Prediction of Density of Stainless Steel

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The change of the density of stainless steel with phase at temperature range from 773 K to 1973 K has 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 both of undercooling and the shrinkage within the sample during solidification. Accuracy of experimental results was evaluated in comparison with previous studies for pure iron. The density of stainless steel was dependent on the phase but not chromium and nickel contents. Equations for prediction of the density in L, δ and γ phase regions were determined using the experimental results of

$$\begin{aligned}\rho_L &= -7.20 \times 10^{-4} \Delta T_L + 7.04 \\ \rho_\delta &= 2.87 \times 10^{-4} \Delta T_\delta + 7.27 \\ \rho_\gamma &= 4.40 \times 10^{-4} \Delta T_\gamma + 7.43 \\ 18 \text{ mass\%} \leq \text{Cr} \leq 25 \text{ mass\%}, 4 \text{ mass\%} \leq \text{Ni} \leq 25 \text{ mass\%}, 773 \text{ K} \leq T \leq 1973 \text{ K}\end{aligned}$$

The density of δ and γ coexisting phase ($\delta + \gamma$) is then predicted from the following equation.

$$\rho_{(\delta+\gamma)} = \rho_\delta \cdot f_\delta + \rho_\gamma \cdot f_\gamma$$

18 mass% $\leq$ Cr $\leq$ 25 mass%, 4 mass% $\leq$ Ni $\leq$ 25 mass%, 773 K $\leq$ T $\leq$ 1973 K

These estimated values are in good agreement with experimental results.

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

1. Introduction

Understanding of the mechanical properties of stainless steel during solidification is necessary to optimize the continuous casting conditions to improve the quality of slabs. The density of steel seems to characterize one of the mechanical properties at high temperature, therefore, many studies^{1–14)} have been carried. However, many studies were concerned with the density either of pure Fe or of Fe–C binary alloys, there have been few studies on the density of Fe–Cr–Ni ternary alloys in the solidification temperature range.

The solidification modes of stainless steel are very complicated and are changed by both chromium and nickel contents. The initial phase during solidification is either δ phase or γ phase, and then solidification is completed either as a single phase or as a dual phase where δ/γ transformation occurs during solidification. Furthermore, the phase after solidification may become a dual phase through δ/γ transformation. Though, the density of stainless steel seems to vary with phase during solidification, the relationship between density and phase in previous studies was unclear.

To study the relationship in the present paper, the density of Fe–Cr–Ni ternary alloys, that change with both chromium and nickel contents, were measured by a sessile drop

profile method, and the phases of sample changes with both chromium and nickel contents were estimated by equilibrium thermodynamic calculation.¹⁵⁾ From these results, the relationship between density and phase has been made clear, and the validity of the rule of additivity¹⁶⁾ as a first approximation to estimate the density of ($\delta + \gamma$) phase is discussed.

2. Experimental Procedures

2.1. Composition of the Samples

The chemical compositions of the Fe and the Fe–Cr–Ni samples are listed in **Table 1**. In order to investigate the influence of phase on density, both the chromium and nickel contents of the samples were varied. Samples A1 to A4

Table 1. Chemical composition of the samples (mass%).

Sample	Cr	Ni	Fe
A1	18.40	3.81	bal.
A2	18.14	7.62	bal.
A3	18.35	13.70	bal.
A4	18.13	25.55	bal.
B1	25.56	3.91	bal.
B2	25.48	15.00	bal.
B3	25.41	25.16	bal.
FE	tr.	tr.	bal.

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

contained constant amounts of chromium (18 mass%) and samples from B1 to B3 contained constant amounts of chromium (25 mass%). Sample FE was pure iron. The steel ingots were produced using electrolytic iron and alloying elements in a vacuum furnace, and then were hot forged at a temperature of 1473 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 stainless steel was measured by a sessile drop profile method.^{7,13,14} 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 and cooling rate of the sample changed with temperature, the rate was $0.21 \text{ K} \cdot \text{s}^{-1}$ for the temperature range from room temperature to 1400 K and $0.083 \text{ K} \cdot \text{s}^{-1}$ for the range from 1400 K to 1973 K. Measurements were carried out after 120 s holding at a given temperature. The temperature of the sample was controlled by the output voltage of a B-type thermocouple that was held at 2×10^{-3} m above the sample. The B-type thermocouple is accurate at a high temperature range up to 1973 K, but accuracy is lower below 773 K. Accordingly, the density was measured in the temperature range from 773 K to 1973 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 personal computer from a two-dimensional shadow image photographed by CCD camera. The 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 0.25π radian in the horizontal plane. The average value

Fig. 2. Solidification microstructure of sample A4.

