1. Introduction

Recently, there have been many attempts to analyze the phase transformation kinetics and to predict and control the microstructure and mechanical properties more systematically.

However, the quantitative models capable of predicting the microstructures for the heat affected zone (HAZ) of welds have not been sufficiently developed.1,2)

The HAZ, especially the coarsened grain heat affected zone (CGHAZ), has different characteristics from the matrix in microstructure and mechanical properties. During the welding process, CGHAZ has a large prior austenite grain size (hereafter referred to as AGS) and a fast cooling rate due to its severe thermal history. Therefore, the lower temperature phases such as bainite and martensite are observed.

It is the intent of this study to develop a model that describes the transformation kinetics on austenite–ferrite and austenite–pearlite transformation in CGHAZ using the Johnson–Mehl–Avrami equation (hereafter referred to as the JMA equation).

It is well known that the isothermal phase transformation behavior is described by the JMA equation.3–5)

\[ X = 1 - \exp(-K \cdot t^n) \] ..................................(1)

where rate parameter, \( K \) is a function of chemical composition, AGS and temperature. Reaction parameter, \( n \) depends on the growth geometry and the type of nucleation site and \( n \) is generally accepted as a constant if there is no morphological change. \( X \) and \( t \) represent transformed volume fraction and time, respectively.

There are many variables which affect transformation kinetics such as AGS and the cooling rate. Especially, the effects of AGS on transformation kinetics are well known. If AGS is large, the phase transformation kinetics are normally slowed down by reduced nucleation site density.

The ferrite grain size is controlled by AGS and the cooling rate.6,7) The morphology of ferrite is also affected by AGS,8–10) i.e., if AGS is small, the favorable morphology of ferrite is polygonal and changed into Widmanstätten ferrite as AGS becomes larger.

Due to these considerable effects of AGS, it has been quite interesting to find quantitatively the effects of AGS on transformation kinetics.11–13) Thus, this JMA equation was modified by Umemoto et al. to include an AGS parameter, \( m \) and separate the AGS effect from \( K \),12)

\[ X = 1 - \exp\left(-\frac{K \cdot t^n}{AGS^m}\right) \] ..................................(2)

where AGS parameter (\( \mu m \)), \( m \) is constant and controlled by the type of nucleation site and growth geometry.

In this study, this modified JMA equation was used to consider the effects of AGS. AGS parameter, \( m \) was evaluated for ferrite and pearlite, and reaction parameter, \( n \) for ferrite was assumed to be not constant but a function of the isothermal temperature to describe the morphological change in ferrite due to the fast cooling rate and large AGS. The JMA equation was applied to describe the isothermal transformation kinetics and the additivity rule14) was used to apply the JMA equation to continuous cooling transformation. However, the additivity rule was not used to predict the transformation start temperature of the continuous cooling process.

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Instead, the method developed at the Institut de Recherché Siderurgique (IRSID) was applied to predict the transformation start temperature \(A_{r3}\) in the present study.\(^{15}\)

2. Metallurgical Model

Using the kinetics parameters determined by isothermal transformation tests, a model to predict the transformation kinetics in isothermal and continuous cooling transformations was established.

In this model, the reaction parameter, \(n\) of the JMA equation was assumed to be a function of the isothermal temperature because the morphology of ferrite changed as the isothermal temperature decreased.

However, the additivity rule is generally valid only if the instantaneous reaction rate depends only on volume fraction and temperature, that is, only on the state of the assembly, and not on the thermal path by which it reached that state. This condition is mathematically described as,

\[
\frac{dX}{dt} = H(T) \frac{G(X)}{G(X)} \quad \text{...(3)}
\]

where \(H(T)\) and \(G(X)\) respectively, are functions only of the temperature and volume fraction transformed. Thus, if reaction parameter, \(n\) depends on temperature, the application of the additivity rule is invalid because the \(n\) terms are not separated from the volume fraction term, \(G(X)\).\(^{16}\) However, it was proposed by Kamat et al.\(^{17}\) that the additivity rule can be experimentally applied to the morphological change from polygonal into Widmanstätten ferrite. Moreover, this has been proven by stepped isothermal transformation tests.

