The Analysis of Phase Transformation for the Prediction of Microstructure Change after Hot Forming

Jinshan LIU, Akira YANAGIDA1), Sumio SUGIYAMA1) and Jun YANAGIMOTO1)

Graduate Student, Institute of Industrial Science. The University of Tokyo Komaba Meguro-ku, Tokyo 153-8505 Japan.
1) Institute of Industrial Science, The University of Tokyo, Komaba, Meguro-ku, Tokyo 153-8505, Japan
(Received on January 15, 2001; accepted in final form on August 3, 2001)

A new model of phase transformation for continuous cooling after hot forming is proposed. It is based on incremental formulation of conventional nucleation and grain growth theory, and dislocation density is introduced to describe the effect of hot forming to phase transformation. Upsetting experiments under different cooling rates, plastic strains and deformation temperatures are performed to validate the accuracy of the proposed model. The proposed model has been applied to simulate phase transformation and final microstructure after 4-pass bar rolling.

KEY WORDS: numerical analysis; phase transformation; continuous cooling; bar rolling; microstructure evolution.

1. Introduction
The major objectives of hot forming are to form products with desired geometry and to optimize their microstructure. Simultaneous optimization of geometry and microstructure of formed products is gaining an increasing importance in hot forming technologies. The analytical model to predict microstructure as well as plastic deformation is strongly requested to realize this technology. It should be capable of predicting final microstructure as a function of forming conditions and alloy composition of material. For the hot forming of steels, the evolution of microstructure should be traced consistently from austenite phase to ferrite/pearlite/bainite phase. The analysis based on FEM (Finite Element Method) to predict microstructure in austenite phase has been proposed.1,2) The analysis of phase transformation should be combined with this analysis to predict final microstructure after cooling with arbitrary cooling rate.

For the isothermal transformation (ITT) of austenite to ferrite/pearlite/bainite, the Avrami equation3) can be adopted to evaluate the transformed fraction. Boundary nucleation theory proposed by Cahn4) formulizes the isothermal phase transformation. For the continuous cooling transformation (CCT), Kirkaldy et al. proposed an approach to predict CCT curves from ITT curves using the “additivity rule”.5) It was extended to a wide range of materials and forming processes by Brimacombe et al.6–8) However, those methods require accurate ITT curves, because error would easily occur in the transforming procedure from ITT to CCT curves. Suehiro et al. developed a model for CCT on the basis of physical metallurgy.9–11) This model requires smaller number of empirical parameters, which can be obtained by phase transformation experiments, so that it could be regarded having comparatively better accuracy for predicting the microstructure of plain carbon steels. But the influence of hot forming, which affects the microstructure in and after hot forming, is eliminated.

An incremental formulation for the prediction of microstructure evolution in phase transformation is proposed in this paper. This formulation can be easily coupled with the incremental formulation for the prediction of microstructure evolution in hot forming.1,2) Combined analysis of proposed model with microstructure analysis in austenite phase1,2) can be used in consistent analysis for the evolution of microstructure for any kind of hot forming such as rolling, forging and extrusion. Dislocation density and austenite grain size are introduced to represent the effect of plastic deformation prior to cooling, and the change in nucleation rate and carbon concentration in $\alpha/\gamma$ interface caused by plastic deformation are implemented. To reveal the effects of residual dislocation density to phase transformation, the hot upsetting test is performed. The accuracy of proposed formulation has been validated also by hot upsetting test. Finally, numerical studies for 4-pass bar rolling will be made, and the effects of forming sequence to microstructure evolution in and after cooling is discussed.

2. Mathematical Formulation for Phase Transformation after Plastic Deformation
2.1. Incremental Phase Transformation Model in Continuous Cooling
An incremental formulation is adopted to describe phase transformation accurately, and to realize consistent analysis starting from hot forming. The grain size and residual dislocation density at $A_{3}$ temperature, obtained by incremen-
tional analysis for hot forming,1,2) are initial parameters for the incremental analysis of phase transformation. Based on Suehiro’s model,3–11) incremental description to phase transformation is formulated as follows.