Fig. 3. Comparison of the density of pure iron in the present study with that of the previous study.

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 3.0×10^{-5} m and the measuring error was within 1.5%.

3. Results and Discussions

3.1. Evaluation of Experimental Method

Figure 2 shows a longitudinal cross section of the solidification microstructure of sample A4 after the experiment. The solidification microstructure under optical microscopy was revealed by an electrolytic etching method using 10 mass% oxalic acid solution. The solidification microstructure was not uniform within the sample and the size of the microstructure in the upper part of the sample was larger than in the lower part. An equiaxed microstructure existed near the bottom surface within the sample. As it is thought that the equiaxed microstructure is formed within undercooled melt,¹⁷ the undercooling may have occurred during solidification under cooling conditions. Furthermore, a cavity formed during solidification was observed below the surface in the upper part of the sample. Therefore, in this experiment the density of the sample was measured under heating conditions to avoid these influences.

In order to examine the validity of this measurement method, the density of pure Fe in the present study was compared with a previous study. Figure 3 shows the relationship between density and temperature in comparison

Fig. 4. Change of fraction of phase with temperature.
(a) sample A1, (b) A2, (c) A3, (d) A4, (e) B1, (f) B2 and (g) B3.

with previous studies.^{1,2,5,7,13)} The relationship between phase and temperature that was estimated by equilibrium thermodynamic calculation is also shown in Fig. 3. As the measured values were within the range of the previous study, this seemed to confirm the validity of this method.

3.2. Phase Transformation of Stainless Steel

Figures 4(a)–4(g) show the relationship between the L, δ or γ phase fraction and temperature given by the calculation. The relationship between phase and temperature of stainless steel was predicted by the equilibrium thermodynamic calculation.

Figure 4(a) shows the change of phase fraction with temperature for sample A1. The initial phase of this sample during solidification was the δ phase and the phase just after solidification remained a single δ phase. The γ phase was precipitated at a temperature of 1486 K and a (δ + γ) coexisting phase was formed. The γ phase fraction increased with decreasing temperature, and then this fraction showed a maximum value. Then, the γ phase fraction decreased again and disappeared. The behavior of δ phase fraction was opposite to that of γ phase.

Figure 4(b) shows the relationship between phase frac-

tion and temperature for sample A2. The phase of this sample changed with temperature. The initial phase of sample A2 during solidification was the δ phase the same as sample A1, and a single δ phase was formed after solidification. After the δ / γ phase transformation started, the γ phase fraction increased with decreasing temperature. On the other hand, the δ phase fraction decreased with decreasing temperature. The δ phase disappeared and the δ phase precipitated again.

The change of phase of sample A3 with temperature is shown in Fig. 4(c). Chromium content of sample A3 was about 18mass% the same as samples A1 and A2, but the initial phase during solidification was the γ phase unlike samples A1 and A2 because the nickel content was different from samples A1 and A2. The single γ phase was formed just after solidification, and the δ phase precipitated at a temperature of 994 K and then a (δ + γ) coexisting phase was formed.

The behavior of phase of sample A4 is shown in Fig. 4(d). After the precipitation of the primary γ phase, the phase was kept up the same single γ phase in the experimental temperature range unlike other the samples.

Figure 4(e) shows the relationship between phase of sam-

Fig. 5. Change of density with temperature. Open circles represent the experimental results on heating condition and solid line represents the calculated result.
(a) sample A1, (b) A2, (c) A3, (d) A4, (e) B1, (f) B2 and (g) B3.

ple B1 and temperature. The δ phase solidified primarily and the δ/γ phase transformation started. The fraction of both δ and γ phase did not change monotonically and the fraction of δ phase changed opposite to that of γ phase.

