OUKA
The University of Osaka
Institutional Knowledge Archive

Title	A Computational Model of Phase Transformation for Welding Processes(Mechanics, Strength & Structural Design)
Author(s)	Ueda, Yukio; Murakawa, Hidekazu; Luo, Yu
Citation	Transactions of JWRI. 1995, 24(1), p. 95-100
Version Type	VoR
URL	https://doi.org/10.18910/7571
rights	
Note	

The University of Osaka Institutional Knowledge Archive : OUKA

https://ir.library.osaka-u.ac.jp/

The University of Osaka

Trans. JWRI, Vol. 24 (1995), No. 1

A Computational Model of Phase Transformation for Welding Processes†

Yukio UEDA*, Hidekazu MURAKAWA**, Yu LUO***

Abstract

A new computational model of phase transformation for welding processes is developed. In this model, the SH-CCT diagram is used to decide when the phase transformations start, while the TTT diagram is used to calculate the fraction of the new phase. Since this model is not strongly influenced by the time increment during a nucleation period, it is suitable for the thermo-mechanical-metallurgical analysis of welding processes. The evolution of phase transformation for bead on plate welding has been simulated successfully. A good prediction of the phase transformation is achieved using the present model.

KEY WORDS: (Welding) (Phase Transformation) (Computational Model) (SH-CCT) (Bead on Plate Welding)

1. Introduction

An accurate prediction of the evolution of phase transformation during welding processes is necessary for the analysis of thermal-elastic-plastic stress in which phase transformation has an important role. It is also important to evaluate the strength of the welded joint by considering metallurgical factors. In general, there are two methods for the analysis of phase transformation[1], one is based on TTT (Time Temperature Transformation, or isothermal transformation) diagrams, another is based on CCT (Continuous Cooling Transformation) diagrams. By using a TTT diagram, the fraction of a new phase can be calculated easily according to the Mehl and Avrami phase growth law, but it is difficult to decide accurately when the transformation starts during the continuous cooling process. In order to maintain accuracy of computation, it is necessary to use very small time increments. On the other hand, it is easy to decide the starting time of transformation if a CCT diagram is used, but it is difficult to calculate the fraction of a new phase.

In the present research, a new computational model is developed, in which the SH-CCT diagram (Continuous Cooling Transformation diagram of a Synthetic Heat-affected zone) is used to decide when the phase transformations start, and the TTT diagram is used to calculate the fractions of a phase. The model was applied to predict the evolution of phase transformations during bead on plate welding.

2. Computational Model

The solid state phase transformations that occur in welding processes can be roughly categorized into the diffusional and the diffusionless transformations[8]. For welding structural steels, the diffusional transformations involve Ferrite, Pearlite and Bainite transformations.The diffusionless transformation usually is Martensite transformation.

2.1 Diffusional transformation

Simulation of diffusional phase transformation comprises two stages: nucleation and phase growth.

2.1.1 nucleation

When the TTT diagram is used, the nucleation time can be determined by the condition that the Scheil sum is equal to unity[2]. However, the accuracy of computation is

† Received on May 25, 1995
* Professor
** Associate Professor
*** Graduate Student

Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan.

