Kinetics of Phase Transformations in Steels: A New Method for Analysing Dilatometric Results

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A dilatation curve records the detail of the phase transformation kinetics. The dilatometric technique may be applicable to the investigation of the phase transformation kinetics if the information contained in the dilatation curve can be extracted effectively. A detailed analysis has been made of the length change of a hypoeutectoid steel during a continuous cooling. A model has been developed in which the transient dilatation is calculated based on the fraction of the phases present. The model takes into account the redistribution of carbon and is applicable to the determination of the phase transformation kinetics from the dilatation data during a cooling of a hypoeutectoid steel. The model was validated by comparing the model results with the experimental results of an interstitial free steel. Experiments have been done with a bainitic steel. The model has been applied to the determination of the phase transformation kinetics from the dilatation curves of this steel. Excellent agreements between the model and experiments have been obtained.

KEY WORDS: steels; thermal expansion; phase transformation; kinetic; theory and modeling.

1. Introduction

The structure of a steel changes with temperature due to phase transformations. This phase change is generally accompanied by a variation in the specific volume which is exhibited as a departure from the behaviour of the thermal expansion or contraction, at the temperature at which the change occurs. This behaviour can be detected as a change in the dimensions of a suitable test piece, and forms the operating principle of dilatometry. The dilatometric technique may be applicable to the investigation of the phase transformation kinetics if the relation between the fractions of phases, the temperature, the compositions of phases and the dilatation can be built up. Efforts have been made to analyze the dilatation during an isothermal transformation1,2) or to calculate the dilatation during the heating of plain carbon steels using the thermodynamic function.3) The existing models are, however, not directly applicable to the determination of the phase transformation kinetics from a dilatation curve.4) In the literature, the relation between the amount of the product phase at a certain stage of a transformation and the associated volume change is often assumed to be linear, unjustly also for the case where the final reaction product is formed in a separate, consecutive decompositions. The volume fraction of phases is determined from a curve of the relative length change as a function of temperature by using the lever rule illustrated in Fig. 1.

The lever rule is, however, only applicable in the case of a process which involves only one phase transformation. In addition, it does not give any information about the composition of phases. These have hampered the application of the dilatometric technique to the investigation of the phase transformation kinetics. A model was therefore developed to determine the phase transformation kinetics from a dilatation curve that may correspond to a multistep phase transformation. The model was validated by comparing its results with the experimental results for an interstitial free steel. Experiments have been done with a bainitic steel. The model has been applied to the determination of the phase transformation kinetics from the dilatation curves of this steel. Excellent agreements between the model and experiments have been obtained.

Fig. 1. The dilatation during a cooling of the interstitial free steel. The solid line is the measured dilatation and the dotted line the dilatation calculated for the equilibrium transformation.
steel which involved only one phase transformation during a cooling through the austenite phase region. Experiments were also done with a bainitic steel. The model was successfully applied to the determination of the phase transformation kinetics from the dilatation curves of this steel.

2. Physical and Mathematical Analyses

From the mathematical point of view, the density of a phase can be related to the thermal expansion coefficient of the phase by:

$$ k_\text{T} = \frac{1}{3} \left[ \rho(T, C) \right]^{-1} \frac{\partial \rho(T, C)}{\partial T} \quad \text{(1)} $$

Where $k_\text{T}$ is the thermal expansion coefficient of the phase, $T$ is the temperature, $C$ is the carbon concentration of the phase, and $\rho$ is the density of the phase.

Experiments with pure iron were carried out to investigate the effect of temperature on the lattice parameter of ferrite and austenite. They demonstrated that the lattice parameter of ferrite increased approximately linearly with temperature up to $1200^\circ C$, although small differences exist between the thermal expansion coefficients given by different authors. They also indicated that above $300^\circ C$ the lattice parameter of ferrite increased approximately linearly with temperature. This can be seen from Table 1.

Table 1. Thermal expansion coefficient of $\alpha$-iron.