As shown in Fig. 4(f), the change of phase of sample B2 was different from that of other samples. The δ/γ phase transformation started between liquidus and solidus temperature and the δ phase solidified first and then the γ phase precipitated leaving the L phase. The $(\delta+\gamma)$ phase was formed just after solidification. The γ phase fraction increased with decreasing temperature and reached a maximum value, and then decreased. The fraction of δ phase changed in the opposite way to that of γ phase.

Figure 4(g) shows the change of fraction of phase with temperature. The γ phase solidified initially during the solidification sequence and a single γ phase was formed below the solidus temperature. At first the δ phase precipitated and the fraction of δ phase increased with decreasing temperature.

3.3. Density of Stainless Steel

Figures 5(a)–5(g) shows the change of density with temperature measured under heating conditions. The relationship between phase and temperature is also shown in Figs. 5(a)–5(g).

The density of sample A1 plotted against temperature is shown in Fig. 5(a). Under heating conditions, the density decreased with increasing temperature. The difference of density between liquidus and solidus temperature was large. In the L phase region, the density decreased with increasing temperature.

Figure 5(b) shows the relationship between density of sample A2 and temperature. The density decreased with increasing temperature and the change of density in the liquidus–solidus temperature range was large. The difference of density between liquidus and solidus temperature was almost the same as that of sample A1 because it seemed that the behavior of phase transformation during solidification was the same as that of sample A1.

Figure 5(c) shows the change of density of sample A3 with temperature. In the L phase region, the density de-

creased with increasing temperature. The primary phase of this sample was the γ phase.

Figure 5(d) shows the relationship between density of sample A4 and temperature. The primary phase of this sample was the γ phase, and then a single γ phase was formed below the solidus temperature. The density of sample A4 decreased with increasing temperature and the density between liquidus and solidus temperature changed a lot. The initial phase of samples A3 and A4 was the γ phase, but that of samples A1 and A2 was the δ phase. The density seemed to be governed either by the δ phase or the γ phase from these results.

The chromium content of samples B1 to B3 was different from samples A1 to A4. Figure 5(e) shows the density of sample B1 varying with temperature. The behavior of density was the same as that of samples A1 and A2 and the δ phase was formed just after solidification. The density of sample A4 decreased with increasing temperature and the change of density between liquidus and solidus temperature was large unlike the case of δ/γ phase transformation. As the difference of density during solidification was the same as that of samples A1 and A2, the density seemed not to be determined by the content of either chromium or nickel but by the δ phase or the γ phase.

Figure 5(f) shows the relationship between density of sample B2 and temperature. The δ and γ coexisting phase ($\delta+\gamma$) was formed just after solidification unlike in the other samples. The density of sample B2 decreased with increasing temperature and the difference of density between liquidus and solidus temperature was large. In the L phase, the density decreased with increasing temperature.

Figure 5(g) shows the change of density of sample B3 with temperature. The behavior of density was the same as that of sample A3 shown in Fig. 5(c).

From the results shown in Fig. 5, the density of stainless steel under these conditions seemed to change depending on either the δ or the γ phase.

The density of Fe–Cr binary alloys¹⁸⁾ decreases with increasing chromium concentration. Oppositely, the density of Fe–Ni binary alloys¹⁸⁾ increases with increasing nickel concentration. It seems that the density of Fe–Cr–Ni ternary alloys is influenced by the effect of both the decrease of the density like the chromium element and the increase of the density like the nickel element. Therefore, it is thought that the concentration dependency such as the Fe–Cr alloys or Fe–Ni alloys was not found in this measurement results of the density of Fe–Cr–Ni ternary alloys.

