Prediction of Density of Chromium Steels by Using the Relation Obtained from Sessile Drop Method and Thermodynamic Phase Calculation Data

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The change in the density of chromium steels with phase at a temperature range from 1 000 to 1 973 K have been studied by a sessile drop profile method. Measurement of the density by a sessile drop profile method has to be carried out under heating conditions to avoid the influence of both undercooling and the shrinkage within the sample during solidification. The density of chromium steels were dependent on the phase but not chromium contents. The density in the liquid, δ and γ single phase, (liquid+δ), (liquid+γ), (δ+γ) coexisting states and (liquid+δ+γ) coexisting state could be predicted using the experimental results.

KEY WORDS: density; sessile drop; chromium steel; phase; transformation.

1. Introduction

The high temperature physical properties such as the density, the tensile strength and the elongation are important factors to decide the continuously cast conditions for improving the quality of chromium steel products. Therefore, many researchers1–14) have studied the density at high temperature range.

Solidification modes of chromium steels are complicated and are changed by chromium content according to the equilibrium phase diagram. The primary phase during solidification is a δ phase, and then solidification is completed either as a single phase or as two phases where δ/γ transformation occurs during solidification. Furthermore, the phases after solidification may become two phases through δ/γ transformation. Though the density of chromium steels seems to vary with phase during solidification as well as the Fe–Cr–Ni ternary alloys15) and the Fe–C steels,16) the relationship between density and phase for chromium steel was unclear in previous studies.

To study the relationship in the present paper, the density of chromium steels were measured by a sessile drop profile method, and the constituent phases of sample changes with concentrations of chromium were predicted by the Thermo-Calc17) which is a software and database package for equilibrium thermodynamic calculation. From these results, the relationship between density and phase for chromium steel was unclear in previous studies.

2. Experimental Procedures

2.1. Composition of the Samples

The chemical compositions of the chromium steel samples are listed in Table 1. In order to investigate the influence of phase on density, the chromium contents of the samples were varied. The steel ingots were produced using electrolytic iron and alloying elements in a vacuum furnace, and then were hot forged at a temperature of 1 473 K. The samples were machined to the given size and shape from round bars of 2.5×10⁻² m.

2.2. Experimental Apparatus

The density of chromium steel was measured by a sessile drop profile method.7,13–16) Figure 1 shows a schematic diagram of the experimental apparatus. A sample 6×10⁻³ m in diameter and 6×10⁻³ m in height was set on a plate made of magnesia in a vacuum vessel. The atmosphere in the vacuum vessel was replaced by argon gas after evacuation with a rotary pump. The argon gas was purified through a dehydrating cartridge-type device connected to a deoxidizing cartridge-type device. The heating rate of the sample changed with temperature, and the rate was 0.21 K·s⁻¹ for the temperature range from room temperature to 1 400 K and 0.083 K·s⁻¹ for the range from 1 400 to 1 973 K. Measurements were carried out after 120 s holding at a given temperature. The temperature of the sample was con-

| Samples | C  | Si  | Mn  | P   | S   | Cr  |
|---------|----|-----|-----|-----|-----|-----|
| C       | 0.20 | 0.24 | 0.90 | 0.012 | 0.0011 | tr  |
| 2C      | 0.20 | 0.24 | 0.88 | 0.011 | 0.0010 | 1.98 |
| 5C      | 0.20 | 0.25 | 0.89 | 0.011 | 0.0010 | 4.90 |
| 9C      | 0.20 | 0.22 | 0.90 | 0.011 | 0.0010 | 8.91 |
| 15C     | 0.20 | 0.23 | 0.89 | 0.010 | 0.0010 | 12.40 |
trolled by the output voltage of a B-type thermocouple that was held at $2 \times 10^{-3}$ m above the sample. The B-type (Pt–Rh) thermocouple is accurate at a high temperature range up to 1 973 K, but accuracy is lower below 773 K. Therefore, the density was measured in the temperature range from 1 000 to 1 973 K in this experiment.