2.1.1. Ferrite transformation

Ferrite transformation starts at $A_{13}$ temperature. Increment in ferrite volume $\Delta X_f$ can be expressed by Eq. (1), following the nucleation and grain growth. After nucleation sites are saturated, Eq. (1) is replaced by Eq. (2). $\langle N \rangle$ means the number of step in incremental analysis, and $\Delta t^{(N)}$ is the time step. Change in temperature in $\Delta t^{(N)}$ is analyzed by FEM.12)

$$\Delta X_f^{(N)} = 4\left(\frac{\pi}{3}\right)^{1/4} \left(\frac{G_f^{(N)}}{d_f^{(N)}}\right)^{1/4} \left(\frac{N}{1 - X_f^{(N-1)}}\right)^{3/4} \times (1 - X_f^{(N-1)}) \Delta t^{(N)} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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2.2.1. Change in Free Energy

Change in carbon concentration at the phase transformation interface, which is caused by residual dislocation density \( \rho \), is described using a simplified binary Fe–C thermodynamics. If we assume that dislocation is edge type and a quarter of Burgers vector corresponds radius of the core of dislocation, the change in free energy \( \Delta G_\rho \), can be calculated by Eq. (10)\(^{15}\):

\[
\Delta G_\rho = \rho \left[ \frac{\mu b^2}{4\pi(1-\nu)} \right] \ln \left( \frac{2}{b \sqrt{\rho}} \right) \tag{10}
\]

\( b \) is Burgers vector, and \( \nu \) is Poisson’s ratio. This increase in free energy of austenite can cause shift of phase equilibrium between austenite, ferrite and carbides,\(^{6,14}\) as is shown in Fig. 1. From Fig. 1, we can see that the variation in carbon concentration caused by increase in residual dislocation density cannot be ignored for the precise calculation of microstructure change after hot forming.

Although the increase in free energy caused by the dislocation density is comparatively small, the free energy change \( \Delta G_\rho \) in Eq. (5) should be replaced by \( \Delta G_\rho + \Delta G_\rho \) can be expressed by Eq. (11).

\[
\Delta G_{\rho+p} = \Delta G_\rho + \Delta G_\rho \tag{11}
\]

\( \Delta G_{\rho+p} \) is the change of free energy caused by dislocation density relief. It can be calculated by Eq. (10).

2.2.2. Nucleation Rate after Hot Forming

Austenite grain size \( d_\gamma \) and the dislocation density \( \rho \) at \( A_{\alpha 3} \) temperature reflect the effect of hot forming to phase transformation. Ferrite nucleation rate can be calculated as a function of austenite grain size, temperature and free energy at \( A_{\alpha 3} \) temperature as is shown in Eq. (5). However, Eq. (5) determines the nucleation rate for non-deformed austenite. The increase in nucleation rate in deformed austenite \( \Delta T_{\gamma F}^{\text{vol}} \), can be expressed in the simplest form by a power function as Eq. (12)\(^{17}\):

\[
I_{\gamma F}^{\text{vol}} = \left( \frac{\rho}{\rho_0} \right)^n I_{\gamma F}^{\text{vol}} \tag{12}
\]

\( \rho_0 \) is the dislocation density in non-deformed austenite, and it could be a value of 10\(^8\) cm\(^3\) for annealed steel. \( n \) is a power factor indicating the influence of the dislocation density on ferrite nucleation rate, and can be determined by phase transformation experiment.