It seems that the measurement errors are included in the measured results of the density in this experimental condition. There are the evaporation loss of sample, the surface oxidation of sample, the axial asymmetry of sample, the thermal deformation of magnesia plate in the measurement temperature range and the accuracy of thermocouple as factor of measurement errors.^{3,19)} The ratio of weight decreases of sample before and after the experiment was 0.13% or less, which was seemed to be included the evaporation and the surface oxidation of sample. The axial asymmetry of sample and the amount of thermal deformation of the magnesia plate were hard to measure in the experimental temperature range. It seems that the temperature measurement error depends on the accuracy $\pm 0.5\%$ of the B-type ther-

Fig. 6. Relationship between density and temperature difference. (a) L phase, (b) δ phase and (c) γ phase.

mocouple.

3.4. Phase Dependence of Density of Stainless Steel

In order to investigate the dependence of density upon the L, δ 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. 6.

Figure 6(a) shows the relationship between density in the L phase region for samples A1 to A4 and samples B1 to B3. The temperature difference was defined on the basis of liquidus temperature. The density for all the samples decreased with increasing temperature and with increased difference from the liquidus temperature. When the temperature difference was the same, the density of all the samples had almost the same value. Neither chromium nor nickel content influenced the density under these conditions.

In many previous studies on Fe–C binary alloy, the dependency of the density upon carbon content at constant temperature in the L phase region 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 L phase region. 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 difference on the basis of the liquidus temperature was summarized by Jimbo *et al.*¹¹⁾ The regression line based on the present experimental results shown here, was within the

range of previous results.

Figure 6(b) shows the relationship between density and temperature difference in the δ phase region. The results for samples A1, A2 and B1 that were initially in the δ phase before solidification and in a single δ phase after solidification, were summarized. In either case, the density increased with increasing temperature difference. When the temperature difference was the same, the density of all samples had almost the same value.

In the γ phase region, the relationship between density and temperature difference is shown in Fig. 6(c). Samples A3, A4 and B3 were initially in the γ phase and a single γ phase after solidification. The density was given by the temperature difference the same as in the case of the L phase and the δ phase, and the density increased with increasing temperature difference. There was no influence from either chromium or nickel content under these conditions.

It was found that the density of stainless steel was dependent on the phase, for example the L, the δ and the γ phase under these experimental conditions and the density in the L, the δ or the γ phase region was given by the temperature difference in all three cases. The regression lines shown in Figs. 6(a)–6(c) are given by the following equations, respectively.

$$\rho_L = -7.20 \times 10^{-4} \Delta T_L + 7.04 \dots\dots\dots (1)$$

$$\rho_\delta = 2.87 \times 10^{-4} \Delta T_\delta + 7.27 \dots\dots\dots (2)$$

$$\rho_\gamma = 4.40 \times 10^{-4} \Delta T_\gamma + 7.43 \dots\dots\dots (3)$$

18 mass% $\leq$ Cr $\leq$ 25 mass%, 4 mass% $\leq$ Ni $\leq$ 25 mass%,
773 K $\leq$ T $\leq$ 1973 K

3.5. Estimation of Density of Stainless Steel

The density of single δ phase and single γ phase can be expressed in terms of the temperature difference as shown in Figure 6. On the other hand, if the temperature difference on the basis of the equilibrium thermodynamic calculation is known, the density of L, δ or γ phase can be estimated. Besides either the δ single phase or the γ single phase, ($\delta + \gamma$), (L + δ), (L + γ) phase and (L + $\delta + \gamma$) phase was present during solidification of stainless steel. Therefore, in order to estimate the density of stainless steel, it seems to be 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 L, δ and γ phase was estimated using the rule of additivity as a first approximation. By comparing estimated values with measured values, the validity of the estimation method was investigated.

The density of ($\delta + \gamma$) phase is represented by the rule of additivity as follows,

$$\rho_{(\delta+\gamma)} = \rho_\delta \cdot f_\delta + \rho_\gamma \cdot f_\gamma \dots\dots\dots (4)$$

ρ_δ and ρ_γ were calculated from Eqs. (2) and (3), respectively, and f_δ and f_γ were used by the relation shown in Fig. 4.

