Melting Behavior of Hydrogen-Reduced DRI in a Simulated EAF Steel Bath

J. Govro [1], A. Meena[1], S. Chakraborty[1], A. Meshram[2], I. Korobeinikov[2,3], K. Phillips[1], V. Athavale[1], L. Bartlett[1], J. Smith[1], A. Emdadi[1], S. Seetharaman [2], R. O'Malley[1]

[1]Missouri University of Science and Technology

[2]Arizona State University

[3]Technische Universität Bergakademie Freiberg

INTRODUCTION

The melting behavior of carbon-free DRI produced by hydrogen reduction has been investigated in a simulated electric arc furnace (EAF) melting environment. A testing apparatus was created to document the melting rates under various bath conditions in slag and steel. This investigation is specific to pellets melted in a steel bath. A model was developed to simulate the shell growth and melting rate of a non-reactive DRI pellet in molten steel. Data acquired from preliminary experiments are utilized to validate the model. This investigation sheds light on the potential effects of melting hydrogen-reduced DRI in the EAF.

OVERVIEW OF LABORATORY HYDROGEN PELLET REDUCTION

Commercial iron ore pellets were directly reduced in a laboratory scale reduction furnace (Figure 1) at Arizona State University (ASU). Pellets reduced in a pure hydrogen atmosphere at 700C were used for this study, although pellets were also reduced under several different conditions. Future experiments will investigate the effects of different reduction conditions on melting behavior. Reduced pellets were delivered to Missouri University of Science and Technology (MST) for melting studies.

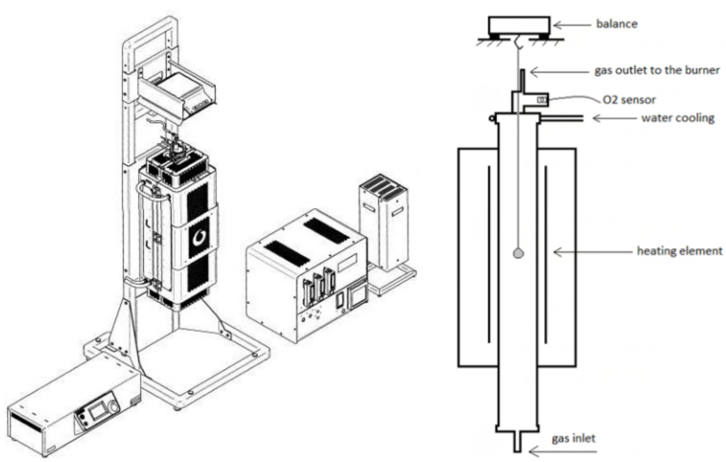

Figure 1. Laboratory-scale reduction furnace located at ASU

DEVELOPMENT OF MELTING EXPERIMENT

Furnace Configuration

DRI melting experiments took place in the MST laboratory-scale foundry. Melting of the steel bath took place in a 200-lbs induction furnace with a 100-lbs crucible. A diagram of the melting apparatus can be seen in Figure 2. A graphite susceptor was added around the outside of the crucible to increase temperature at the slag line to aid future pellet melting studies focused on melting in the slag and at the slag-metal interface. It should be noted that there was no slag added in the experiments described in this paper.