The volume of the sample was calculated by a method of image sectioning of the sample profile assuming that the shape of the sample was symmetrical. Thus, from knowledge of the weight of the sample, the density of the sample could be easily calculated. Both the shape and the size of the sample were analyzed by using a computer from a two-dimensional shadow image photographed by a CCD camera. Shadow image of the sample was made using flash facing the CCD camera. Both the shape and the size of the sample at a given temperature were measured from four directions by rotating the sample slowly at an interval of $0.25 \pi$ radian in the horizontal plane. The average value of the volumes of the sample taken from the four directions was regarded as the volume of the sample, and the density was calculated. In order to increase the accuracy of measurement for both the shape and size of the sample, the CCD camera was connected to a telescopic lens and a magnified image was displayed on the screen of a computer. The resolution of this measurement system was $3.0 \times 10^{-5}$ m and the measuring error was within 1.5%.

From the results of observation of solidification microstructure for a Fe–Cr–Ni sample in the previous study, it was found that an undercooling occurred and a cavity formed during solidification. Therefore, in this experiment the density of the sample was measured under heating conditions to avoid these influences which will cause errors in measurement.

3. Results

3.1. Phase Transformation of Chromium Steels

Figures 2(a)–2(e) show the relationship between the liq-

![Diagram of experimental apparatus for measurement of density.](image)

Fig. 1. Schematic diagram of the experimental apparatus for measurement of density.

![Graphs showing fraction of constituent phases with temperature for chromium steel samples.](image)

Fig. 2. Change in fraction of constituent phases with temperature for chromium steel samples. (a) Sample 0CR, (b) 2CR, (c) 5CR, (d) 9CR and (e) 13CR.
uid, $\delta$ or $\gamma$ phase fraction and temperature given by the equilibrium thermodynamic calculation. The relationship between phase and temperature of chromium steel was also predicted by that calculation.

Figure 2(a) shows the relationship between mass fraction of phases and temperature for sample 0CR, which does not contain with chromium element. The primary phase of this sample during solidification was the $\delta$ phase, the fraction of $\delta$ phase decreased rapidly, and the (liquid $+\delta+\gamma$) state and the (liquid $+\gamma$) state was formed. The $\delta/\gamma$ transformation was finished before complete solidification. At solidus temperature, the $\gamma$ single phase was formed. When the temperature decreased, $\alpha$ phase was formed in the $\gamma$ phase and the structure became the ($\gamma+\alpha$) coexisting state.

Figure 2(b) shows the change in fraction of phases with temperature for sample 2CR. The primary phase of this sample during solidification was the $\delta$ phase and the $\gamma$ phase was formed during solidification and the (liquid $+\delta+\gamma$) coexisting state was formed. The fraction of $\gamma$ phase increased with decreasing temperature and the fraction of $\delta$ phase became zero before complete solidification and the (liquid $+\gamma$) state was formed. After transformation of the $\alpha$ phase, the fraction of $\gamma$ phase decreased and the fraction of $\alpha$ phase increased.

Figure 2(c) shows the relationship between fraction of phases and temperature for sample 5CR. The solidification mode of this sample was the same as that of 0CR and 2CR. The $\delta$ phase was solidified as a primary phase, and the $\gamma$ phase was formed during solidification and the (liquid $+\delta+\gamma$) coexisting state was formed. Before complete solidification, the $\delta$ phase was disappeared and the phase became a single $\gamma$ phase at solidus temperature.

The change in phase of sample 9CR with temperature is shown in Fig. 2(d). The solidification mode of this sample was different from that of 0CR, 2CR and 5CR. The primary phase of this sample was the $\delta$ phase and the fraction of $\delta$ phase increased before the $\gamma$ phase formation, and the fraction of $\delta$ phase showed the maximum value which was smaller than 1.0. After the $\delta/\gamma$ transformation started, the fraction of $\delta$ phase decreased with increasing the fraction of $\gamma$ phase. The $\delta/\gamma$ transformation did not finish during solidification and the ($\delta+\gamma$) coexisting state formed at solidus temperature. When the temperature decreased, the $\gamma/\alpha$ transformation started and the fraction of $\gamma$ phase decreased.