The density of (L + δ) phase between liquidus and solidus temperature was given using the difference of density between liquidus and solidus temperature, and the δ phase fraction as the primary phase,

$$\rho_{(L+\delta)} = \rho_L^0 + \Delta \rho_{L/\delta} \cdot f_\delta \dots\dots\dots (5)$$

The density of (L + γ) phase and (L + $\delta + \gamma$) phase were given by,

$$\rho_{(L+\gamma)} = \rho_L^0 + \Delta \rho_{L/\gamma} \cdot f_\gamma \dots\dots\dots (6)$$

$$\rho_{(L+\delta+\gamma)} = \rho_L^0 + \Delta \rho_{L/\delta} \cdot f_\delta + \Delta \rho_{L/\gamma} \cdot f_\gamma \dots\dots\dots (7)$$

Estimated values of density are represented by solid lines in Figs. 5(a)–5(g) and were compared with measured values.

Figure 5(a) shows the relationship between the estimated value of density and the temperature of sample A1. The estimated values of L, δ and ($\delta + \gamma$) phase were in good agreement with the measured values. The estimated value of ($\delta + \gamma$) phase did not change continuously with an increase in temperature the same as for the L phase and the δ phase, because the fraction of both the δ phase and the γ phase varied irregularly with temperature. The estimated density of (L + δ) phase varied linearly with temperature.

The estimated density of sample A2 change with temperature as shown in Fig. 5(b). The behavior of the phase changed with temperature was complicated as shown in Fig. 4(b). The estimated density varied with both temperature and phase fraction, and was in good agreement with the measured values.

Figure 5(c) shows the change of estimated density of sample A3 with temperature. The solidification sequence of sample A3 was different from those of samples A1 and A2, and the γ phase was formed as the primary phase. It seemed possible to estimate the density whether the primary phase was the δ or the γ phase.

The solidification sequence of sample A4 was the same as that of sample A3 and the density was able to be estimated as shown in Fig. 5(d).

The δ phase solidified primarily in the solidification sequence of sample A4 the same as samples A1 and A2, and the δ phase was formed completely after solidification and then the γ phase was precipitated with an decrease in temperature. As shown in Fig. 5(e), the estimated value of sample B1 varied depending on phase and the estimated value was in agreement with the measured value.

Figure 5(f) shows the relationship between the estimated value of sample B2 and temperature. The (L + $\delta + \gamma$) phase was formed during solidification uniquely in this experiment. The slope of the two lines between liquidus and solidus temperature was different because the δ/γ phase transformation started in this temperature range.

Figure 5(g) shows the change of estimated value of sample B3 with temperature. The same as the other samples, the estimated value was in good agreement with the measured value.

From these results shown in Fig. 5, it seemed possible to estimate the density for a combination of L, δ and γ phases on the basis of the rule of additivity.

3.6. Change of Density during Solidification

In previous studies, the difference of density during solidification was measured between liquidus and solidus temperature. Both liquidus and solidus temperature varied with chromium and nickel contents, and the difference of temperature between liquidus and solidus also varied with

Fig. 7. Change of $\Delta\rho$, $\Delta\rho/\Delta T$ and nickel content. (a) constant chromium content of 18 mass% and (b) 25 mass%.

these elements. In the case of the evaluation of the temperature difference during solidification, it seems to be necessary to consider not only the difference of density but also the difference of temperature between liquidus and solidus.

Figure 7 shows the relationship between the difference of density $\Delta\rho$, and the ratio of density to temperature difference between liquidus and solidus $\Delta\rho/\Delta T$. Temperature difference ΔT was estimated by the equilibrium thermodynamic calculation. The difference of density was defined as the difference either between the L and the δ phase or between the L and the γ phase at a temperature difference of 0 K as shown in Fig. 6.