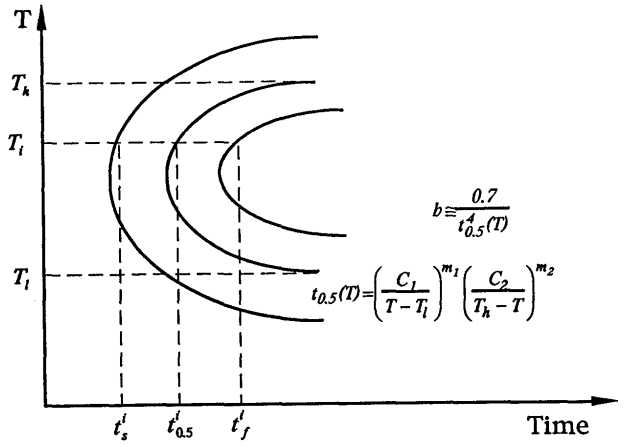


Fig.1 Schematic drawing for calculation of material constant b

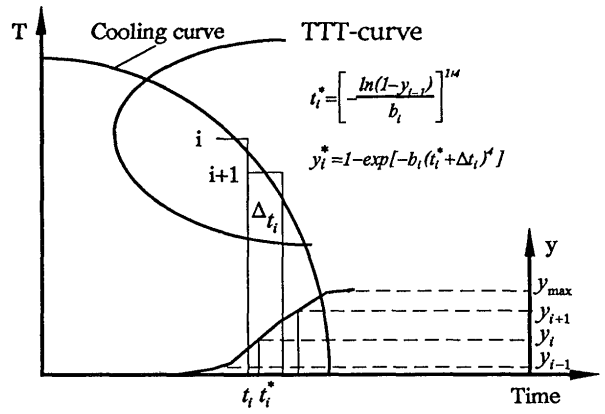


Fig.2 The computational procedure of the fraction

greatly influenced by the cooling rate and time increment. Thus, a method based on the SH-CCT diagram is employed in present model. In this method the nucleation time is determined as the time when the cooling curve crosses with SH-CCT curve.

2.1.2 phase growth

The experimental kinetics is fitted using a law proposed by Johnson and Mehl and Avrami[3)-6)] that describes the phase growth during the isothermal transformation:

$$y = 1 - exp(-bt^n) \tag{1}$$

where,

y: the fraction of new phase

t: time of isothermal transformation

b, n: temperature dependent material constants

In this paper, it is assumed that n is equal to 4 (for homogeneous nucleation) and b is a function of temperature given according to the TTT diagram. For example, 50% phase transformation time ($t_{0.5}$) can be used to determine the material constant b. **Figure 1** is a reference diagram for the calculation of the material constant b.

In this paper, the function $t_{0.5}(T)$ is assumed to be expressed as:

$$t_{0.5}(T)=\left(\frac{C_1}{T-T_l}\right)^{m_1}\left(\frac{C_2}{T_h-T}\right)^{m_2} \tag{2}$$

where,

$t_{0.5}$:50% phase transformation time

T : temperature

T_h: higher limit temperature of 50% transformation

T_l : lower limit temperature of 50% transformation

It is reasonable to suppose that C_1, C_2, m_1 and m_2 are constants dependent only on material.

From Eq.(1), it is found that,

$$1-exp\left\{-b[t_{0.5}(T)]^4\right\}=0.5$$

$$b[t_{0.5}(T)]^4 \cong 0.7$$

$$b \cong \frac{0.7}{t_{0.5}^4(T)}=0.7\left(\frac{T-T_l}{C_1}\right)^{4m_1}\left(\frac{T_h-T}{C_2}\right)^{4m_2} \tag{3}$$

If TTT diagram is given, it is easy to determine constants C_1, C_2, m_1, m_2, T_l and T_h. Then the function b can be decided.

The procedure of computing the fraction of new phase during the cooling process is shown in **Fig.2**. To calculate the fraction of phase at the i-th step, the fictitious time t_i^* is calculated first. The fictitious time can be considered as the time at which the fraction of the phase under fictitious isothermal transformation at temperature T_i becomes the value achieved before the i-th step in the real process. From the fraction of phase y_{i-1} formed up to the end of the preceding time step, the fictitious time t_i^* can be calculated, i.e.,

$$t_i^* = \left[-\frac{ln(1-y_{i-1})}{b_i}\right]^{1/4} \tag{4}$$

Then this fictitious time is increased by an increment Δt_i and a fictitious fraction of phase y_i^* is computed according the following equation.

$$y_i^* = 1 - exp[-b_i(t_i^* + \Delta t_i)^4] \tag{5}$$

The fraction of new phase y_i can be computed from the fictitious fraction of phase y_i^* , further corrected to take into account the maximum amount of new phase, i.e.,

$$y_i = y_i^* y_{max} \tag{6}$$

where y_{max} is the maximum amount of new phase that can be taken as a temperature-dependent variable, found from isothermal kinetics data.

2.2 Diffusionless transformation

In a welding process, the diffusionless transformation is Martensite transformation.

2.2.1 *incubation*

The problem of deciding when the diffusionless transformation starts is similar to that for the diffusional transformation. At the moment when the cooling curve crosses the Martensite transformation starting curve on the CCT diagram, the phase transformation starts.