Figure 2(e) shows the relationship between phase of sample 13CR and temperature. The behavior of phase change of this sample was the same as that of 0CR and the $\delta$ phase was the primary phase. The $\delta/\gamma$ transformation started during solidification but did not finished at solidus temperature. The ($\delta+\gamma$) coexisting state was formed below solidus temperature. The temperature range for the ($\delta+\gamma$) state of this sample was larger than that of sample 9CR. The $\gamma/\alpha$ transformation started at low temperature in this experiment.

![Fig. 3. Change in density with temperature for chromium steel samples. Closed circles represent the experimental results on heating condition and solid line represents the calculated results. (a) Sample 0CR, (b) 2CR, (c) 5CR, (d) 9CR and (e) 13CR.](image-url)
3.2. Density of Chromium Steels

Figures 3(a)–3(e) show the density as a function of temperature measured under heating conditions. The relationship between phase and temperature is also shown in Figs. 3(a)–3(e).

The density of sample 0CR plotted against temperature is shown in Fig. 3(a). In the liquid phase the density increased with decreasing temperature. The difference between densities at liquidus temperature and at solidus temperature was large. There was an irregular change in the density at the δ/γ transformation temperature. In the γ phase, the density increased with decreasing temperature.

Figure 3(b) shows the relationship between density of sample 2CR and temperature. The density decreased with increasing temperature and the change of density in the liquidus–solidus temperature range was large. The difference between densities at liquidus temperature and at solidus temperature was almost the same as that of sample 0CR.

Figure 3(c) shows the density of sample 5CR as a function of temperature. In the liquid phase, the density decreased with increasing temperature. The difference between densities at liquidus temperature and at solidus temperature was large. The density of γ phase changed linearly with temperature the same as the other samples. It seems that the density changes depending on the phase state the same as sample 0CR and 2CR.

Figure 3(d) shows the relationship between density of sample 9CR and temperature. The primary phase of this sample was the δ phase, and then the (liquid + δ + γ) coexisting state was formed. The (δ + γ) coexisting state was formed at solidus temperature unlike samples 0CR, 2CR and 5CR. The density of sample 9CR decreased with increasing temperature and the density between liquidus and solidus temperature changed a lot.

Figure 3(e) shows the density of sample 13CR as a function of temperature. Though the solidification mode was the same as sample 9CR, the region of (δ + γ) coexisting state was larger. The density of these samples increased with decreasing temperature and the difference between densities at liquidus temperature and at solidus temperature was large.

From the results shown in Fig. 3, the density of chromium steels are governed either by the liquid, δ or γ phase fraction.

4. Discussion

4.1. Phase Dependence of Density of Chromium Steels

In order to investigate the dependence of density upon the liquid or γ phase, the density was arranged by the temperature difference on the basis of the start temperature of phase transformation as shown in Fig. 4.

Figure 4(a) shows the change of density in the liquid phase for samples 0CR to 13CR and previous results for stainless steel samples15) and carbon steel samples1,2,13,16) with temperature difference. The temperature difference was defined on the basis of liquidus temperature. The density for all the samples decreased with increasing temperature difference from the liquidus temperature. When the temperature difference was the same, the density of all the samples had almost the same value. The density in liquid phase was not influenced by chromium, nickel and carbon concentration under these experimental conditions.

In many previous studies on Fe–C binary alloy, the dependence of the density upon carbon content at constant temperature in the liquid phase was investigated. As the liquidus temperature varied with carbon content, superheat above the liquidus temperature was different for each carbon content under the constant temperature conditions in the liquid phase. Therefore, it would seem to be hard to investigate the dependence of density upon carbon content under constant temperature conditions. The dependence of density upon the temperature deviation from the liquidus temperature was summarized by Jimbo et al.11) and the regression line based on the present experimental results shown here, was within the range of previous results.

As the δ single phase after solidification was not formed for samples 0CR to 13CR, that relationship was used for previous results.1,2,13,15,16)

In the γ phase, the relationship between density and the temperature difference is shown in Fig. 4(b). Samples 0CR, 2CR, 5CR and previous results for stainless steel samples15) and carbon steel samples1,2,13,16) which were the single γ phase after solidification. The density was given by the temperature difference the same as in the case of the liquid phase, and the density increased with increasing temperature difference. There was no influence from chromium content under these experimental conditions.

