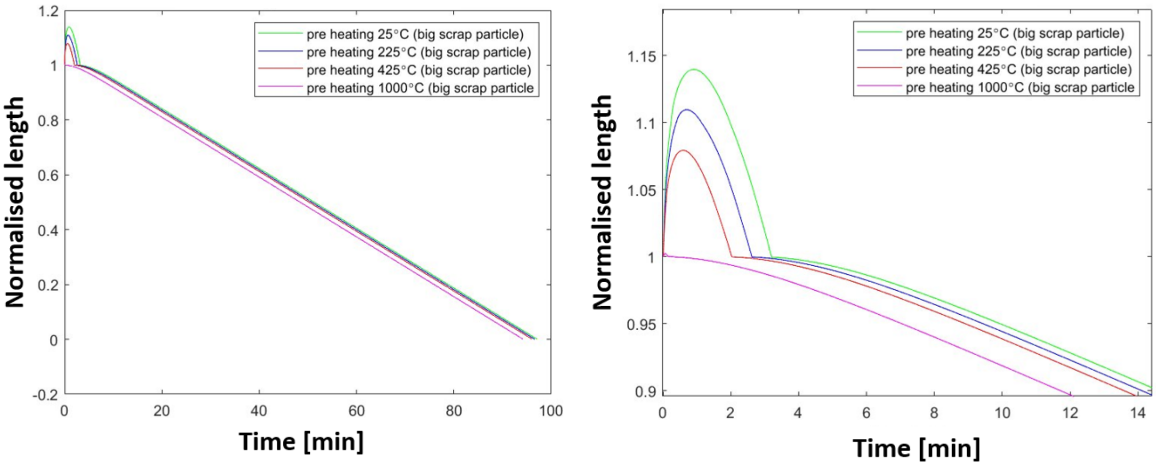


FIG 6 – (a) The influence of pre-heating temperature on melting behaviour of large scrap (b) Magnification of the early stage of the melting

Similar to the feed pile effect, Figure 6 shows that preheating the large scrap particle before entering the feed pile does not have a beneficial influence on total melting time and only influences the shell formation phase. Therefore, from purely melting time point of view it could be argued that pre-heating is not contributing to the scrap melting. However, if pre-heating is meant to increase the heat input to the system or decrease the electrical power input, then it might be beneficial.

CONCLUSIONS & RECOMMENDATIONS

In this work, a phenomena-based model was built in order to simulate the heating and melting behaviour of a single scrap particle in an OSBF. Based on the validation study, it can be concluded that there is a reasonable agreement between the model and utilized experimental data. However, there is some discrepancy in predicting the initial shell formation phase between the model and the experiments partly due to the numerical approach used. Using a different FDM approach would allow a higher Fourier number, affording greater flexibility.

Furthermore, due to the inherent limitations of the model such as having a 1-D approach and constant physical properties, 2-3 D simulation with temperature and composition dependent physical properties would greatly improve the reliability of the simulation.

Based on the parametric study, the role of carbon in hot metal is proved to be critical for the total melting time. Specifically in mass transfer controlled melting regime when the liquid hot metal temperature is close to its liquidus temperature, increasing carbon content in the hot metal while keeping the same temperature significantly speeds up the melting process. In the case study, a 15 times increase in melting was observed for carbon increase in hot metal from 1.0wt% to 2.0wt%.

Similarly, the temperature of the hot metal has a considerable influence on the melting rate. In particular, increasing temperature from 1400°C to 1500°C results in ~72% shorter melting time. The role of temperature is more significant in mass transfer controlled regime than heat transfer controlled regime.

The scrap size was also found to be a key factor in scrap melting, with larger scraps requiring ~9 times longer melting time. Pre-heating prior to entering the OSBF showed very little influence on the total melting time even though for large scrap particle the initial shell thickness was decreased at higher pre-heating temperatures.

The chemical interaction of the slag and cold scrap requires further fundamental research to clarify the underlying chemistry. This would bring further insight into the role of slag during the rather short contact time with scrap.

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