Density of Liquid IF Steel Containing Ti

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Density of liquid IF Steel containing Ti was measured with the modified sessile drop method at a temperature range from 1 530 to 1 610°C. Densities of pure molten Fe measured at a temperature range between 1 550°C and 1 600°C were quite close to those obtained by Saito et al., but a little lower than their results at temperature higher than 1 600°C. Thermal expansion coefficient of molten IF steel containing Ti increased linearly with an increase in titanium content. The density of the liquid IF steel was described as a function of the temperature and Ti content as follows:

\[ \rho = 7.05 - 4.73 \times 10^{-2} \% \text{Ti} - (1.05 + 0.66 \% \text{Ti}) \times 10^{-3} (T - 1530) \]

KEY WORDS: liquid IF steel containing Ti; density measurement; modified sessile drop method.

1. Introduction

Density of molten steel at high temperature is an important physical property in ferrous metallurgy. Density of liquid steel in ladles, tundishes and moulds and its variation with temperature and compositions at high temperature must be determined when transport phenomena, such as, momentum, heat and/or mass transfer, are investigated. The precise density values of molten steel should be known when interfacial properties of the molten steel with solid inclusions are researched with sessile drop method. Therefore, the precise measurement on density of liquid steel at high temperature is of importance for the research on momentum, heat and/or mass transfer process of molten steel in metallurgical reactors and high temperature interfacial phenomena.

Methods usually used for density measurement of melt at high temperature are maximum bubble pressure method, Archimedean method, modified Archimedean method, levi- tation drop method, sessile drop method and modified sessile drop method. Many researchers have measured the density of pure liquid iron or molten steel with different methods.1–13) For the sessile drop method, if a smaller drop is used, larger error in density may occur due to the smaller volume, but if a larger drop is applied, it is difficult to keep the drop in good symmetry, which also results in error. The density of liquid IF steel (Interstitial Free steel with much low carbon content for automobile bodies) containing titanium at high temperature was measured with the modified sessile drop method developed by Mukai11) in the present work in order to avoid the above disadvantages in the sessile drop method and to improve the measurement accuracy.

2. Experimental Method

In the density measurement with the modified sessile drop method, a metal sample was put into an alumina crucible (Al2O3). At high temperature, the metal sample melts into liquid, as shown in Fig. 1. If the melt volume, \( V \) at a certain temperature is known, the density of the melt, \( \rho \) at the temperature can be calculated out with the formula, \( \rho = m/V \) from the average mass, \( m \) of the metal sample before and after measurement. It is known from Fig. 1 that the melt volume can be divided into two parts, that is,

\[ V = V_1 + V_2 \]

where, \( V_1 \) is the volume of the liquid inside the crucible and \( V_2 \) is the volume of the liquid above the crucible. \( V_1 \) can be worked out from the initial volume, \( V_0 \) and the linear expansion, \( \alpha \) of the crucible:

\[ V_1 = V_0 (1 + \alpha \phi) \]

\( V_2 \) can be evaluated from the shape of the upper part of the liquid above the crucible:

Fig. 1. Schematic of a crucible with a sample at high temperature in the density measurement.
where, \( x \) is radius of the melt at the height, \( z \). In such a method of density measurement, there are advantages not only to use larger mass of a metal sample but also to assure the good symmetry of the upper liquid profile above the crucible. Therefore, better accuracy in the measurements is expected.

The apparatus used for the measurements consisted of a LaCrO₃ electric resistance furnace with a maximum power of 6 kVA, a gas purification system, an oxygen potential measurement system, a camera and a computer used to calculate the upper liquid volume, \( V_2 \). Figure 2 presents a schematic diagram of the apparatus. Two high purity alumina (99.8% Al₂O₃) tubes were applied in the furnace for air-tightness of the furnace chamber. The outer and inner tubes were 50 mm and 37 mm O.D., 42 mm and 30 mm I.D. and 650 mm and 700 mm in length, respectively. Both ends of the tubes were sealed with water-cooling stainless steel caps and plastic “O” rings. The temperature of the furnace was measured with a 20 : 40 Pt–Rh thermocouple and was controlled by using a PID digital program controller. The heating rate was 5°C/min. The experimental temperature range was from 1520 to 1610°C. The compositions of the metal samples used in the measurements were shown in Table 1. The effect of different oxygen and carbon content among the samples on the density was ignored due to their very small content in the samples.