It is found that the density of chromium steels are dependent on fraction of the constituent phases, for example the liquid and γ phase and the density in the liquid or γ phase is given by the temperature difference in all three cases. The regression lines shown in Figs. 4(a), 4(b) are given by the following equations:

\[ \rho_L = -7.50 \times 10^{-4} \Delta T_L + 7.02 \] ............................(1)

\[ \rho_\gamma = 4.80 \times 10^{-4} \Delta T_\gamma + 7.41 \] ............................(2)

The equation of regression for a δ phase was used by the

\[ \rho_\delta = -7.50 \times 10^{-4} \Delta T_\delta + 7.02 \] ............................(3)

\[ \rho_\gamma = 4.80 \times 10^{-4} \Delta T_\gamma + 7.41 \] ............................(4)
previous result.\textsuperscript{16)  
\[ \rho_\delta = 3.07 \times 10^{-4} \Delta T_\delta + 7.27 \] ..............(3)  

4.2. Prediction of Density of Chromium Steels during and after Solidification  
The densities of liquid, \( \delta \) and \( \gamma \) phase can be expressed in terms of the temperature difference as shown in Eqs. (1)–(3). On the other hand, if the temperature difference on the basis of the equilibrium thermodynamic calculation is known, the densities of liquid, \( \delta \) or \( \gamma \) phase can be predicted. Besides either the \( \delta \) single phase or \( \gamma \) single phase, the (\( \delta + \gamma \), liquid+\( \delta \)), (\( \delta + \gamma \)) coexisting states and (liquid+\( \delta + \gamma \)) coexisting state are present during solidification of chromium steels. Therefore, in order to estimate the density of chromium steels, it is necessary to know the density of both binary and ternary phases.  

In the present study, the density of both binary and ternary phases that were composed of liquid, \( \delta \) and \( \gamma \) phase were estimated using the rule of additivity as a first approximation the same as the previous studies.\textsuperscript{15,16)  By comparing estimated values with measured values, the validity of the estimation method was investigated.  

The average density in the (\( \delta + \gamma \)) coexisting state is represented by the rule of additivity as follows:  
\[ \rho_{\delta+\gamma} = \rho_{\delta} \cdot f_{\delta} + \rho_{\gamma} \cdot f_{\gamma} \] .................(4)  
\( \rho_{\delta} \) and \( \rho_{\gamma} \) were calculated from Eqs. (2) and (3), respectively, and \( f_{\delta} \) and \( f_{\gamma} \) were used by the relation shown in Fig. 2.  

The average density in the (liquid+\( \delta \)) coexisting state is given using the difference between densities at liquidus temperature and at solidus temperature, and the fraction of \( \delta \) phase:  
\[ \rho_{L+\delta} = \rho_{L} + \Delta \rho_{L+\delta} \cdot f_{\delta} \] .................(5)  

The average density in the (liquid+\( \gamma \)) state and in the (liquid+\( \delta + \gamma \)) coexisting state are given by:  
\[ \rho_{L+\gamma} = \rho_{L} + \Delta \rho_{L+\gamma} \cdot f_{\gamma} \] .................(6)  
\[ \rho_{L+\delta+\gamma} = \rho_{L} + \Delta \rho_{L+\delta} \cdot f_{\delta} + \Delta \rho_{L+\gamma} \cdot f_{\gamma} \] .................(7)  

Predicted values of density are represented by solid lines in Figs. 3(a)–3(i) and were compared with measured values.  

Figure 3(a) shows the relationship between predicted value of density and the temperature of sample 0CR. The estimated values of liquid and \( \gamma \) phase were in good agreement with the measured values and varied linearly with temperature in either phase. After the \( \alpha \) phase precipitating, the density could not be predicted because there was no equation of regression for a \( \alpha \) single phase in this experimental range.  

The estimated density of sample 2CR changed with temperature as shown in Fig. 3(b). The mass fraction of phases changed with temperature as shown in Fig. 2(b). The estimated density varied with both temperature and fraction of phases, and was in good agreement with the measured values.  

Figure 3(c) shows the change in estimated density of sample 5CR with temperature. As the solidification mode was the same as samples 0CR and 2CR, the behavior of estimated density was similar to those samples. The estimated values of density agreed with the measured values.  