<table>
<thead>
<tr>
<th>Temp. in °C</th>
<th>300</th>
<th>400</th>
<th>500</th>
<th>600</th>
<th>700</th>
<th>800</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_\text{T}$ $\times 10^8$ °C$^{-1}$</td>
<td>14.87</td>
<td>14.85</td>
<td>14.83</td>
<td>14.81</td>
<td>14.78</td>
<td>14.76</td>
</tr>
<tr>
<td>$k_\text{T}$ $\times 10^8$ °C$^{-1}$</td>
<td>15.5</td>
<td>16.2</td>
<td>16.25</td>
<td>15.8</td>
<td>15.8</td>
<td>15.4</td>
</tr>
<tr>
<td>$k_\text{T}$ $\times 10^8$ °C$^{-1}$</td>
<td>17.55 (from 527 to 927 °C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Generally, the addition of alloying elements does not affect the linear dependence of lattice parameter on temperature. It is a common phenomenon that a low carbon steel contracts with temperature approximately linearly during cooling above $300^\circ C$ if no phase transformations occur. Supposing the lattice parameters for both ferrite and austenite of a given composition vary linearly with temperature, the density of the phases in this temperature range may be obtained by integrating Eq. (1): 

$$ \rho_i(T, C) = \rho_i(T_0, C)e^{-3k_\text{T}(T-T_0)} \quad \text{(2)} $$

Where $T_0$ is a temperature arbitrarily selected within the temperature range $300$–$1200^\circ C$, the subscript $i$ refers to different phases: the austenite, the primary ferrite, the ferrite formed during the pearlite decomposition and the bainitic ferrite.

Investigations on the effect of carbon content on the lattice parameter of austenite and ferrite have shown that the density of austenite and ferrite varied linearly with carbon content for a constant temperature. The linear relation was given as:

$$ \rho_i(T_0, C) = \rho_i(T_0, C=0)g_i(C) \quad \text{(3)} $$

Where $g_a(C) = 1 - 0.0146\%$ C for austenite and $g_f(C) = 1 - 0.0262\%$ C for ferrite.

One can find by inserting Eqs. (2) and (3) into Eq. (1) that the carbon content of a phase does not affect the thermal expansion of the phase. This means that the equilibrium ferrite and the bainitic ferrite should have the same thermal expansion coefficient. This has also been shown by the experiments with a bainitic steel, see Fig. 4 where the dilatation–temperature curve for samples cooled at different rates have approximately the same slope below $440^\circ C$, although they consist of different amount of primary ferrite and bainitic ferrite.

The relative length change of a sample, $\varepsilon = (L - L_0)/L_0$, can be divided into three parts: The relative length change of phases due to the variation in temperature, $\varepsilon^T_i$, the relative length change due to the variation of the composition of phases, $\varepsilon^c_i$, and the relative length change due to the phase transformation, $\varepsilon^{\text{TR}}_{i\rightarrow j}$. The increase in the relative length change in a time step $\Delta t$ due to the variation in the temperature is given by:

$$ \Delta \varepsilon^T_i(t) = f_i(t)k_\text{T} \rho_i(T(t)) \Delta t $$

Where $f_i(t)$ is the volume fraction of phase $i$ at time $t$, and $T = \partial \rho / \partial t$ is the changing rate of the temperature.

Considering the fact that generally the diffusional coefficients for substitutional alloying elements are much smaller compared to that for carbon, the redistributions of substitutional elements between phases during a phase transformation are neglected. Further, considering the kinetic characteristics of each kind of transformations, it may be reasonable to assume that only the primary ferrite and the austenite can change their compositions after formation. The dilatation due to the change in the carbon content of a phase can be calculated by:

$$ \Delta \varepsilon^c_i(t) = f_i(t)k_c \frac{\partial g_i(C)}{\partial t} \Delta t $$

Where $k_c$ is the solute expansion coefficient, $g_i(C)$ is the derivative of $g_i(C)$.

The dilatation due to the phase transformation in a time step can be calculated by:

$$ \Delta \varepsilon^{\text{TR}}_{i\rightarrow j}(t) = -k_{\text{TR}}^{i\rightarrow j}(t) \frac{\partial f_j}{\partial t} \Delta t $$

Where $k_{\text{TR}}^{i\rightarrow j}(t)$ is the expansion coefficient of the phase transformation $i \rightarrow j$.

The phase transformations during a cooling of a hypoeutectoid austenite can be divided into three groups:

1) The nucleation and growth type transformation which includes the formation of the primary ferrite and the formation of the bainitic ferrite during the first period of an upper bainitic transformation.