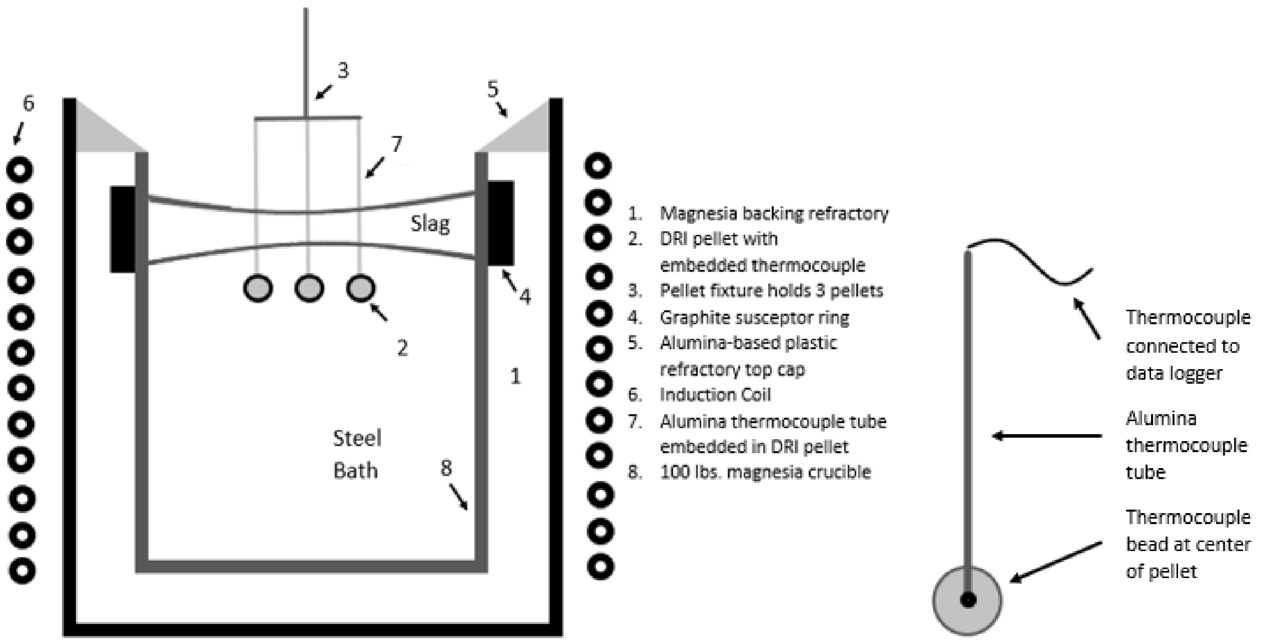

Figure 2. Apparatus for Preforming Melting Study and Mounted pellet

Pellet Mounting

Before mounting, each pellet was weighed, and its dimensions were measured individually. Each pellet was bored to the center using a milling machine. K-type thermocouples were sheathed using alumina thermocouple tubes and the exposed wires were welded to form a junction. The thermocouple assembly was then pressed into the bored pellet so that the junction contacted the pellet center and the assembly was fixed in place using an alumina-silicate refractory cement.

Fixture configuration

Nine identical fixtures were fabricated which each can hold three pellets. A mounting process has been developed that ensures the center of all three pellets will be at the same relative height in the bath. Alumina tubes were cemented to the steel pellet fixtures. Preliminary tests were immersed manually; however future tests will employ the use of a pneumatic frame to control the immersion of the pellet into the steel bath and to ensure repeatability of the test.

Test Procedure and Results

Several experiments with both laboratory hydrogen-reduced pellets and commercially produced DRI pellets were conducted during the development of the testing procedure and the initial set up of the test. The preliminary results reported here were performed using interrupted melting tests, i.e., the pellet was held in the bath for between 6 and 8 seconds and then removed from the bath to observe the steel shell growth and melting of the pellet while also measuring the temperature rise at the pellet center on the sample.

It should be noted that gas evolution was not observed with the hydrogen-reduced pellets during immersion into the steel bath, whereas conventional DRI experienced several seconds of gas evolution when the pellet was immersed into the bath. This is important since carbon monoxide evolution from the reaction of carbon and unreduced FeO in commercial DRI pellets occurs during pellet heating and melting. This gas evolution can contribute to slag foaming in the EAF, which is essential for high efficiency operation, [1] and influence the pellet melting process by enhancing the convective heat transfer in the melt. The absence of carbon in hydrogen reduced DRI does not exhibit such gas evolution and therefore may experience lower melting efficiency in the EAF.

Temperature data from the imbedded thermocouple was logged during the immersion test. A sample of the centerline temperature data is shown in Figure 3.