Figure 3(d) shows the relationship between estimated density and temperature for a sample 9CR. It is characteristic that the (\( \delta + \gamma \)) coexisting state is formed just after solidification. The estimated density was good agreement with the measured values in the liquid, (liquid+\( \delta \)), (liquid+\( \delta + \gamma \)), (\( \delta + \gamma \)) states and \( \gamma \) phase, respectively.  

Figure 3(e) shows the change in estimated density of sample 13CR with temperature. The solidification mode was the same as sample 9CR and the \( \delta/\gamma \) transformation was not completed during solidification. The average density in the (\( \gamma + \alpha \)) state could not be estimated because there was no equation of regression for a \( \alpha \) single phase in this experimental range. The estimated value was in good agreement with the measured value.  

From these results shown in Fig. 3, it seems to predict the density for combination of liquid, \( \delta \) and \( \gamma \) phases on the basis of the rule of additivity.  

4.3. Change in Density during Solidification with \( \delta/\gamma \) Transformation  
The density during solidification is indispensable for simulation of solidification and deformation process, especially accompanied with \( \delta/\gamma \) transformation. Therefore, it is necessary to clarify the change of density during solidification.  

The solidification temperature range is thought to be one of dominant factors, which characterize the solidification behavior. Then, Fig. 5 shows the change in solidification temperature range given by the equilibrium thermodynamic calculation with chromium concentration under various carbon concentrations. Though the solidification temperature range changed with both chromium and carbon concentration, there was no characteristic behavior which was indicated in this relation. The solidification temperature range monotonously increased with an increase in the chromium concentration. For the same chromium concentration, the higher the carbon concentration was, the wider the solidification temperature range was.  

Figure 6 shows density change from liquidus temperature to solidus temperature as a function of carbon concentration. The phase formed at solidus temperature was \( \gamma \) or (\( \delta + \gamma \)) coexisting state in these cases. The difference in average density in the (\( \delta + \gamma \)) state during solidification was given as follows:  
\[ \Delta \rho = \Delta \rho_{L+\delta} \cdot \Delta f_{\delta} + \Delta \rho_{L+\gamma} \cdot \Delta f_{\gamma} \] .................(8)
When the carbon concentration is 0.2 mass%, the difference in density was constant up to chromium concentration of 6.0 mass% and decreased with increasing chromium concentration higher than 6.0 mass%. It seems that the phase is a single phase at solidus temperature up to chromium concentration of 6.0 mass% and the fraction of phase decreased with increasing chromium concentration higher than 6.0 mass%. When the carbon concentration was 0.3 mass%, the range of chromium concentration which the phase formed became larger compared with the case of carbon concentration of 0.2 mass% and then the difference in density became larger. When the carbon concentration was 0.1 mass%, the difference in density decreased with increasing chromium concentration and became lower than the case of carbon concentration of 0.2 and 0.3 mass%. However, these relations do not show the characteristic behavior of density change during \( \delta / \gamma \) transformation.

The change of density is thought to depend on the phase transformation during solidification because the density changes according to the phase such as liquid, \( \delta \) and \( \gamma \) phases.

Figure 7 shows the behavior of \( \delta / \gamma \) transformation during solidification given by the calculation for chromium steels accompanied with 0.2 mass% C.

Figure 7(a) shows the relationship between fraction of phases at solidus temperature and chromium concentration under various carbon concentrations. The \( \gamma \) single phase was formed at solidus temperature when chromium concentration was lower than 6.0 mass%. After the \( \delta \) phase forming at solidus temperature, the fraction of \( \delta \) phase increased with increasing chromium concentration. At chromium concentration of 10.5 mass%, the ratio of \( \delta \) to \( \gamma \) phase changed and the fraction of \( \delta \) phase was larger than that of \( \gamma \) phase. Therefore, the ratio of \( \delta \) to \( \gamma \) phase in the \(( \delta + \gamma )\) coexisting state at solidus temperature changed with chromium concentration. Figure 7(b) shows the change in fraction solid at both \( \delta / \gamma \) transformation start and finish with chromium concentration. The fraction solid at \( \delta / \gamma \) transformation start increased with increasing chromium concentration in the chromium concentration of 3.3 mass% or more. The \(( \text{liquid} + \delta + \gamma )\) coexisting state was formed in all chromium concentration range. The \( \delta / \gamma \) transformation finished during solidification when chromium concentration was lower than 6.0 mass%. Higher than the chromium concentration of 6.0 mass%, the \( \delta / \gamma \) transformation did not finish and the \(( \delta + \gamma )\) coexisting state was formed at solidus temperature.