2.3. Ferrite Grain Diameter

Suehiro proposed a model to evaluate the final ferrite grain size for low carbon steel,\(^9\) in which austenite grain size is used to calculate nucleation boundary area and the temperature when 5% ferrite transformed \( T_{0.05} \) is as a factor to represent the influence of cooling rate. Considering the difference of carbon content in medium steel and the residual dislocation density, an Eq. (13) for ferrite grain size is used to evaluate the ferrite grain diameter, which is obtained by the experimental measurement shown later. The accuracy of Eq. (13) will be shown in the following chapter.

\[
d_a = \left[ 1.22 \times 10^{10} \, d_{\gamma}^{-0.15} \left( \frac{\rho}{\rho_0} \right)^{0.25} \exp \left( \frac{21430}{T_{0.05}} \right) X_f \right]^{1/3} \tag{13}
\]

2.4. Material Data

Five material constants \( K_1 – K_5 \) are necessary for the analysis of phase transformation described before. These material data take different value for different materials. For plain C–Mn–Si steel, they could be determined as Eq. (14)\(^{10}\):

\[
k_1 = 8.933 \times 10^{-12} \exp \left( \frac{21100}{T} \right)
\]

\[
k_2 = 17476.0
\]

\[
k_3 = 1.305 \times 10^7 [\text{cal}^{1/3} / \text{mol}^{1/3}]
\]

\[
k_4 = 3.0 \times 10^3
\]

\[
k_5 = 6.816 \times 10^{-4} \exp \left( \frac{3431.5}{T} \right) \tag{14}
\]

The starting temperature of bainite transformation, which is also a temperature to finish pearlite transformation, is expressed by experiment Eq. (15).

\[
B_\beta[^{\circ}\text{C}] = 717.5 – 425C[\text{wt\%}] – 42.5Mn[\text{wt\%}] \tag{15}
\]
mental condition. To freeze the microstructure at desired temperature after hot forming, a rapid quenching system is used. Optical microscope is used to investigate the microstructure of specimens etched by Nital, and the fractions of ferrite and pearlite are measured by the point-count method from the picture of microstructure. FEM analysis of plastic deformation for cylindrical specimen is made to estimate an amount of plastic deformation at the point of observation.

3.2. Experiment to Determine Nucleation Rate of Deformed Austenite

About the nucleation rate of ferrite transformation, it is necessary to determine the power \( n \) that indicates the relationship between the rise in nucleation rate and residual dislocation density \( \rho \) after hot forming. Upsetting tests for the different amount of plastic deformation is conducted at the same temperature and in same cooling condition (see experiment 1 in Table 1). Micrographs are shown in Fig. 3. The total number of ferrite nuclei can be expressed by Eq. (16). It is an integrated form of Eqs. (5) and (12).

\[
N = \int S_{\nu_1}I_{\nu_1}Idt = \left( \frac{\rho}{\rho_0} \right)^n \int S_{\nu_1}I_{\nu_1}Idt \quad \text{(16)}
\]

As the growth of austenite grains is slow at lower temperature, we could assume that the nucleation area is constant. Then, Eq. (17) can be obtained by removing the nucleation area \( S_{\nu_1} \) out of integration.

\[
\frac{N}{S_{\nu_1}} = \left( \frac{\rho}{\rho_0} \right)^n \int I_{\nu_1}Idt = \left( \frac{\rho}{\rho_0} \right)^n C_0 \quad \text{(17)}
\]

Dislocation density \( \rho \) at \( \text{A}_{e3} \) temperature can be estimated for all the plastic strain levels by the incremental formulation for the prediction of microstructure evolution in hot forming. Number of ferrite nuclei can be counted from Fig. 3 as a function of plastic strain. Then the optimum value of \( n \) could be determined. Figure 4 shows the relationship between number of ferrite nucleus and residual dislocation density at \( \text{A}_{e3} \) temperature. Dislocation density in Fig. 4 is estimated by incremental analysis for austenite phase. We could observe the rise in ferrite nucleus, and the power \( n \) is almost 1.0. Then, \( n = 1.0 \) is used in the numerical analysis to reflect hot deformation prior to phase transformation.