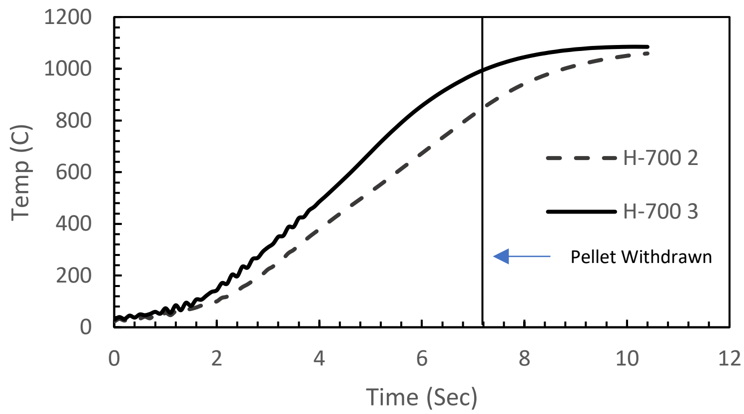

Figure 3. Raw temperature data from interrupted pellet immersion test in a low C steel bath. Vertical line indicates approximate time of pellet removal from bath.

Shell Thickness Measurement

After the interrupted immersion tests, the DRI samples were cooled, mounted in epoxy and sectioned to perform shell thickness measurements. These measurements were performed using digital microscope and taking the average shell thickness at multiple locations around the perimeter of the pellet. Figure 4 shows an example of a pellet cross section after an interrupted immersion test, as well as measurements around said shell.

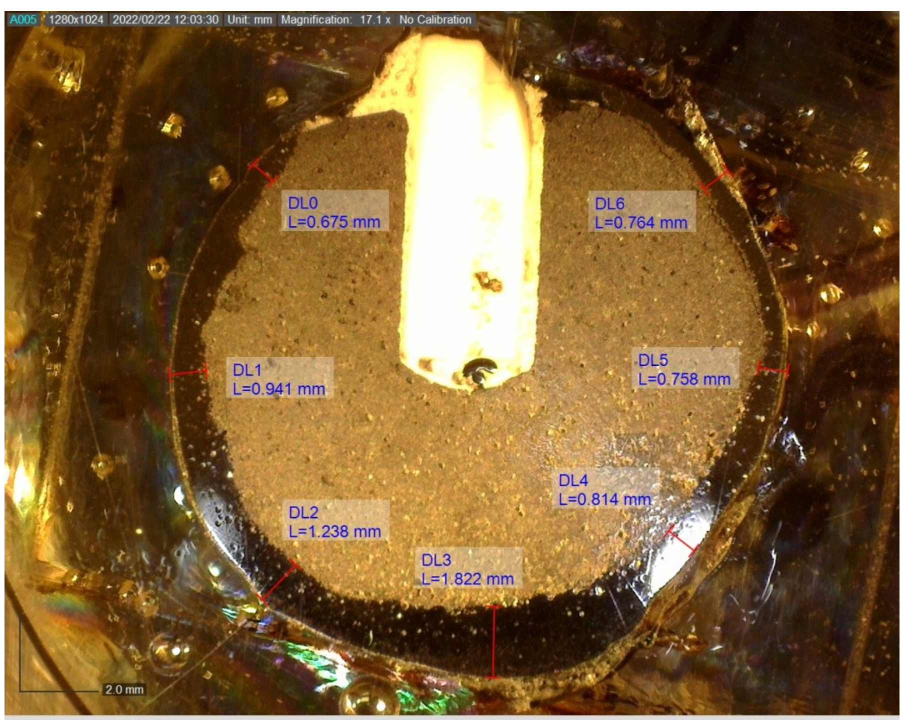

Figure 4. Shell measurements from immersed hydrogen reduced pellet. Average shell thickness =1mm.

RELEVANT CHARACTERIZATION

SEM images and macros were taken of both commercial DRI pellets and hydrogen reduced DRI pellets to determine if there were any obvious differences is structure that would influence the melting behavior of the pellets. (Figure 5) Although the hydrogen reduced pellets were produced in a laboratory setting, they exhibited a similar structure to that of the commercially produced hydrogen pellets. A more detailed comparison of the DRI pellet structures is ongoing.