The primary phase of the sample used in this experiment was a \( \delta \) phase and the \( \delta / \gamma \) transformation occurred during solidification. The average density of sample changed depending on the ratio of \( \delta \) to \( \gamma \) phase in \(( \delta + \gamma )\) coexisting state during solidification, because the change of density to fraction of \( \delta \) or \( \gamma \) phase was different.

Figure 8 shows the relationship between the change in
density of both \( \delta \) and \( \gamma \) phases during solidification accompanied with \( \delta/\gamma \) transformation and chromium concentration.

Figure 8(a) shows the relationship between amount of density change in the \( \delta \) and \( \gamma \) phases during \( \delta/\gamma \) transformation in solidification temperature range and chromium concentration for a Fe–Cr–0.1 mass%C steel. The amount of density change in both \( \delta \) and \( \gamma \) phases decreased with an increase in the chromium concentration. The amount of density change in \( \gamma \) phase was larger than that of \( \delta \) phase.

Figure 8(b) shows the relationship between amount of density change during solidification and chromium concentration for a Fe–Cr–0.2 mass%C steel. The amount of density in \( \delta \) and \( \gamma \) phases increased with increasing the chromium concentration and showed the maximum value at 6.0 mass% Cr, and then that value decreased. The amount of density change in \( \gamma \) phase was larger than that of the \( \delta \) phase.

Figure 8(c) shows the relationship between amount of density change and chromium concentration for a Fe–Cr–0.3 mass%C steel. The amount of density change in both \( \delta \) and \( \gamma \) phases increased with increasing the chromium concentration the same as a Fe–Cr–0.2 mass%C steel. However, the chromium concentration, which showed the maximum value was 10.0 mass%.

The amount of density change in both \( \delta \) and \( \gamma \) phases varied with both chromium concentration and carbon concentration. It is thought that the range of fraction solid where the change of density occurs depends on the range of fraction solid where \( \delta/\gamma \) transformation occurred during solidification concerning with Fig. 7(b).

**Figure 9** shows the relationship between range of fraction solid where \( \delta/\gamma \) transformation occurs during solidification and chromium concentration varying with carbon concentration. The range of fraction solid decreased monotonously as the chromium concentration increased for a Fe–Cr–0.1 mass%C steel. For both the carbon concentration 0.2 and 0.3 mass%, that range increased as the chromium concentration increased and showed the maximum value. The chromium concentration, which showed the maximum value of the range of fraction solid was 6.0 mass% for a Fe–Cr–0.2 mass%C steel and that concentration was 9.0 mass% for a Fe–Cr–0.3 mass%C steel.

Therefore, it is necessary to take the difference of both density and fraction solid during \( \delta/\gamma \) transformation into consideration to examine the characteristic of density change. The values of the difference of density divided by the difference of fraction solid during \( \delta/\gamma \) transformation are defined as the rate of density change and shows in **Fig. 10**.

For carbon concentration of 0.1 mass%, the rate of density change depended greatly on chromium concentration. The rate of density change decreased to as chromium concentration increased once and increased, and then showed maximum value and decreased again. That value was zero in chromium concentration of 10.0 mass% or more because of no \( \delta/\gamma \) transformation.

The difference between rate of density change for carbon concentration of 0.2 and 0.3 mass% was small, and that value decreased as chromium concentration increased once and then increased. Though these rates of density change were smaller compared with the case of carbon concentration of 0.1 mass% when the chromium concentration was lower than 10.0 mass%, these values were larger oppositely in chromium concentration of 10.0 mass% or more.