The measurement was carried out in an Ar atmosphere. 100 mL/min of argon was passed through an Ar purifier first and further deoxidized with magnesium chips heated at 598°C in a magnesium furnace. The gas from the LaCrO₃ furnace was led into a furnace to measure the oxygen partial pressure with an oxygen probe fabricated with calcia-stabilized zirconia solid electrolytes and Ni–NiO as a reference electrode at 800°C. The oxygen partial pressure of the gas from the LaCrO₃ furnace was between 10⁻¹⁸ MPa and 10⁻¹⁹ MPa.

A steel sample with about 9–10 g weight was polished to remove any surface oxide. The substrate was placed on one end of an alumina support and its horizon was adjusted with two water levels. Then, the crucible with the steel sample was set on the center position of the substrate. The support was placed carefully into the chamber of the inner tube.

Photographs of the molten sample in the crucible were taken by using a camera. The camera was placed on a mechanical frame that can move at three dimensions. In order to obtain the results in equilibrium state the first photograph was taken at 30 min after the furnace reached the experimental temperature. Then the photographs were taken every 5 min. Three photographs were taken at one experimental temperature.

The upper liquid contour in a photograph was input into a computer with a digitizer. Its volume was calculated by determining the contour curve with best fit between the numerical solution to the classical Laplace’s equation and experimentally measured points, according to Rotenberg’s method with a software.

Because expansion coefficient of crucibles was considered to be dependent on the material and manufacture method of the crucibles, the expansion of the crucibles was measured in the present work. Photographs of the crucibles with molten sample were taken on nega films in the density measurement experiments. Dimensions of the crucibles on the nega films obtained at different temperature were enlarged and measured by a gauging microscope with 0.001 mm accuracy. Therefore, the expansion coefficients of the crucibles were calculated from the linear dimensions at room temperature.

3. Experimental Results and Discussion

Figure 3 presents the relationship between the linear expansion of the alumina crucibles and temperature. The linear expansion was about 1.5–2.0% at the temperature range from 1520 to 1610°C. The linear expansion increases linearly with an increase in the temperature. In the figure there seems to be a little difference among the three crucibles, but it was found that most experimental data were within the measurement error. By substituting the expansion, \( \alpha \) obtained into Eq. (2), the crucible volume, \( V_1 \) at different experimental temperature can be worked out from the initial crucible volume, \( V_0 \).

<table>
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<th>Sample</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Al</th>
<th>Ti</th>
<th>O</th>
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<td>0.002</td>
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<td>0.003</td>
<td>0.0025</td>
<td>0.020</td>
<td>0.001</td>
<td>0.0017</td>
<td>0.0009</td>
</tr>
<tr>
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<td>0.003</td>
<td>&lt;0.005</td>
<td>0.003</td>
<td>0.0024</td>
<td>0.021</td>
<td>0.126</td>
<td>0.001</td>
<td>0.0021</td>
</tr>
<tr>
<td>3</td>
<td>0.0019</td>
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<td>0.021</td>
<td>0.240</td>
<td>0.001</td>
<td>0.0026</td>
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</table>
Figure 4 shows the density of molten pure iron (Sample 1) obtained in this work and the reported values by various investigators with different methods. It is evident from this work that the density of pure Fe is a linear function of temperature. The results from different researchers exist large difference among them. In the temperature range between 1550°C and 1650°C, Kingery et al. got the maximum results for pure iron using sessile drop method, being 7.25–7.08 Mg/m³, whereas Adachi et al. obtained the lowest values using levitation drop method, being 6.95–6.85 Mg/m³. The density of molten pure iron obtained in the present work was almost the same with that measured by Saito et al. using maximum bubble pressure method in the temperature from 1550–1600°C, but a little bit lower than their result at the temperature higher than 1600°C.