2.2.2 *phase growth*

The fraction of Martensite is given by the following equation:

$$y_m = 1 - exp\{\Phi(T)\} \tag{7}$$

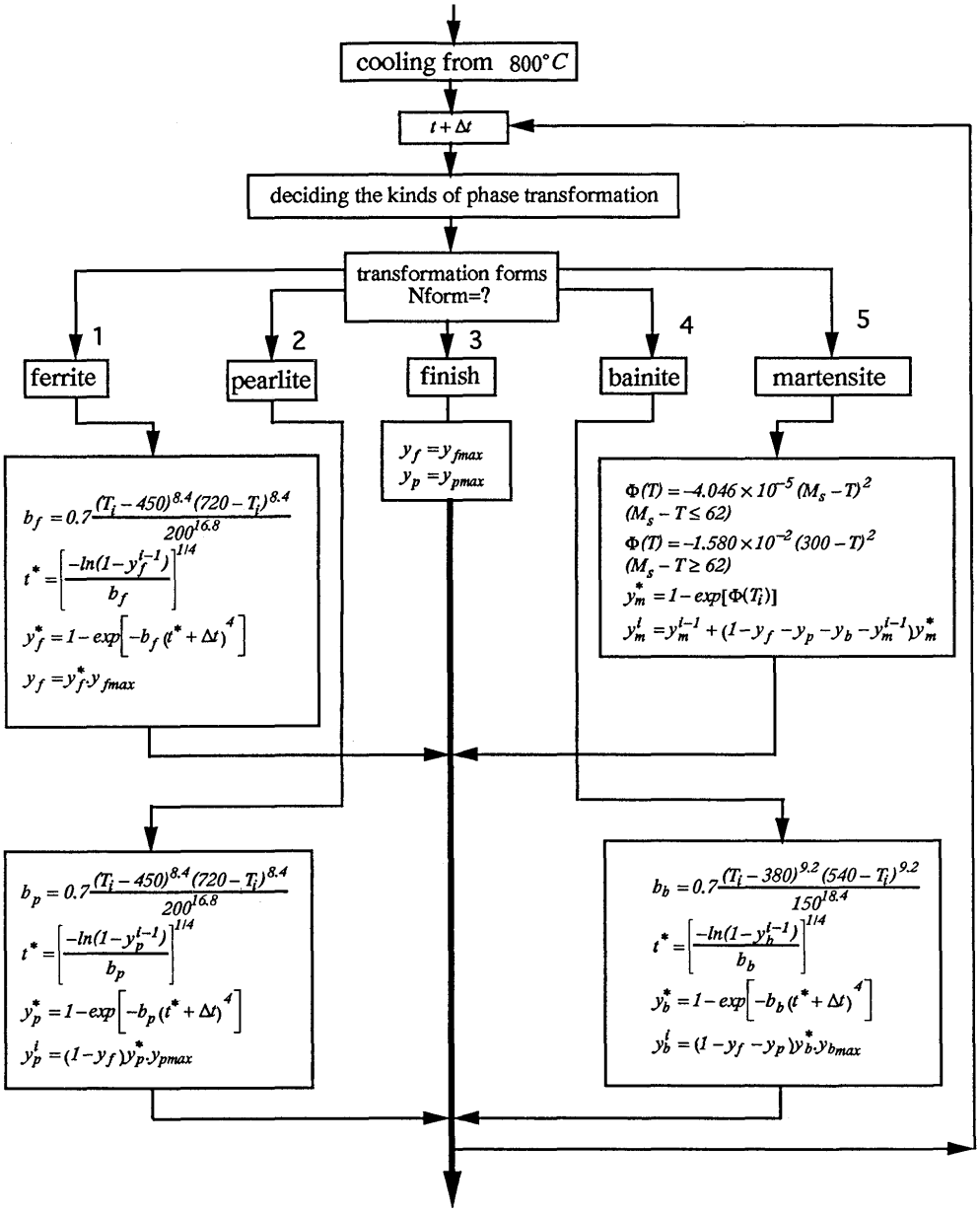


Fig.3 The flowchart of phase transformation calculation

The dilatation-temperature diagrams experimentally measured under high cooling rate from austenite temperature are employed to express the function of $\Phi(T)$. For example, T. Inoue[7] employed the following function $\Phi(T)$ for S45C steel:

$$\Phi(T)=\begin{cases}-4.046\times10^{-5}(M_S-T)^2, if & M_S-T<62\\ -1.580\times10^{-2}(328-T)^2, if & M_S-T\geq 62\end{cases} \quad (8)$$