The rate of density change became large when both carbon and chromium concentration was low or high. It is thought that the cracks and porosity of continuously cast steel products is generated easily when the rate of density change is larger because the density changes with a small fraction solid. The rate of density change seems to be qualitatively corresponding to the frequency of crack and porosity generation.\(^{39}\)

However, these experimental results show average values of density over the whole sessile drop-shaped sample. The dominant factor for high temperature deformation behavior of steel products is not only density change but also tensile strength and elongation, it seems to be necessary to evaluate these overalls. Tensile strength and elongation, which show the characteristics of high temperature properties, appears at a fraction solid of 0.8\(^{201}\) where dendrites forms a network\(^{21}\) during solidification and then the tensile strength and elongation increases with increasing fraction solid over fraction solid of 0.8. Therefore, when the deformation behavior in the continuously cast steel products are analyzed, the density seems to influence the deformation behavior in the shell over the fraction solid of 0.8.

5. Conclusions

The density of chromium steels were measured using a sessile drop profile method and the relationship between
density and phase that was estimated by an equilibrium thermodynamic calculation was investigated. The average density in the \((\delta + \gamma)\) coexisting state was estimated by the rule of additivity as a first approximation and the validity of this rule was investigated by comparing with the measured values.

1) The density of chromium steels were determined by temperature and fractions of phase the same as carbon steels.
2) The density in liquid and \(\gamma\) phase of chromium steels were calculated as a function of temperature difference based on transformation temperature.
3) The average density in \((\text{liquid} + \delta), (\text{liquid} + \gamma), (\text{liquid} + \delta + \gamma)\) and \((\delta + \gamma)\) coexisting states of chromium steels were calculated as a function of phase. The estimated values were in good agreement with the measured values.
4) The difference between densities at liquidus temperature and at solidus temperature for chromium steels changed with both chromium and carbon concentration because the phase at solidus temperature depended on both chromium and carbon concentration.
5) The difference of density and the difference of fraction solid during \(\delta/\gamma\) transformation in solidification temperature range depended on the amount of change in both \(\delta\) and \(\gamma\) phases. The rate of density change depended on chromium and carbon concentration.

**Nomenclature**

\[
\begin{align*}
\rho_L & : \text{Density in the liquid phase (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\rho_\delta & : \text{Density of the } \delta \text{ phase (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\rho_\gamma & : \text{Density of the } \gamma \text{ phase (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\rho_{L+\delta} & : \text{Average density of (liquid} + \delta \text{) state (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\rho_{L+\gamma} & : \text{Average density of (liquid} + \gamma \text{) state (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\rho_{\delta+\gamma} & : \text{Average density of (}\delta + \gamma\text{) state (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\rho_{L+\delta+\gamma} & : \text{Average density of (liquid} + \delta + \gamma \text{) state (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\rho_L' & : \text{Density of the liquid phase at a temperature difference } \Delta T \text{ of } 0 \text{ K (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\Delta \rho & : \text{Difference in density between liquidus and solidus temperature (}\times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\Delta \rho_{L,\delta} & : \text{Difference in density between liquidus and solidus temperature of the } \delta \text{ phase (0.25} \times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
\Delta \rho_{L,\gamma} & : \text{Difference in density between liquidus and solidus temperature of the } \gamma \text{ phase (0.39} \times 10^3 \text{ kg} \cdot \text{m}^{-3}\) \\
f_\delta & : \text{Mass fraction of the } \delta \text{ phase} \\
f_\gamma & : \text{Mass fraction of the } \gamma \text{ phase} \\
\Delta f_\delta & : \text{Difference in mass fraction of the } \delta \text{ phase between liquidus and solidus temperature} \\
\Delta f_\gamma & : \text{Difference in mass fraction of the } \gamma \text{ phase between liquidus and solidus temperature} \\
\Delta T & : \text{Temperature difference between liquidus and solidus temperature (K)} \\
\Delta T_L & : \text{Temperature difference on the basis of the liquidus temperature (K)} \\
\Delta T_\delta & : \text{Temperature difference on the basis of the solidus temperature of the } \delta \text{ phase (K)} \\
\Delta T_\gamma & : \text{Temperature difference on the basis of the solidus temperature of the } \gamma \text{ phase (K)}
\end{align*}
\]

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