Variation of the density of liquid IF steel containing Ti against temperature is shown in Fig. 5. For the three samples, their densities decrease linearly with an increase in temperature as shown in Fig. 5. According to Steinberg’s formula, density can be represented by the following equation:

\[ \rho = \rho_m + k(T - T_m) \] ...........................(4)

where \( \rho_m \) stands for density at the melting point \( T_m \) and \( k \) for temperature coefficient at constant pressure. The following regression equations for the three steel samples can be achieved from the experimental data:

\[ \text{Sample 1} \quad \rho = 7.06 - 1.05 \times 10^{-3}(T - 1530) \quad (\text{Mg/m}^3) \] ...........................(5)

\[ \text{Sample 2} \quad \rho = 7.05 - 1.13 \times 10^{-3}(T - 1530) \quad (\text{Mg/m}^3) \] ...........................(6)

\[ \text{Sample 3} \quad \rho = 7.04 - 1.21 \times 10^{-3}(T - 1530) \quad (\text{Mg/m}^3) \] ...........................(7)

From the temperature coefficients and the titanium contents of the three steel samples, a following equation can be given out by the least square method:

\[ k \times 10^3 = -(1.05 + 0.66[\%\text{Ti}]) \] ...................(8)

Thermal expansion coefficient is defined as follows:

\[ \beta = - \frac{1}{\rho_m} \left( \frac{\partial \rho}{\partial T} \right)_p \] ...........................(9)

Therefore, the thermal expansion coefficient of each sample can be calculated with Eq. (9) from Eqs. (5)–(7) and the coefficient values are 1.49×10⁻⁴ K⁻¹ for sample 1, 1.60×10⁻⁴ K⁻¹ for sample 2 and 1.71×10⁻⁴ K⁻¹ for sample 3. Figure 6 presents the thermal expansion coefficient of liquid IF steel containing Ti as a function of titanium content. It is obvious that the addition of titanium into liquid IF steel increases linearly the thermal expansion coefficient. A re-
gression equation for the thermal expansion coefficient is obtained:

$$\beta = (1.49 + 0.92[\%\text{Ti}]) \times 10^{-4}$$ ................(10)

Figure 7 expresses the variation of density of molten IF steel containing Ti with titanium content at different temperatures. It is indicated in the figure that the density of liquid IF steel bearing Ti at a certain temperature decreases with an increase in titanium content. The decrease in density of IF steel containing Ti is less at 1530°C than others at the temperature higher than 1550°C. Linear regression equations at different temperature for the density of liquid IF steel as a function of titanium content can be gained from the experimental data in Fig. 7. With the assumption of linear relationship between the density and temperature, and between temperature coefficient of density and titanium content, a following equation can be derived from Eq. (8) and the linear regression equation at 1530°C in Fig. 7:

$$\rho = 7.05 - 4.73 \times 10^{-2}[\%\text{Ti}] - (1.05 + 0.66[\%\text{Ti}]) \times 10^{-3}(T - 1530)$$ ..........................................(11)

4. Conclusion

Density of molten IF steel containing titanium was measured with the modified sessile drop method. The following conclusions could be drawn from this research.

(1) The density of liquid pure Fe measured at a temperature range between 1550°C and 1600°C was quite close to those obtained by K. Saito et al. with maximum bubble pressure method, whereas a little lower than their results at temperature higher than 1600°C.

(2) The thermal expansion coefficient of molten IF steel containing Ti increases linearly with an increase in titanium content.

(3) The density of liquid IF steel containing Ti was expressed as a function of temperature and titanium content.

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REFERENCES