2) The pearlite type transformation which includes the pearlite decomposition and the last period of an upper bainitic phase transformation when the carbon-enriched residual austenite transforms into a mixture of bainitic ferrite and cementite (the expansion may be
calculated just as if the austenite decomposed into a mixture of ferrite and cementite, although in reality the cementite precipitates form the austenite).

3) The martensitic transformation which does not involve any redistributions of alloying elements, including carbon. The martensitic transformation will not be discussed in this paper because it takes place very often below 300°C, where the ferrite does not expand linearly with temperature according to some literatures. The lower bainitic transformation is not mentioned because of the uncertainty about the redistribution of carbon in this transformation. The lower bainitic transformation is being studied using the dilatation technique with the help of the model developed here and the results will be reported elsewhere.

For a nucleation and growth type transformation, it is assumed that the transformation completes in two steps. First a small region of austenite adjusts its carbon content to \( C_{\gamma}^{\text{eq}} \) which is the equilibrium carbon content of the primary ferrite \((C_{\gamma}^{\text{eq}})\) for the formation of the primary ferrite and/or the carbon content of the bainitic ferrite \((C_{\gamma}^{\text{B}})\) for the formation of the bainite ferrite, through the rejection of the excess carbon \((C_{\gamma}^\gamma - C_{\gamma}^{\text{eq}})\). Then this region transfers to primary ferrite or bainitic ferrite. Therefore, \( k_{\gamma}^{\text{trans}} \) and \( C_{\gamma} \) are given by:

\[
k_{\gamma}^{\text{trans}} = k_{\gamma}^{\text{trans}'} + k_{\gamma}^{C} (C_{\gamma}^\gamma - C_{\gamma}^{\text{eq}}) \tag{8}
\]

\[
k_{\gamma}^{\text{trans}'} = 3 \frac{\rho_{\gamma}^\prime(T_{a}, C = 0)}{\rho_{\gamma}^{\text{eq}}(T_{a}, C = 0)} \frac{e^{C_{\gamma}^{\text{eq}}(T_{a} - T)}}{e^{C_{\gamma}^{\gamma}(T_{a} - T)}} - 1 \tag{9}
\]

\[
\frac{\partial C_{\gamma}}{\partial t} = -(C_{\gamma}^\gamma - C_{\gamma}^{\text{eq}}) \frac{1}{f_{\gamma}} \frac{\partial f_{\gamma}}{\partial t} - \frac{f_{\gamma}}{f_{\gamma}} \frac{\partial C_{\gamma}}{\partial T} \tag{10}
\]

Where the subscript \( P_{a} \) indicates the primary ferrite, the subscript \( B_{a} \) the bainitic ferrite.

The two-step transformation assumption is applied to a phase transformation of the pearlite type, too. In this case it is assumed that the carbon content of the residual austenite always follows the phase diagram for the pearlite decomposition and/or the \( B_{a} \) line for the later stage of the bainitic transformation. That is, a small region of austenite adjusts its carbon content to \( C_{\gamma}^{\text{eq}} \) to allow the residual austenite to change its concentration according to the phase diagram; this region then decomposes into ferrite and cementite at a mass ratio of \( a_{i} \) which depends on the composition of the small region and the temperature. \( a_{i} \) is determinable by using the phase diagram based on carbon conservation relation. The density of the mixture of ferrite and cementite is given by:\n
\[
\rho_{\text{mix}} = \frac{\rho_{\gamma} a_{i} \rho_{Fe,C}}{a_{i} \rho_{Fe,C} + (1 - a_{i}) \rho_{\gamma}} \tag{11}
\]

Where the subscript \( x \) takes E for the pearlite decomposition and EB for the bainitic transformation, \( \rho_{Fe,C} \) is the density of cementite.