| Plastic strain | Temp. of water quenching (°C) | Cooling rate (°C/s) | Forming temperature (°C) |
|----------------|-------------------------------|----------------------|---------------------------|
| 1              | 0.25–1.0                      | 400                  | 6.0                       | 800                       |
| 2              | 1.0                           | 400–636              | 6.0                       | 800                       |
| 3              | —                             | 400                  | 1.6–13.5                  | —                         |
| 4              | 0.81                          | 400                  | 6.0                       | 786–930                   |

| Fig. 3. Change of F/P structures for the different plastic deformation prior to transformation. |

| Fig. 4. The relationship between residual dislocation density and number of ferrite nucleus. |

\[
y = 1.02x - 7.83 \\
R^2 = 0.949
\]
3.3. Validation of Numerical Model

Figure 5 shows comparison of ferrite volume fraction for different plastic strain levels. Ferrite volume fraction increases according to the increase in plastic strain. Numerical results underestimate ferrite volume fraction at higher amount of plastic strain, but as a whole, there observed a good agreement between analysis and experiment.

Figure 6 shows progress of ferrite transformation and pearlite transformation. The transient progress of transformation is overestimated in analysis, but volume fraction at the end of transformation is predicted with sufficient accuracy. The difference between analysis and experiment may be caused by the fundamental model, which assumes that pearlite transformation starts when the carbon concentration in austenite meets the extrapolated Acm line in the phase equilibrium diagram.

Figure 7 shows change in ferrite volume fraction obtained by different rate of cooling. Ferrite volume fraction decreased at higher rate of cooling. The analytical values agree well with the experimental measurement, although experimental value may include errors caused by point count method.

Figure 8 shows experimental and simulated values of ferrite volume fraction at different forming temperatures. For all the forming temperatures, the ferrite volume fraction shows little difference. It means that the forming temperature has slight effects on the ferrite volume fraction. But for high forming temperature, microstructure pictures show regular pearlite grain shape and clearly ferrite boundary precipitation, which indicate that recrystallization and recovery have occurred before transformation. On the contrary, for low forming temperature, the microstructures of ferrite and pearlite show irregular grain shape, which mean that the austenite grains possess higher dislocation density.

Figure 9 shows ferrite grain sizes calculated and observed considering the influence of plastic deformation. The consideration of residual dislocation density provides good agreement between analysis and experiment. This result proves that the final ferrite grain size can be evaluated quantitatively by using incremental phase transformation model and incremental formulation for the prediction of
microstructure evolution in hot forming.

4. Numerical Case Studies for Bar Rolling Process

To demonstrate the proposed transformation model for microstructure evolution, a four-pass bar rolling is selected as example of numerical case study. Figure 10 shows employed roll profile, and Table 2 shows employed rolling conditions. Austenite grain size and dislocation density at $A_{e3}$ temperature are calculated by the incremental formulation for the prediction of microstructure evolution in hot forming.\(^1\),\(^2\) Temperature field of bar on the rolling line is simulated by a quasi three-dimensional analysis model.\(^1\),\(^2\)

Figure 11 shows influence of austenite grain size and the dislocation density at $A_{e3}$ temperature on cross-sectional distribution of ferrite volume fraction at $t=135$ (s) after rolling. Fast precipitation of ferrite can be observed with fine austenite grain and higher residual dislocation density. But the final distribution of ferrite volume fraction in cross-section is relatively uniform for this rolling schedule.

Figure 12 shows final ferrite grain size distribution after cooling.

| Table 2. Employed rolling conditions. |
|---------------------------------------|
| Material | S45C |
| Initial bar radius | 15mm |
| Flow stress | $\sigma = 128^{(\text{min})} 213^{(\text{max})}$ (MPa) |
| Friction coefficient | $\mu = 0.4$ |
| Heat transfer coefficient | $H_{\text{cm}}=30000$ (W/m²K) |
| Specific heat | $H_{\text{cm}}=709.49$ (W/m³K) |
| Thermal conductivity | $C = 996$ (J/kgK) |
| Radiation coefficient | $k = 23.6$ (W/Km) |
| Shape factor | $\varepsilon = 0.52$ |
| Forming temperature | $850$ °C |
| Initial grain size | $80$ μm |
| Speed at entry of pass | $3$ m/s |
| Distance between passes | $1000$ mm |

Fig. 10. Roll profile.