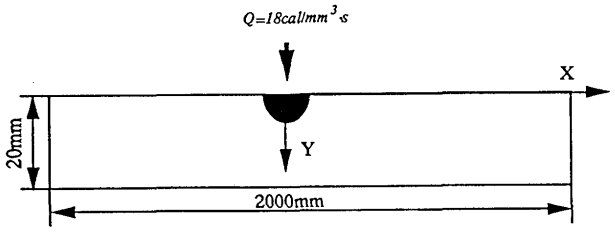


Fig.4(a) Bead on plate welding model

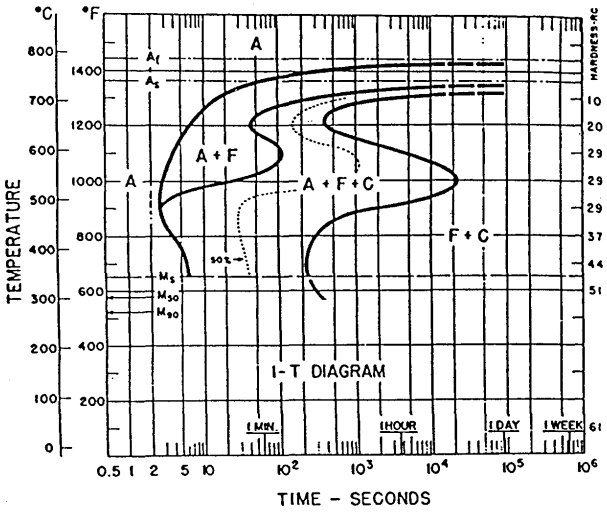


Fig.4(b) TTT diagram

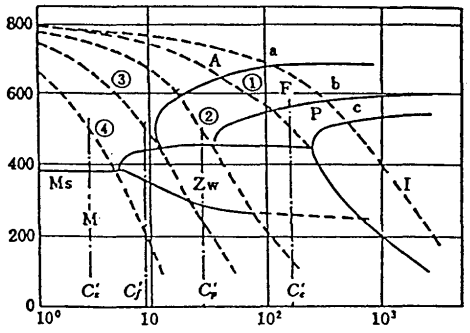


Fig.4(c) SH-CCT diagram

3. Computational Program

The temperature distribution during a welding process has been calculated by FEM. The flowchart of the phase transformation analysis is given in **Fig.3**. At first, it is necessary to find the time when the element is cooled to $800°C$. From this point, analysis of phase transformation for each element is carried out step by step. The second step is to decide which transformations occur in the element according to the position at which the cooling curve crosses the CCT curve. Then the fraction of new phase can be calculated based on Eqs.(3) -(8).

4. Application

As an example, the simulations of phase transformation in bead on plate welding were carried out using the program developed in this research.

4.1 Model for analysis

Figure 4(a) shows an example model of bead on plate welding computed by FEM. The width and the thickness of the plate are 2000mm and 20mm, respectively. The heat input rate for the present model is $Q=18cal/mm^3\cdot s$. The thermal properties are assumed to be the same as mild steel. The temperature distribution is calculated by FEM. The time step (Δt) is chosen to be 0.5 second in the present analysis. In this example, both the weld metal and the base metal are assumed to have the same properties. The TTT diagram is shown in **Fig.4(b)**, and the SH-CCT diagram is given in **Fig.4(c)**. To decide the material parameter b, describing the diffusional transformation, the TTT diagram and Eq.(3) are used. However, it is assumed that

$m_1=m_2 \qquad C_1=C_2$

for simplicity. Then, the functions of b for Ferrite, Pearlite and Bainite transformations are given as follows, respectively

for Ferrite transformation:

$$b_f=0.7\frac{(T_i-450)^{8.4}(720-T_i)^{8.4}}{200^{16.8}} \quad (9)$$

for Pearlite transformation:

$$b_p=0.7\frac{(T_i-450)^{8.4}(720-T_i)^{8.4}}{200^{16.8}} \quad (10)$$

for Bainite transformation:

$$b_b=0.7\frac{(T_i-380)^{9.2}(540-T_i)^{9.2}}{150^{18.4}} \quad (11)$$

The function of $\Phi(T)$ which describes the Martensite transformation is assumed to be expressed as Eq.(8).