Figure 7(a) shows the relationship between the difference of density $\Delta\rho$ and the ratio of the difference of density divided by the temperature difference between liquidus and solidus $\Delta\rho/\Delta T$, and nickel content at constant chromium content of 18 mass%. The phase formed after complete solidification is represented as δ , ($\delta + \gamma$) and γ in the figure. The difference of density in both the δ phase and the γ phase was constant independent of nickel contents, because the density at both liquidus and solidus temperature was determined by the phase as shown in Fig. 6. The difference of density of ($\delta + \gamma$) phase just after solidification was given as follows in the formation of Eqs. (4)–(7).

$$\Delta\rho = \Delta\rho_{L/\delta} \cdot \Delta f_{\delta} + \Delta\rho_{L/\gamma} \cdot \Delta f_{\gamma} \dots \dots \dots (8)$$

The difference of density in the ($\delta + \gamma$) phase region varied with nickel content because the fraction of the δ to the γ phase depended on nickel contents. The difference of density in the ($\delta + \gamma$) phase region was larger than in the δ phase region and lower than in the γ phase region.

The ratio $\Delta\rho/\Delta T$ varied with nickel content in the same phase, because the difference of density does not vary with nickel content and the difference of temperature between liquidus and solidus depends on nickel content.

As the ratio $\Delta\rho/\Delta T$ increased with decreasing temperature difference between liquidus and solidus if the phase was same, the ratio $\Delta\rho/\Delta T$ varied with a small change of

temperature.

For example, if the temperature gradient within the solidified shell in the mold of a continuous caster is constant, the ratio $\Delta\rho/\Delta T$ increases with increasing difference of density $\Delta\rho$. Then the stress in the solidified shell caused by the change of density seems to increase. It seems that the stress in the solidified shell is caused by the density increase and unevenness of the shell increases.

Figure 7(b) shows the change of the difference of density $\Delta\rho$, the ratio $\Delta\rho/\Delta T$ with nickel content at a constant chromium content of 25 mass%. The phase is shown in the same figure. The difference of density changed with phase, but was independent of nickel content as shown in Fig. 7(a). The ratio $\Delta\rho/\Delta T$ depended on nickel content because of the change of temperature difference between liquidus and solidus.

It was found that the density of stainless steel varied with L, δ and γ phases, from this experiment. As the deformation behavior of the solidified shell seems to determine the quality of continuously cast slabs of stainless steel, it is important to understand the dependence of the density of phase during solidification accompanied with the δ to γ phase transformation.

4. Conclusions

The density of stainless steel was 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 density of ($\delta + \gamma$) phase 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 stainless steel varied with L, δ and γ phases, and was independent of the chromium and nickel contents.

(2) The density in L, δ and γ phase regions of stainless steel was calculated by the following equations.

$$\rho_L = -7.20 \times 10^{-4} \Delta T_L + 7.04$$

$$\rho_{\delta} = 2.87 \times 10^{-4} \Delta T_{\delta} + 7.27$$

$$\rho_{\gamma} = 4.40 \times 10^{-4} \Delta T_{\gamma} + 7.43$$

$$18 \text{ mass\%} \leq \text{Cr} \leq 25 \text{ mass\%}, 4 \text{ mass\%} \leq \text{Ni} \leq 25 \text{ mass\%}, 773 \text{ K} \leq T \leq 1973 \text{ K}$$

(3) The density of ($\delta + \gamma$) phase was estimated by the rule of additivity as a first approximation. The estimated values were in good agreement with the measured values.

$$\rho_{(\delta+\gamma)} = \rho_{\delta} \cdot f_{\delta} + \rho_{\gamma} \cdot f_{\gamma}$$

$$18 \text{ mass\%} \leq \text{Cr} \leq 25 \text{ mass\%}, 4 \text{ mass\%} \leq \text{Ni} \leq 25 \text{ mass\%}, 773 \text{ K} \leq T \leq 1973 \text{ K}$$

(4) The degree of change of density during solidification depended on phase but did not depend on either chromium or nickel content. The ratio of change of density to temperature during solidification depended on chromium and nickel contents because of the dependence of temperature difference between liquidus and solidus as a result of chromium and nickel contents.

(5) It was necessary to measure the density during

heating process by a sessile drop profile method. During the cooling process, both the appearance of undercooling within the sample during solidification and unevenness of formation of solidification microstructure might cause measurement error.