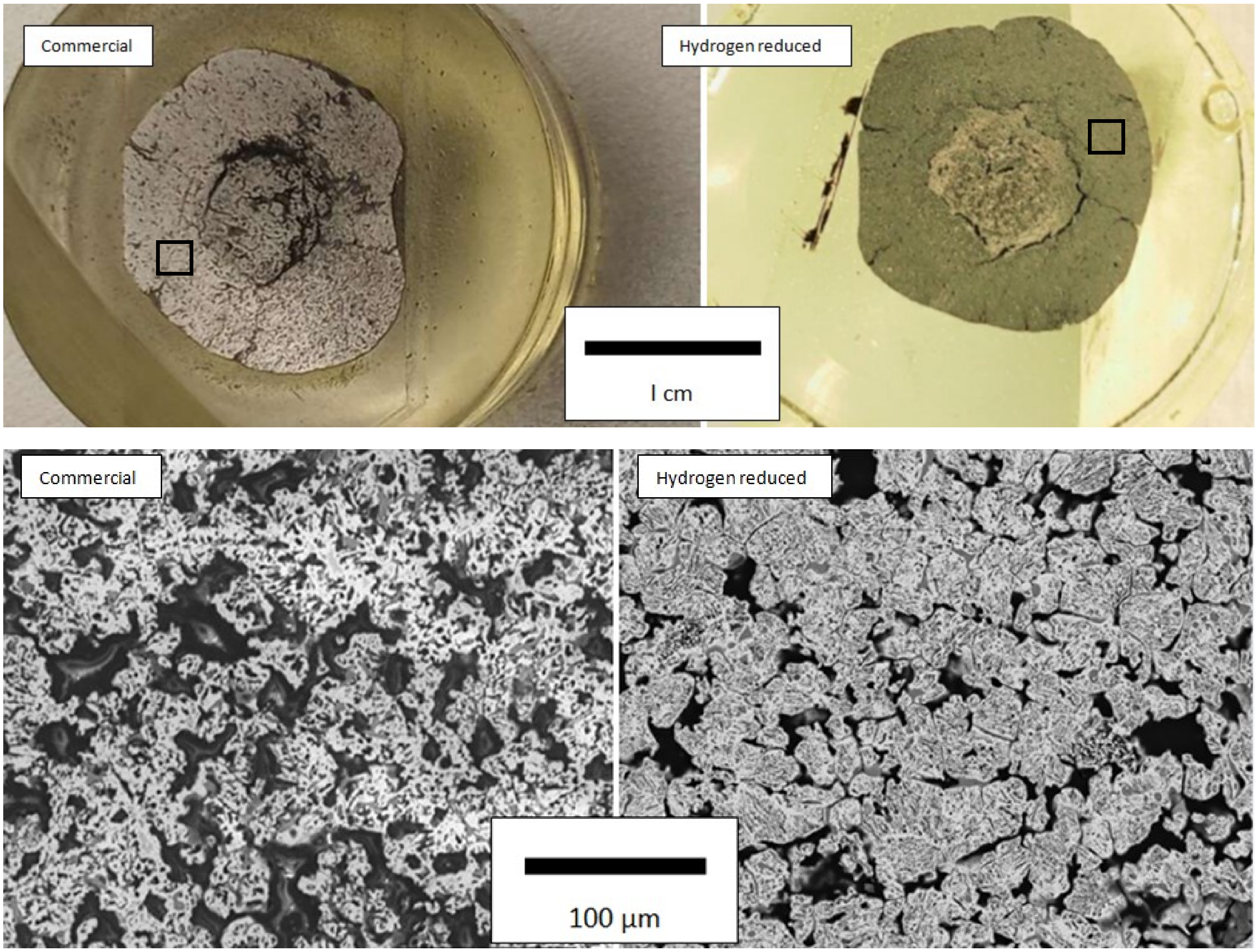

Figure 5. Macro images (top) and SEM images (bottom) of sectioned DRI pellets. It should be noted from the macros that both pellets have a distinct core region that is a product of the pelletization process. This indicates that similar oxide pellet feedstock was used for both pellets.