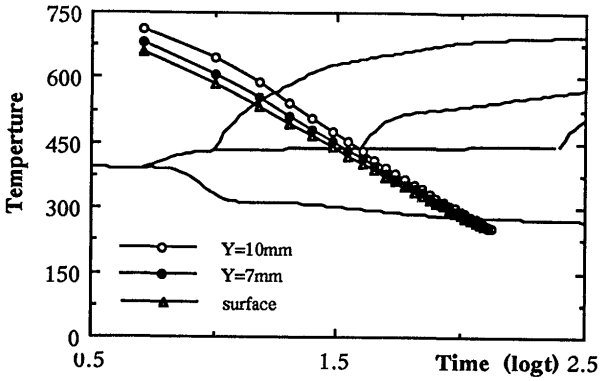


Fig.5 The relation between cooling curve and SH-CCT diagram

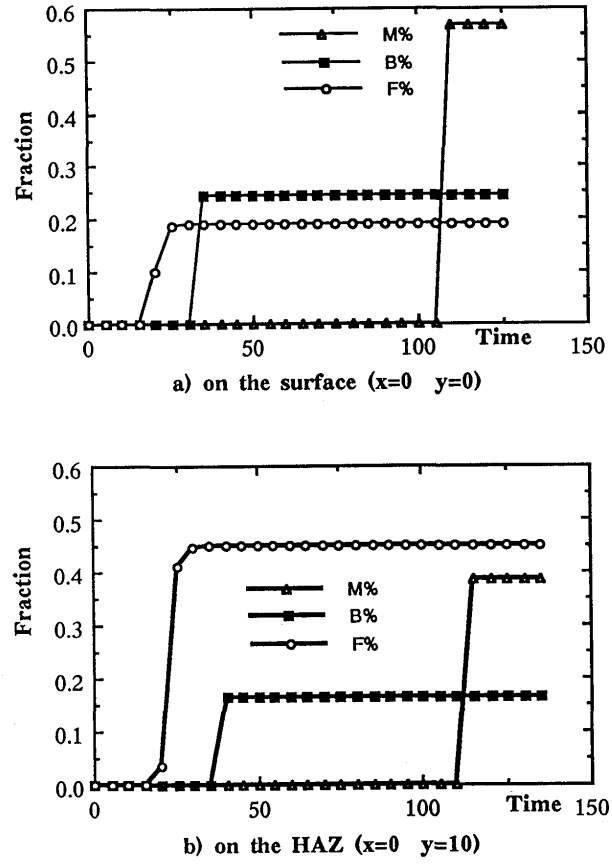
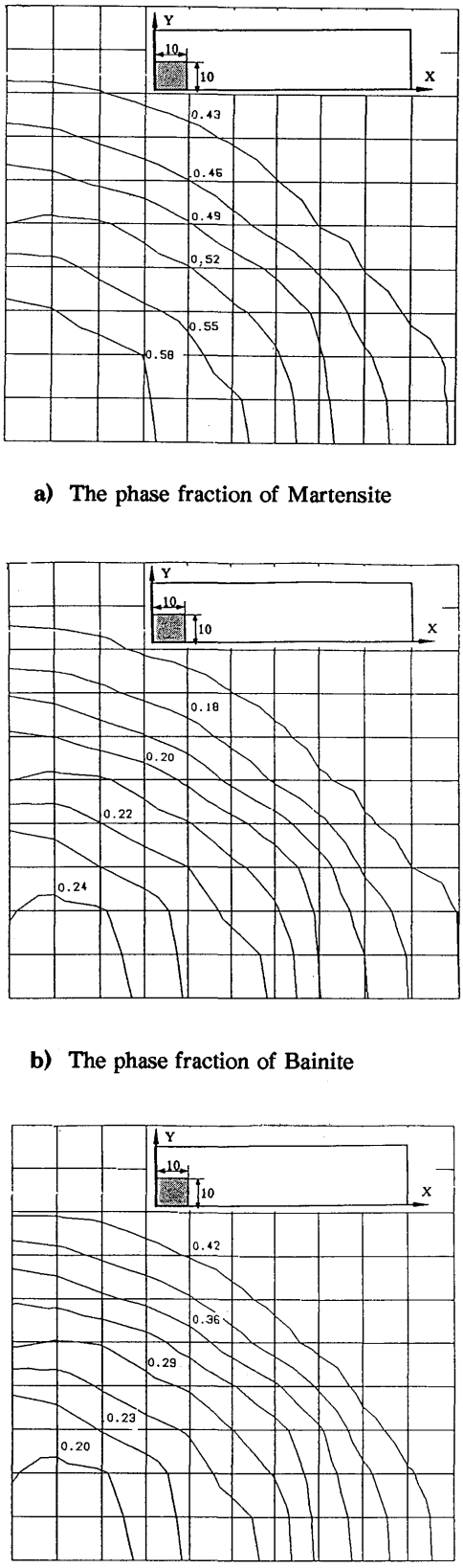