For continuous cooling, after determining the transformation start temperature for each cooling rate, volume fractions of each phase were calculated by the additivity rule and the JMA equation using determined kinetics parameters. The transformation start temperature of ferrite \(A_{r3}\) for each cooling rate is calculated by the equation below,\(^{15}\)

\[
A_{r3} = A_{r3}^o \times C_r^{-a} \quad \text{...(4)}
\]

where \(A_{r3}^o\) is the temperature at the beginning of the austenite-to-ferrite transformation when the cooling takes place at 1 K/s, \(C_r\) is the cooling rate, and the exponent, \(a\) is a positive constant.

The bainite start temperature and Martensite start temperature were determined by the reported empirical equations.\(^{18,19}\)

3. Experiments

The chemical compositions of JIS G3101 SS400 steel used in this study are given in Table 1. Isothermal and continuous-cooling tests were conducted with the objectives of measuring the phase transformation kinetics of the austenite–ferrite and austenite–pearlite reactions. The transformation kinetics were measured by using a dilatometer system (Bahr–Geratebau GmbH Model 805A). Cylinder type specimens, with dimensions of 3 mm diameter by 10 mm length were employed in the experiments to minimize the thermal gradient.

On the basis of the ideal thermal cycle of CGHAZ, thermal cycles were selected to determine the parameters in the JMA equation and to obtain different AGSs for analyzing the effects of AGS on phase transformation kinetics quantitatively. Schematic thermal cycles for the isothermal and continuous cooling transformation tests are respectively depicted in Figs. 1 and 2. As shown in Fig. 2, cooling rate conditions were selected from 1 K/s to 120 K/s. Because AGS should be the same for isothermal and continuous cooling experiments, the thermal cycles of each condition except the cooling regime were maintained as the same. The AGS of each cycle was determined by the ASTM E112-95 and an image analyzer on the specimens which were quenched to room temperature (120 K/s) by helium gas. These determined AGS values are shown in Table 2. In addition, the volume fractions for ferrite were determined

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### Table 1. Chemical composition of specimen. (mass%)\(^{11}\)

|     | C   | Si  | Mn | P  | S   | Cr | Ni | Cu |
|-----|-----|-----|----|----|-----|----|----|----|
| JIS G3101 SS400 | 0.15 | 0.01 | 0.64 | 0.01 | 0.01 | 0.02 | 0.02 |

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### Table 2. Measured values of prior austenite grain size for each thermal cycle.\(^{11}\)

| Peak temperature (K) | 1623 | 1623 | 1623 | 1173 |
|----------------------|------|------|------|------|
| Holding time (s)    | 5    | 10   | 25   | 5    |
| AGS (μm)            | 185  | 250  | 275  | 50   |

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by the image analyzer.

4. Result and Discussion

It is almost impossible to detect the transition between ferrite and pearlite from isothermal experiments, as there are almost no differences in the thermal expansion coefficients of each phase. Therefore, the isothermal data were separated by the method of Hawbolt et al.,19,20 where the \( \gamma/\text{Fe}_3\text{C} \) and \( \alpha/\gamma \) phase boundaries of the phase diagram calculated by Thermo-Calc were linearly extrapolated to lower temperatures and the transition points between ferrite and pearlite were determined from the volume fractions which were calculated with the lever rule at each temperature. The isothermal data were plotted as \( \ln[\ln(1/(1-X))] \) vs. \( \ln t \) to determine the parameters in the JMA equation, that is, the mal holding temperature.

Determined parameters were analyzed with AGS and the isothermal data were plotted as \( \ln[\ln(1/(1-X))] \) to \( \ln K \) for ferrite and pearlite were respectively analyzed for isothermal temperatures and AGS conditions, and these are shown in Figs. 7 and 8. As seen in these Figures, the \( K \) values for both phases increase with decreasing temperatures at constant AGS and decrease with increasing AGS at constant temperatures. Thus AGS parameters, \( m \) in Eq. (2) for the both phases were obtained by comparing the relative values of \( K \) for each AGS condition. The obtained values of \( m \) were 1.54 for ferrite and 1.24 for pearlite. The empirical equations for \( K \), considering the effects of AGS and isothermal temperature could be evaluated as follows,

\[
\ln K_{\text{ferrite}} = -21.41 + 0.24 \cdot T - 1.88 \times 10^{-4} \cdot T^2 - 1.54 \cdot \ln \text{AGS} \tag{5}
\]

\[
\ln K_{\text{pearlite}} = -22.94 + 0.31 \cdot T - 2.57 \times 10^{-4} \cdot T^2 - 1.24 \cdot \ln \text{AGS} \tag{6}
\]

4.1. Analysis of Isothermal Transformation

Figures 3 and 4 show the values of \( n \) determined by isothermal transformation tests for pearlite and ferrite, respectively. As depicted in Fig. 3, the value of \( n \) for pearlite was 0.906 and this result was consistent with those reported by a previous author.19 However, the value of \( n \) for ferrite was not a constant but a function of isothermal temperature as shown in Fig. 4.