Nomenclature

ρ_L	: the density in the L phase ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
ρ_δ	: the density of the δ phase ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
ρ_γ	: the density of the γ phase ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
$\rho_{(L+\delta)}$	: the density of (L + δ) phase ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
$\rho_{(L+\gamma)}$	: the density of (L + γ) phase ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
$\rho_{(\delta+\gamma)}$	: the density of (δ + γ) phase ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
$\rho_{(L+\delta+\gamma)}$	: the density of (L + δ + γ) phase ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
ρ_L^0	: the density of the L phase at a temperature difference ΔT_L of 0 K ($7.04 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
$\Delta\rho$	: the difference of density between liquidus and solidus temperature ($\times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
$\Delta\rho_{L/\delta}$	: the difference of density between liquidus and solidus temperature of the δ phase ($0.23 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
$\Delta\rho_{L/\gamma}$	: the difference of density between liquidus and solidus temperature of the γ phase ($0.39 \times 10^3 \text{ kg} \cdot \text{m}^{-3}$)
f_δ	: the mass fraction of the δ phase
f_γ	: the mass fraction of the γ phase
Δf_δ	: the difference of mass fraction of the δ phase between liquidus and solidus temperature
Δf_γ	: the difference of mass fraction of the γ phase between liquidus and solidus temperature
ΔT	: the temperature difference between liquidus and solidus temperature (K)
ΔT_L	: the temperature difference on the basis of the liquidus temperature (K)

ΔT_δ	: the temperature difference on the basis of the solidus temperature of the δ phase (K)
ΔT_γ	: the temperature difference on the basis of the solidus temperature of the γ phase (K)

REFERENCES

- 1) G. Tammann and G. Bandel: *Arch. Eisenhüttenwes.*, **7** (1934), 571.
- 2) L. D. Lucas: *Mem. Sci. Rev. Met.*, **61** (1964), 97.
- 3) T. Saito, Y. Shiraishi and Y. Sakuma: *Trans. Iron Steel Inst. Jpn.*, **9** (1969), 118.
- 4) Z. Morita, Y. Ogino, H. Kaito and A. Adachi: *J. Jpn. Inst. Met.*, **34** (1970), 248.
- 5) L. D. Lucas: *Mem. Sci. Rev. Met.*, **69** (1972), 479.
- 6) P. J. Wray: *Metall. Trans.*, **5** (1974), 2602.
- 7) S. Watanabe, Y. Tsu, K. Takano and Y. Shiraishi: *J. Jpn. Inst. Met.*, **45** (1981), 242.
- 8) A. Olsson: *Scand. J. Metall.*, **10** (1981), 263.
- 9) W. D. Drotning: *High Temp.-High Press.*, **13** (1981), 441.
- 10) A. Jablonka, K. Harste and K. Schwerdtfeger: *Steel Res.*, **62** (1991), 24.
- 11) I. Jimbo and A. W. Cramb: *Metall. Mater. Trans. B*, **24** (1993), 5.
- 12) A. Sharan, T. Nagasaka and A. W. Cramb: *Metall. Mater. Trans. B*, **25** (1994), 939.
- 13) T. Yokoyama, Y. Ueshima, Y. Mizukami, H. Kakimi and M. Kato: *Tetsu-to-Hagane*, **83** (1997), 557.
- 14) Y. Itoh, M. Kawamoto, F. Kawahigashi, N. Yoshida and M. Kato: *CAMP-ISIJ*, **9** (1996), 55.
- 15) B. Jansson, M. Schalin, M. Selleby and B. Sundman: Computer Software in Chemical and Extractive Metallurgy, eds. by C. W. Bale and G. A. Irons, The Met Soc of CIM, Quebec, (1993), 57.
- 16) Z. Fan, P. Tsakiroopoulos, P. A. Smith and A. P. Miodownik: *Philos. Mag. A*, **67** (1993), 515.
- 17) W. Kurz and D. J. Fisher: *Fundamentals of Solidification* 4th. Ed., Trans. Tech. Publications, Switzerland, (1998), 63.
- 18) Data-book on Physical Properties of Liquid Iron, Alloys and Slags, ISIJ, Tokyo, (1971), 11, 14.
- 19) A. F. Crawley: *Int. Metall. Rev.*, **19** (1974), 32.