Fig.6 The evolution of phase fraction in bead on plate

4.2 Computed results

Figure 5 shows the cooling curves for the positions in the bead and the HAZ, superposed on the SH-CCT diagram. The average cooling rate from 800 °C to 250 °C is 4.35 °C/sec. and 4.29 °C/sec. for the surface (y=0mm) and HAZ (y=10mm), respectively. On the surface, the starting time of Ferrite, Bainite and Martensite transformations is 15sec., 35sec. and 105sec., and



a) The phase fraction of Martensite

b) The phase fraction of Bainite

c) The phase fraction of Ferrite

Fig.7 The phase fraction distribution on phase transformation zone

Table.1 Model Comparison

	Model I	Model II
Transformation beginning time	When Scheil Sum is equal to unity	When cooling curve crosses with SH-CCT
Calculation of b and n	According to two points on TTT	According to $t_{0.5}$ of TTT curve
Merit	CCT is unnecessary	Accurate prediction of nucleation time
Demerit	Poor accuracy for nucleation period	CCT is necessary

temperature is 531.3°C, 441.1°C and 276.0°C, respectively. In the HAZ, the starting time is 20sec., 40sec., and 110sec. The temperature is 587.9°C, 451.8°C, and 279.6°C, respectively. From Fig.5, it is seen that the differences between the cooling process on the plate surface and that at the HAZ are observed essentially in the time and the temperature at which the cooling curve crosses with CCT curve, not in the cooling rate. The evolution of phase fraction on the plate surface (x=0, y=0) and that at the HAZ (x=0, y=10) are shown in **Figs.6 a) and b)**, respectively. From Fig.6 a) and Fig.6 b), it is seen that the structure on the surface is Ferrite 19.1%, Bainite 24.3% and Martensite 56.6%, while at the HAZ, that is 44.9%, 16.5% and 38.6%, respectively. It is clear that the fraction of each phase is very different. From Fig.5 and Fig.6, it can be summarized that the starting time of transformation plays an important role in phase transformation. **Figure 7** shows phase fraction distribution near the welding bead after welding process. Figures 7. a), b) and c) show the phase fraction of Martensite, Bainite and Ferrite, respectively.

5. Conclusions

The main results obtained in this research are summarized as follows,

(1) A computational model has been developed for phase transformation during a welding process. **Table 1** shows the comparisons between the present model (model II) and a model[2] (model I) which is based on only TTT diagram.

(2) The evolution of phase transformation for bead on plate welding has been simulated successfully. It has been shown that a good prediction of the phase transformation during welding process is achieved using present model.

(3) Since the proposed model is not strongly influenced by the time increment during nucleation period, it is suitable for the thermo-mechanical-metallurgical analysis.

Acknowledgment

The authors would like to thank Prof. Jacek RONDA for the valuable advice and suggestions.

References

1) D. A. Porter, and K. E. Easterling, "Phase Transformations in Metals and Alloys", Chapman & Hall, (1993).
2) F. M. B. Fernandes, "Mathematical model coupling phase transformation and temperature evolution during quenching of steels", Materials Science and Technology, October 1985, Vol.1.
3) W. A. Johnson and R. F. Mehl, Trans. AIME, 1939, **135**, 416.
4) M. Avrami, J. Chem. Phys., 1939, **7**, 1103.
5) M. Avrami, J. Chem. Phys., 1940, **8**, 212.
6) M. Avrami, J. Chem. Phys., 1941, **9**, 177.
7) T. Inoue, "Description of Transformation Kinetics, Heat Conduction and Elastic-Plastic Stress in the Course of Quenching and Tempering of Some Steels", Ingenieur-Archiv, Vol.50 (1981), pp.315-327.
8) Y. Ueda, J. Ronda, H. Murakawa, K, Ikeuchi, "Thermo-Mechanical-Metallurgical Model of Welded Steel", Trans. JWRI, Vol. 23 (1994), No. 2, pp.149-167.