The expansion coefficient of the phase transformation can be calculated by using the following equation:

\[
k_{\gamma}^{\text{trans}} = k_{\gamma}^{\text{trans}'} + k_{\gamma}^{C} (C_{\gamma}^{\text{mix}} - C_{\gamma}^{\gamma}) \tag{12}
\]

\[
k_{\gamma}^{\text{trans}'} = \frac{\rho_{\gamma}(T_{a}, C = 0)}{\rho_{\gamma}^{\text{eq}}(T_{a}, C = 0)} \frac{1}{3} \frac{e^{C_{\gamma}^{\text{eq}}(T_{a} - T)}}{e^{C_{\gamma}^{\gamma}(T_{a} - T)}} - 1 \tag{13}
\]

Taking into account the change of the carbon content of the primary ferrite and austenite during the transformation, \( C_{\gamma}^{\text{mix}} \) is determined by:

\[
C_{\gamma}^{\text{mix}} = C_{\gamma} + f_{\gamma} T \frac{\partial C_{\gamma}}{\partial T} \left( \frac{\partial f_{\gamma}}{\partial T} \right)^{-1} + f_{\gamma} T \frac{\rho_{Fe,C}}{\rho_{\gamma}} \frac{\partial C_{\gamma}}{\partial T} \left( \frac{\partial f_{\gamma}}{\partial T} \right)^{-1} \tag{14}
\]

It should be mentioned that the enrichment of the residual austenite with carbon starts at the transformation interface. This may lead to a carbon concentration profile across the austenite grain. However, when the two-step transformation assumption model is used for the detail of the phase transformation, it does not affect the calculated value of the expansion coefficient of a phase transformation. As \( g_{j}(C) \) is close to unity, the inhomogeneity in carbon distribution in the grains has only a negligible effect on \( k_{\gamma}^{C} \). Therefore, instead of calculating the carbon concentration profile across the grain, the average concentration of carbon in the austenite is used.

Taking all three terms of dilatation into account, the total relative length change is determined by:

\[
\frac{\partial \varepsilon}{\partial t} = \sum_{j} f_{j}(t) k_{j}^{\gamma} \frac{\partial f_{\gamma}}{\partial t} + k_{\gamma}^{\gamma} \frac{\partial C_{\gamma}}{\partial t} + k_{\gamma}^{C} f_{\gamma}^{\gamma} \frac{\partial C_{\gamma}}{\partial T} \tag{15}
\]

The thermal expansion coefficient \( k_{j}^{\gamma} \) and the density \( \rho_{j}(T_{\alpha}, C=0) \) for the phases are the kinetic parameters needed for the calculation. Generally \( k_{j}^{\gamma} \) is relatively easy to be determined from the dilatation datum. The key for the calculation is the determination of \( \rho_{j}(T_{\alpha}, C=0) \). It should be mentioned that \( \rho_{j}(T_{\alpha}, C=0) \) is essentially the true density of the phase. The calculation of it is difficult especially because generally there are defects, i.e. dislocations etc., in steels. In fact, the density functions constructed are used only for the calculation of the dilatation due to the phase transformations. Equations (9) and (13) indicate that this dilatation depends mainly on the ratio \( \rho_{j}(T_{\alpha}, C=0)/\rho_{\gamma}(T_{\alpha}, C=0) \). It has been proved that a small difference in \( \rho_{j}(T_{\alpha}, C=0) \) does affect the calculated results much if this ratio is selected properly. It may, therefore, be practical to calculate the density \( \rho_{j}(T_{\alpha}, C=0) \) using the lattice parameter and take the density \( \rho_{\gamma}(T_{\alpha}, C=0) \) as the value that allows the best match between the model and the experiments. To determine the densities this way has the great ad-
vantage of self-calibration that may help correct for the experimental uncertainties. For a given steel, once a single kinematic parameter set is selected correctly, it can be applied to the calculation of the phase transformation kinetics from the dilatation curves of significantly different cooling rates. The entire procedure will be demonstrated in Sec. 4.

3. Experimental Verifications of the Model

Experiments were carried out with an interstitial free (IF) steel. The chemical composition of the steel is given in Table 2. The steel was heated to 1200 °C, held at this temperature for 2 min and then cooled down at a rate of 12 °C/min. Figure 1 shows the dilatation as a function of temperature during the cooling. It demonstrates clearly a dilatation in three stages. The first stage corresponds to the period of the cooling in the austenite phase field without a phase transformation taking place. It shows a perfect linear dilatation with temperature. In the second stage the austenite transforms to ferrite. The dilatation is a common result of the thermal contraction of phases and the expansion due to the phase transformation. The third stage begins when the phase transformation is finished. It gives again a linear dilatation with temperature. The dilatation under equilibrium conditions was calculated with the model, too. The thermal expansion coefficient for the ferrite and the austenite was taken as 1.61 × 10⁻⁵ and 2.25 × 10⁻⁵ 1/°C according to the experiments. The temperature T_c was taken as 727 °C. At this temperature the lattice parameter of ferrite and austenite for pure iron is 0.28965 and 0.36309 nm, respectively. The effect of the main alloying element Mn on the lattice parameter was taken into account by using Eq. (16a) for the austenite and Eq. (16b) for the ferrite.