DEVELOPMENT OF MODEL

Assumptions

Modeling efforts to date have focused on the melting of non-reactive DRI pellets, i.e., pellets that do not react to liberate CO gas. The melting rate of the carbon free H_2 reduced DRI pellet in a low carbon bath is assumed to be heat transfer controlled. A model was developed by Kim and Pehlke concerning the heat transfer of cylindrica iron samples immersed in a bath. [2] The simulation developed in this paper is similar concerning heat transfer, except for a spherical sample. Due to the lack of carbon in the DRI and the low carbon content of the steel bath, no bath agitation from the evolution of CO gas occurs and convective heat transfer is dominated by other conditions that induce stirring in the furnace. For our induction furnace trials, the power was turned off during pellet immersion to avoid any enhanced convection from induction stirring. In conventional carbon bearing DRI, the mass transfer of the carbon between the DRI and the steel bath, as well as the carbon monoxide evolution, may both influence the melting behavior of DRI in the EAF.

Modeling

The following section summarizes the computational modeling efforts to simulate the melting behavior of the DRI pellet in a steel bath. The heat transfer module in COMSOL Multiphysics software was utilized in this study. The thermophysical properties and the initial temperatures of the hydrogen reduced DRI pellet and the bath are given in Table 1. [3] The carbon content in the bath is assumed to be very low (~0.026 wt.%) for this case.

Table 1. Thermophysical properties of steel bath, shell, and hydrogen reduced pellet

	Bath	Shell	Pellet [2]
Initial temperature [K]	1873	-	298
Melting point [K]	-	1780	1803
Thermal conductivity, k[W/(mK)]	8	30	3.8
Density, ρ [kg/m^3]	7000	7200	3370
Specific heat capacity, Cp [J/(kgK)]	680	780	820
Heat transfer coefficient, h [W/m^{2}K]	300 [2]	-	-

Assumptions and Physics

To predict the heat flow and temperature distribution during pellet melting in a low carbon steel bath, the conservation equation of energy is used (Equation 1) where ρ is the density, $\vec{u}$ is the fluid velocity, Q_{conv} is the convection, T is the temperature, and k is the thermal conductivity. Initial temperature (at t=0 s) of the bath and the DRI pellet are considered as 1873K and 298K, respectively.

$$\rho c_p \left[\frac{\partial T}{\partial t} + \vec{\nabla}.(\vec{u}T) \right] = \vec{\nabla}.(k\vec{\nabla}T) + Q_{conv} \quad (1)$$

Based on experimental observations, three steps are expected to be observed during the DRI pellet heating and melting process:

- As the initial temperature of the DRI pellet is lower than the melting temperature of the steel bath, the molten steel adjacent to the pellet will solidify and a shell of solidified steel will grow around the pellet.
- The shell will grow to a maximum thickness, and then begin to remelt as heat is transferred from the melt. The shell eventually melts completely when the innermost part of the shell reaches the melting temperature of the bath.
- Once the temperature at the pellet surface reaches its melting temperature, the pellet starts to melt in the steel bath.

The conditions at each step in the melting process are presented schematically in Figure 6