In this study, the morphology of ferrite was classified as polygonal ferrite and Widmanstätten ferrite. As seen in Fig. 4, the deviation tendency of \( n \) due to the isothermal temperature was the same in the range of AGS 185–275 \( \mu \text{m} \). However, in the case of a small AGS (50 \( \mu \text{m} \)), the deviation tendency of \( n \) was different from that of a large AGS. This tendency seems to be related to the fact that the Widmanstätten ferrite start temperature \( (W_s) \) is severely affected by AGS.8 However, in this study, \( n \) for ferrite was formulated as a function of isothermal temperature, ignoring the effect of the AGS on Widmanstätten ferrite start temperature because the scope of this study covers the prediction of phase transformation which only occurs in CGHAZ, that is, the condition of a small AGS (50 \( \mu \text{m} \)) does not occur in CGHAZ.

It has been known that the reaction parameter, \( n \), changes due to morphological change, and thus the specimens were examined after the isothermal transformation experiment by an optical microscope and image analyzer to verify this tendency. Figures 5 and 6 show the change in microstructures and the measured volume fraction of Widmanstätten ferrite with the isothermal temperature changes at AGS of 185 \( \mu \text{m} \). By comparing the deviation tendency of \( n \) in Fig. 4, it is seen that there is a quantitative relationship between the reaction parameter, \( n \) and the morphological change in the ferrite. In other words, reaction parameter, \( n \) increases as the volume fraction of Widmanstätten ferrite increases.

Therefore, \( n \) for ferrite is considered to be a function of isothermal temperature and \( n \) for pearlite is considered to be constant based on the measured data. Table 3 shows the determined reaction parameter, \( n \) for ferrite and pearlite.

Rate parameter, \( K \) for ferrite and pearlite were respectively analyzed for isothermal temperatures and AGS conditions, and these are shown in Figs. 7 and 8. As seen in these Figures, the \( K \) values for both phases increase with decreasing temperatures at constant AGS and decrease with increasing AGS at constant temperatures. Thus AGS parameters, \( m \) in Eq. (2) for the both phases were obtained by comparing the relative values of \( K \) for each AGS condition. The obtained values of \( m \) were 1.54 for ferrite and 1.24 for pearlite. The empirical equations for \( K \), considering the effects of AGS and isothermal temperature could be evaluated as follows,

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\[
\ln K_{\text{pearlite}} = -22.94 + 0.31 \cdot T - 2.57 \times 10^{-4} \cdot T^2 - 1.24 \cdot \ln \text{AGS} \tag{6}
\]

4.2. Analysis of Continuous Cooling Transformation

In order to determine the transformation start temperature for each cooling rate, the continuous cooling transformation experiments are conducted. As a result, \( A_3 \) for various cooling rates were obtained and these values are plotted against the cooling rate as \( \ln A_3 \) vs. \( \ln C_t \) to determine the value of \( a \) (the slope of the plotted data) in Eq. (4). Plotted \( \ln A_3 \) vs. \( \ln C_t \) data are depicted in Fig. 9.
5. Prediction

Through the analysis of the experimental results, the parameters of the JMA equation and phase transformation temperatures for ferrite and pearlite were converted into a type of empirical equation. From these data, the model for calculating the phase volume fractions of ferrite and pearlite
was established. However, because this study did not include the bainite and martensite transformation, volume fraction and phase transformation temperature for bainite were determined by the published equations.\textsuperscript{19,21} For martensite, when the decreasing temperature reaches the martensite start temperature determined by the reported equation,\textsuperscript{18} it is assumed that the remaining austenite transforms into martensite. Table 4 shows these empirical equations for bainite and martensite.