\[ a_f = 3.6309(1 + 2.7 \times 10^{-4} \text{Mn}\% \text{at}) \]  
\[ a_a = 2.8965 + 10.00067 \times \text{Mn}\% \text{at} \]

The densities \( \rho_f(T, C=0) \) and \( \rho_a(T, C=0) \) calculated from the lattice parameters are 7735 and 7625 kg/m³, respectively. The dilatation calculated for the equilibrium transformation is shown in Fig. 1, too. It indicates that the practical transformation is away from the equilibrium transformation even for a cooling rate of 12 °C/min. But the good agreement between the measured dilatation curve and the calculated one outside the phase transformation temperature range does prove the correctness of the model.

The composition of the steel and the cooling rate determine that this cooling process involves only one phase transformation, as demonstrated in Fig. 1. The whole austenite transforms to ferrite during the cooling. In addition, the analysis of the dilatation curve indicates that the phase transformation begins at 878 °C where the solubility of carbon in ferrite is close to the carbon content of the steel. This means that the carbon does not redistribute during the formation of ferrite. The volume fraction of phases can, therefore, be accurately predicted with the lever rule demonstrated in Fig. 1. The calculation result is shown in Fig. 2. The information on the phase transformation kinetics contained in the dilatation curves was extracted with the model developed. The calculated volume fraction of the transformed austenite is also shown in Fig. 2. The perfect coincidence between the results calculated with the model and the lever rule verifies the model once again. It also indicates that the proposed model can be used to extract the information on the phase transformation kinetics contained in a dilatation curve effectively.

4. Extraction of the Phase Transformation Kinetics from Dilatations for a Bainitic Steel

Experiments were done with bainitic steel (BG). The chemical composition of the steel is given in Table 2. The equilibrium phase diagram of this steel was calculated with Thermo-Calc. The bainitic transformation start temperature, \( B_T \), was measured experimentally and it was indicated that it could be estimated with the empirical equation given by Steven and Haynes:

\[ B_T(°C)=830 - 270\text{Cr}%\text{wt} - 90\text{Mn}%\text{wt} - 37\text{Ni}%\text{wt} - 70\text{Cr}%\text{wt} - 83\text{Mo}%\text{wt} \]

The steel was heated to 1200 °C, held at this temperature for 2 min and then cooled down at different rates. The microstructures of the samples were examined. It was indicated that the sample cooled at a rate of 6 °C/min consisted of primary ferrite, pearlite and bainite. The volume fraction of the primary ferrite was about 68%, see Fig. 3(a). The volume fraction of the primary ferrite decreased with cooling rate. The sample cooled at a rate of 100 °C/min consisted of about 17% vol primary ferrite, 82.5% vol bainite and 0.5% vol residual austenite, see Fig. 3(b). The sample cooled at a rate of 300 °C/min consisted of about 4% vol primary ferrite, 95.5% vol bainite and 0.5% vol residual austenite.

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Table 2. Chemical composition of the interstitial free steel and the bainitic steel (wt%).

<table>
<thead>
<tr>
<th>Element</th>
<th>IF</th>
<th>GB</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>0.0054</td>
<td>0.155</td>
</tr>
<tr>
<td>Si</td>
<td>0.007</td>
<td>0.024</td>
</tr>
<tr>
<td>Mn</td>
<td>0.97</td>
<td>1.75</td>
</tr>
<tr>
<td>P</td>
<td>0.073</td>
<td>0.0128</td>
</tr>
<tr>
<td>S</td>
<td>38</td>
<td>15</td>
</tr>
<tr>
<td>N</td>
<td>27</td>
<td>20</td>
</tr>
<tr>
<td>S( ppm)</td>
<td>0.043</td>
<td>0.041</td>
</tr>
<tr>
<td>Ni( ppm)</td>
<td>0.01</td>
<td>0.0821</td>
</tr>
<tr>
<td>B</td>
<td>0.025</td>
<td>0.106</td>
</tr>
<tr>
<td>Cr</td>
<td>0.001</td>
<td>0.023</td>
</tr>
<tr>
<td>Ni</td>
<td>0.001</td>
<td>0.023</td>
</tr>
</tbody>
</table>