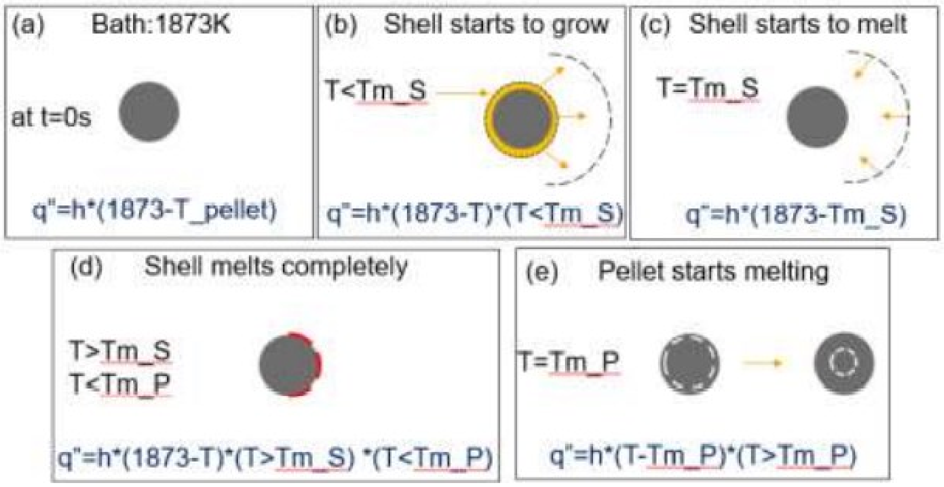

Figure 6. Schematic of convection condition during melting of a DRI pellet in the steel bath: (a) at t=0s, pellet is surrounded by the bath, (b) shell grows to a maximum thickness, (c) shell begins to remelt, (d) The pellet surface heats to reach to the melting temperature of the pellet, (e) and once reached, the pellet will begin to melt into the bath. "h" is the heat transfer coefficient.

Model Setup

A two-dimensional (2D) axisymmetric model was developed to simulate the melting process of DRI pellets in molten steels and slags. Figure 7 shows the geometry of the bath and the initial radius of the DRI pellet. Triangle elements were used to discretize the domain as depicted in Figure 8.

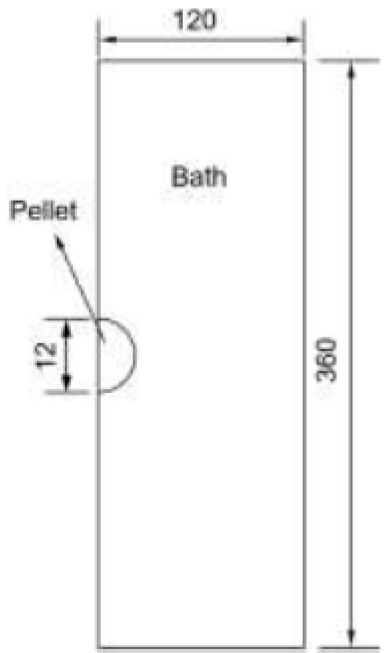

Figure 7. The geometry of the bath and initial radius of the DRI pellet (all units are in mm)