The predicted continuous cooling transformation kinetics were compared with the experimental data to check the reliability of the model and these are shown in Fig. 10. As depicted in this figure, the predicted volume fraction of ferrite on the assumption that $n$ is a function of isothermal temperature, is more consistent with the measured one than on the basis that $n$ is constant.

To know the effects of AGS on phase transformation kinetics, the continuous cooling transformation kinetics were predicted with a changing AGS and compared with experiments as shown in Fig. 11. There are some differences between calculated and measured fractions for intermediate cooling rates. However, as seen in Fig. 10, the predicted results seem to be more consistent with measured values by considering $n$ to be a function of temperature. The volume fraction of ferrite decreased and the volume fraction of pearlite increased as AGS becomes larger. These results are in agreement with the well-known effects of AGS on the transformation kinetics.

6. Summary

A metallurgical model capable of predicting the phase transformation kinetics of austenite to ferrite and pearlite in the CGHAZ was developed.

Phase transformation kinetics were examined by a dilatometer system. In addition, isothermal transformation kinetics were characterized in terms of the modified Johnson–Mehl–Avrami equation to yield the reaction parameter ($n$), rate parameter ($K$) and prior austenite grain size parameter ($m$).

It was found that $n$ for pearlite is independent of the isothermal temperature, however, $n$ for ferrite is dependent. The magnitude of the resulting prior austenite grain size parameter, $m$ was found to be $m=1.54$ for the formation of ferrite and $m=1.24$ for the transformation of pearlite. Thus, rate parameter, $K$ is expressed as a function of temperature and AGS.

From the developed model, the kinetics of the continuous cooling transformation were predicted. When the reaction parameter, $n$ of ferrite was applied as a function of temperature, the predicted transformation kinetics described the actual transformation kinetics more accurately.

From the prediction of the continuous cooling transformation, the effects of AGS were confirmed; when AGS was large, the volume fraction of ferrite was reduced and the volume fraction of pearlite and bainite were increased.

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REFERENCES

1) C. Ion, K. E. Easterling and M. F. Ashby: Acta Mater., 32 (1984), 1949.
2) H. K. D. H. Bhadeshia: Mater. Sci. Technol., 8 (1992), 123.
3) M. Avrami: J. Chem. Phys., 7 (1939), 1103.
4) W. A. Johnson and R. F. Mehl: Trans. AIME, 135 (1939), 416.
5) I. Y. Cho, K. J. Lee and C. H. Lee: J. KWS, 16 (1998), 202.
6) M. Umemoto, Z. H. Guo and I. Tamura: Mater. Sci. Technol., 3 (1987), 249.
7) M. Militzer, R. Pandi and E. B. Hawbolt: Metall. Mater. Trans. A, 27A (1996), 1547.
8) P. R. Krahe, K. R. Kinsman and H. I. Aaronson: Acta Mater., 20 (1972), 1109.
9) J. L. Lee and Y. T. Pan: ISIJ Int., 35 (1995), 1027.
10) G. Spanos and M. G. Hall: Metall. Mater. Trans. A, 27A (1996), 1519.
11) J. W. Cahn: Acta Mater., 4 (1956), 572.
12) M. Umemoto, N. Nishioka and I. Tamura: J. Heat Treat., 1 (1980), 57.
13) M. Umemoto, N. Nishioka and I. Tamura: Proc. of Int. Cong. on Heat Treatment of Materials, Shanghai, China, (1983), 35.
14) E. Scheil: Arch. Eisenhüttenwes., 8 (1935), 565.
15) B. Debray, P. Teracher and J. J. Jonas: Metall. Mater. Trans. A, 26A (1995), 99.
16) M. Lusk and H. J. Jou: Metall. Mater. Trans. A, 28A (1997), 287.
17) R. G. Kamat, E. B. Hawbolt, L. C. Brown and J. K. Brimacombe: Metall. Mater. Trans. A, 23A (1992), 2469.
18) K. W. Andrews: J. Iron Steel Inst., (1965), 721.
19) T. Kunitake and Y. Okada: Tetsu-to-Hagané, 84 (1998), 137.
20) E. B. Hawbolt, B. Chau and J. K. Brimacombe: Metall. Mater. Trans. A, 16A (1984), 565.
21) K. Esaka, J. Wakida, M. Takahashi, O. Kawano and S. Harada: Seitetsu Kenkyu, 32 (1986), 92.