Fig. 11. The influence of austenite grain size and dislocation density on the progress in ferrite phase transformation. (a) Austenite grain size at $A_{e3}$ temperature ($\mu$m). (b) Dislocation density at $A_{e3}$ temperature (1/cm²). (c) Volume fraction of ferrite phase after a cooling time 135 (s).

Fig. 12. Austenite grain size at $A_{e3}$ temperature and ferrite grain size after cooling.

Fig. 13. Transition in pearlite volume fraction.
cooling and austenite grain size at $A_e$ temperature in cross section. Ferrite grain size shows a clearly dependence to austenite grain size.

Figure 13 shows progress in pearlite transformation. Pearlite transformation starts at different time after hot forming. Position with higher dislocation density and finer austenite grain will enter pearlite transformation stage earlier.

5. Conclusion

A new CCT phase transformation model is proposed on the basis of incremental approach. Austenite grain size and dislocation density at $A_e$ temperature are successfully introduced to regard the effects of hot forming to phase transformation. By upsetting experiments, the model has been evaluated with satisfactory agreement and proved to be creditable in practical use. This model has been applied to a four-pass bar rolling, and cross-sectional transformation phenomena have been simulated.

The proposed transformation model can be applicable to all metal hot forming processes such as hot rolling, hot forging and hot extrusion since it is based on plastic deformation and temperature analyses by FEM and a general model for microstructure evolution. Detailed investigation into microstructure evolution during phase transformation may become possible by the proposed transformation model connected with FEM analysis.

REFERENCES

1) J. Yanagimoto, K. Karhausen, A. J. Brand and R. Kopp: Trans. ASME, J. Manufact. Sci. Eng., 120 (1998), No. 2, 316.
2) J. Yanagimoto and J. Liu: ISIJ Int., 39 (1999), No. 2, 171.
3) M. Avrami: J. Chem. Phys., 8 (1940), 212.
4) J. W. Cahn: Acta Metall., 4 (1956), 449.
5) J. S. Kirkaldy and R. C. Sharma: Scr. Metall., 16 (1982), 1193.
6) P. K. Agarwal and J. K. Brimacombe: Metall. Trans., 12B (1981), 121.
7) E. B. Hawbolt, B. Chau and J. K. Brimacombe: Metall. Trans., 16A (1985), 565.
8) Y. Nagasaka, J. K. Brimacombe, E. B. Hawbolt, I. V. Samarasekera, B. Hernandez-Morales and S. E. Chidiac: Metall. Trans., 24A (1993), 795.
9) M. Suehiro, K. Sato, Y. Tsukao, H. Yada, T. Senuma and Y. Matsumura: Trans. Iron Steel Inst. Jpn., 27 (1987), 439.
10) T. Senuma, M. Suehiro and H. Yada: ISIJ Int., 32 (1992), No. 3, 423
11) M. Suehiro, T. Senuma, H. Yada and K. Sato: ISIJ Int., 32 (1992), No. 3, 433.
12) J. Yanagimoto, T. Ito and J. Liu: ISIJ Int., 40 (2000), No. 1, 65.
13) L. Kaufman: Decomposition of Austenite by Diffusional Processes, ed. by V. F. Zackay and H. I. Aaronson, Interscience Publishers, New York, (1962), 313.
14) B. Uhrenius: Hardenability Concepts with Applications to Steel, ed. by D. V. Doane & J. S. Kirkaldy, Metallurgical Society of AIME, New York, (1978), 28.
15) A. Yoshie, T. Fujita, M. Fujioka, K. Okamato, H. Morikawa and H. Mabuchi: Tetsu-to-Hagané, 80 (1994), No. 12, 920.
16) M. Umemoto: 131T and 132nd Nishiyama Memorial Seminar, ISIJ, Tokyo, (1989), 97.
17) H. Morigawa: Transformation Behavior of Steel—Transformations and Properties of Commercial Steel, Materials Research Committee, ISIJ, Tokyo, (1989), 1.
18) O. L. Jimenez, A. Yanagida, S. Sugiyama and J. Yanagimoto: ISIJ Int., 41 (2001), No. 1, 31.