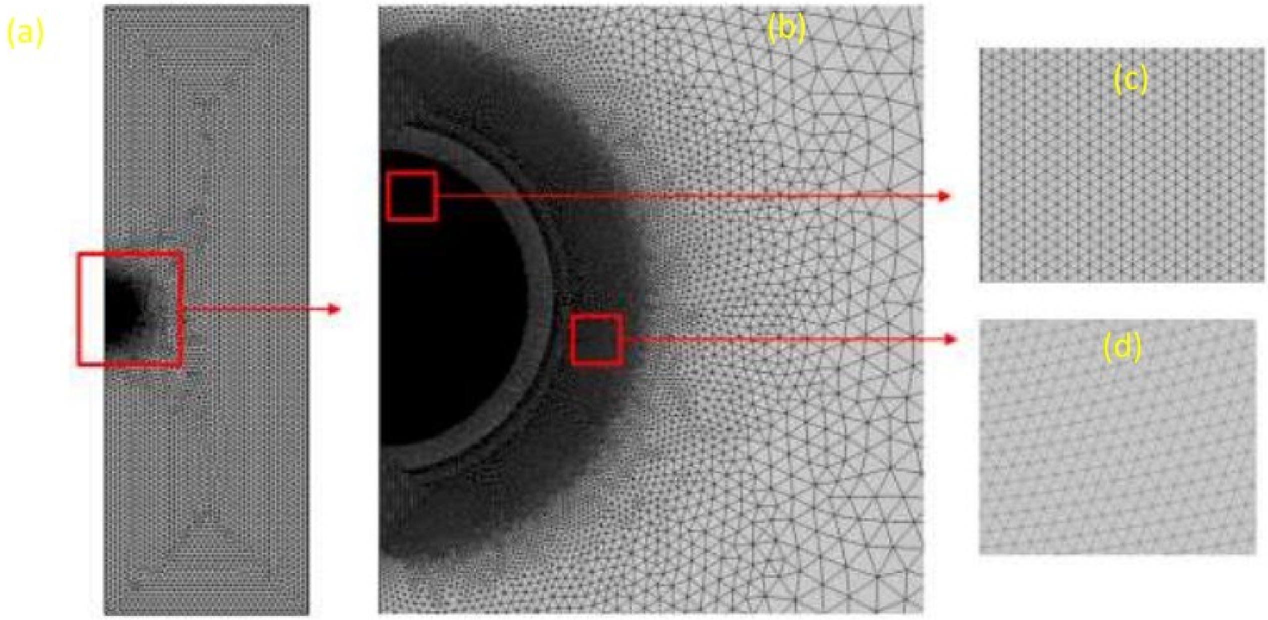

Figure 8. (a) The model discretization by triangular elements, (b) zoomed mesh section of the DRI pellet, (c) zoomed mesh section of the pellet, the pellet mesh size is 0.05 mm, and (d) zoomed mesh section of the shell, shell mesh size is 0.09 mm.

RESULTS AND DISCUSSION

Figure 9 presents a prediction of the melting behavior of an isolated DRI pellet in molten low carbon steel using the COMSOL model. At the beginning of the simulation, the liquid steel adjacent to the pellet solidifies as the liquid's temperature drops below the melting temperature of the bath. The shell thickness increases to a maximum, and then decreases as the shell remelts. The calculated maximum shell thickness is approximately 1 mm for an assumed heat transfer coefficient of 300 W/m^{2}K in the steel bath and the conditions used in the simulation. As the melting temperature of the pellet is slightly above the melting temperature of the steel bath, it takes approximately 5s for the outer surface of the pellet to reach its melting temperature. This stage is represented by the radius plateau between red and green arrow in Figure 9. Once the melting temperature of the pellet is reached, the pellet starts to melt. The COMSOL model currently predicts a total melting time of 39 s for the pellet in the steel bath.

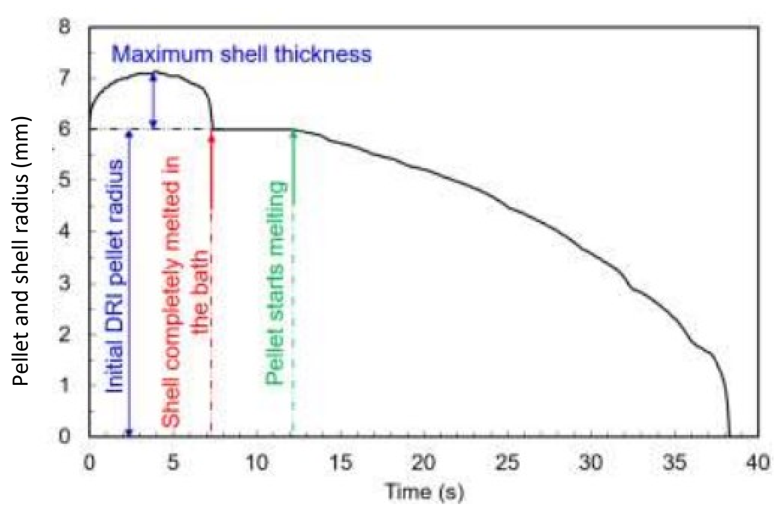

Figure 9. Melting Behavior of the DRI pellet

A comparison between measured and predicted shell thickness and pellet centerline temperatures are shown in Figure 10 for a hydrogen reduced DRI pellet. The predicted shell thickness and the center temperature rise are in reasonable agreement with physical measurements up to 6-7 seconds. This preliminary result demonstrates that the model can be used to predict the shell formation of the DRI pellet in a steel bath. Further experimental results are required to determine when completed dissolution occurs, further model development may be required.