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Fig. 2. The volume fraction of the transformed austenite calculated from the dilatation curve with the model developed (solid line) and with the lever rule (circles) as a function of temperature during a cooling of the interstitial free steel. The dotted line is the volume fraction of austenite predicted according to the equilibrium phase diagram.
The dilatation curves were analysed with the proposed model. The thermal expansion coefficients for the ferrite and austenite determined from the dilatation curves are 1.48×10⁻⁵ and 2.25×10⁻⁵ °C⁻¹, respectively. The temperature T_F was taken as 727°C. The lattice parameter of the carbon-free austenite at T_F was calculated using (18):

\[ a_F = 3.6309(1 + 2.7 \times 10^{-4} \text{ Mn\%at} + 7.8 \times 10^{-4} \text{ Al\%at} \]
\[ + 2.21 \times 10^{-3} \text{ Nb\%at} + 1.7 \times 10^{-4} \text{ Cr\%at} \]
\[ - 5.6 \times 10^{-3} \text{ Ni\%at} + 8.9 \times 10^{-4} \text{ Ti\%at} \]

The density \( \rho_A(T_F, C=0) \), as calculated from the lattice parameters, is 7725 kg/m³. The density of the cementite was calculated using (19):

\[ \rho_C(T) = 7686.4 - 6.63 \times 10^{-2}T - 3.12 \times 10^{-4}T^2 \]

The carbon content in the bainitic ferrite was taken as 0.05%wt. It may be reasonable to assume that \( \rho_B(T, C=0) = \rho_B(0.05\text{ C}) \) and \( \rho_B(T, C=0) = \rho_B(0.05\text{ C}) \). They were taken as 7635 and 7640 kg/m³, the values that allowed the best match between the model and the experimental results.

The dilatation for the equilibrium transformation was calculated using these kinetic parameters. The results are shown in Fig. 4 together with the measured relative length change for the samples cooled at a rate of 6, 100 and 300°C/min. The good coincidence between the measured dilatation curve and the calculated one outside the phase transformation temperature range proves once more the correctness of the proposed model. It also indicates that the kinetic parameter set was selected correctly.

The phase transformation kinetics determined from the dilatation curves for the samples cooled at a rate of 6, 100 and 300°C/min is shown in Fig. 5. Figure 5(a) demonstrates that for the sample cooled at a rate of 6°C/min the formation of the primary ferrite begins at 705°C companied by the enrichment of carbon in the residual austenite. The pearlite decomposition takes place at 628°C when the carbon content of the residual austenite reaches the A_5 line and the bainitic transformation starts at 558°C when the carbon content of the residual austenite reaches the B_6 line. The calculated volume fraction of the primary ferrite is 68%, which coincides with the measured volume fraction. The volume fraction of the transformed austenite calculated using the lever rule shown in Fig. 1 is also shown in Fig. 5(a). The large difference between the results of the model and the lever rule indicates that the lever rule is not applicable to the interpretation of a dilatation curve for a multistep phase transformation.

The calculations indicate that the pearlite decomposition does not take place in the samples cooled at rates of 100 and 300°C/min. The calculated phase constituents are 17% primary ferrite, 82.5% bainite and 0.5% residual austenite for the sample cooled at a rate of 100°C/min, while for the sample cooled at a rate of 300°C/min they are 3.5% primary ferrite, 96% bainite and 0.5% residual austenite. The results are in good agreement with the metallographic examinations, see Figs. 5(b) and 5(c).

5. Conclusions

A detailed analysis has been made of the length change of a hypoeutectoid steel during a continuous cooling. A model has been developed to determine the phase change kinetics from a dilatation curve that may correspond to a multistep reaction process. The model takes into account the effects of the carbon partitioning during a phase trans-
formation. The model was validated by comparing the model results with the experimental results of an interstitial free steel. Experiments were also carried out with a bainitic steel. The model has been applied to the calculation of the phase transformation kinetics from the dilatation curves of this steel. Excellent agreements between the model and the experiments have been obtained.

REFERENCES