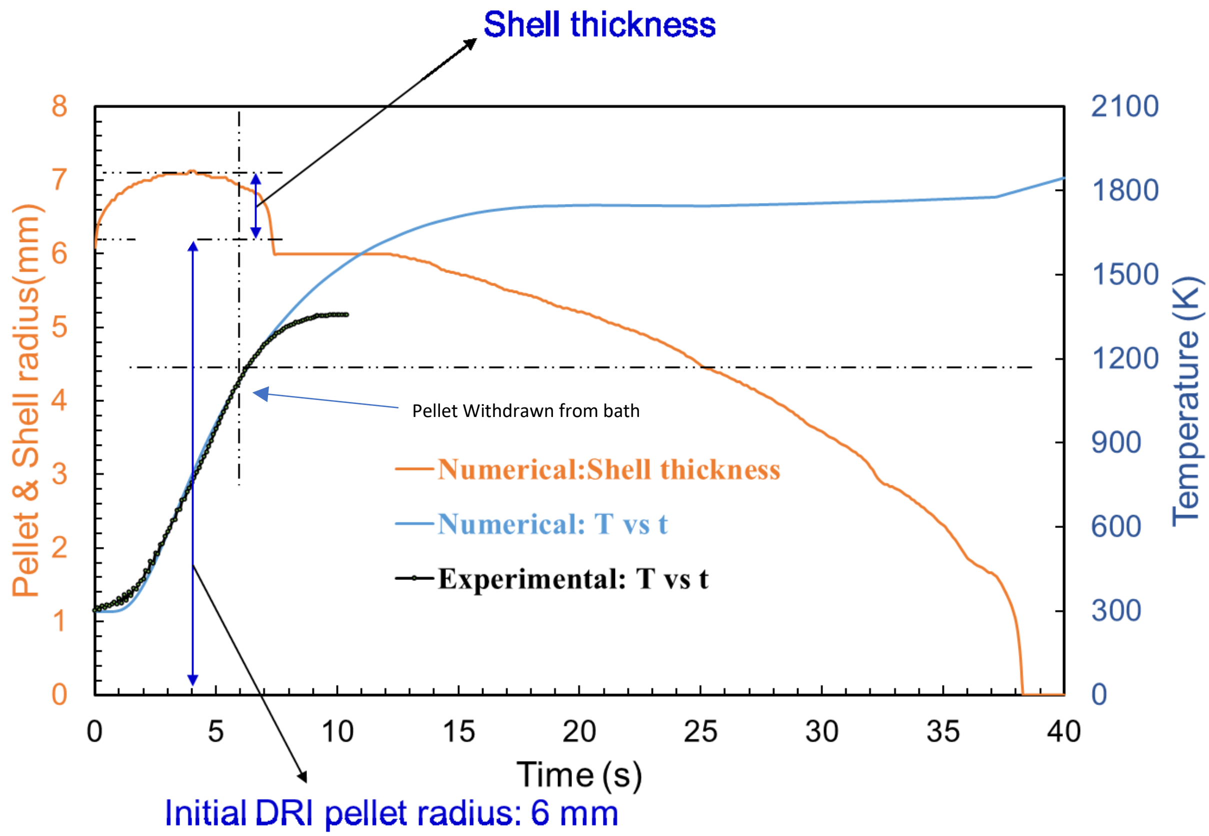

Figure 10. Temperature and Shell Growth Measurement vs. Model

CONCLUSIONS

An experimental procedure was successfully developed that allows the internal temperature of an H_2 reduced DRI pellet to be measured while it is immersed in a slag or steel, as well as the ability to measure the thickness of the transient shell that develops around the pellet prior to pellet dissolution. A model was developed to predict the shell formation as well as melting behavior of a single DRI pellet in a molten low carbon steel bath. Internal pellet temperature, immersion time, and shell thickness can all be utilized to validate the model. Initial results are promising and show that the model predictions are in reasonable agreement with the experimental data. More DRI immersion tests using pellets with varying thermophysical properties and pellets containing reactive oxides and carbon will be employed to further refine the model. Future planned laboratory melting studies also include pellet melting in slag, pellet melting at the slag /metal interface, HBI melting, and bulk addition DRI melting behavior.

ACKNOWLEDGEMENTS

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