Diffusion-Controlled Continuous Cooling Transformation of Austenite: Postprint

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Date: 2023-03-19T00:00:00+00:00

Abstract

A diffusion-controlled model for austenite continuous cooling transformation was established to describe the temperature dependence of proeutectoid ferrite interface position. The model accounts for possible soft impingement during interface migration and the effect of cooling rate on carbon concentration at the austenite side of the interface. Using this model, austenite continuous cooling transformation processes under various initial carbon concentrations, austenite grain sizes, and cooling rates were simulated, yielding the temperature dependence of proeutectoid ferrite interface position, carbon diffusion length on the austenite side of the interface, and carbon concentration distribution under different cooling conditions. For an Fe-0.17C alloy with a grain size of 17 m, transformation processes under different cooling rates were simulated, and the results showed good agreement with literature.

Full Text

Preamble

Acta Metallurgica Sinica, Vol. 51, No. 11
November 2015, pp. 1341-1348

Austenite Transforming in Continuous Cooling Process Under Diffusion Control

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Supported by: Fundamental Research Funds for the Central Universities (No. FRF-IC-14-005)

Manuscript received: 2015-06-10, in revised form 2015-07-30

Abstract

A diffusion-controlled model for austenite transformation during continuous cooling has been established to describe the variation of proeutectoid ferrite interface position with temperature. The model accounts for soft impingement effects that may occur during interface migration and the influence of cooling rate on carbon concentration at the austenite side of the interface. Simulations were performed using this model to analyze the austenite transformation process under various initial carbon concentrations, austenite grain sizes, and cooling rates, yielding the evolution of proeutectoid ferrite interface position, carbon diffusion length at the austenite side, and carbon concentration profiles under different cooling conditions. The model was applied to simulate transformation in Fe-0.17C alloys with a grain size of 17 m at various cooling rates, showing good agreement with literature results.

Keywords: diffusion control, austenite, continuous cooling, proeutectoid ferrite, interface position

Introduction

The transformation of austenite to proeutectoid ferrite involves both long-range diffusion of carbon solute from the interface into the parent austenite phase and an interfacial reaction where the parent austenite with an fcc structure transforms to ferrite with a bcc structure at the interface [1]. Studies [2-10] have shown that the migration behavior of the ferrite-austenite interface over time can reflect the transformation kinetics of austenite. For isothermal austenite transformation, two classical models exist: the diffusion-controlled growth model and the interface-controlled model [2,11-14]. The diffusion-controlled model assumes that the free energy dissipation due to interface migration is negligible, and the interface velocity is determined solely by the diffusion process [11,15-17]. In contrast, the interface-controlled model posits that the transformation driving force is entirely consumed by interface migration, with interface velocity being proportional to the driving force [12,18].

Unlike isothermal transformation, the equilibrium carbon concentrations in austenite and ferrite continuously change with decreasing temperature during continuous cooling, and the effect of cooling rate on interface migration must be considered. Whether the classical models for isothermal transformation can be adapted to study interface migration during continuous cooling remains unexplored in the literature. In industrial practice, austenite transformation during continuous cooling is far more common. Current models describing proeutectoid ferrite transformation under continuous cooling conditions are primarily based on combining the isothermal Johnson-Mehl-Avrami (JMA) equation with the Scheil additivity principle [19-22]. However, since the parameters in the JMA equation are condition-dependent and must be determined from extensive experimental data, and because this equation cannot reveal the underlying microscopic mechanisms of austenite transformation, this work establishes a kinetic model for austenite transformation during continuous cooling based on carbon diffusion theory for the austenite-to-proeutectoid ferrite transformation. The model incorporates soft impingement effects during interface migration and the influence of cooling rate on carbon concentration at the austenite side of the interface.

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1. Model Establishment

According to diffusion-controlled theory, the interface migration and carbon concentration distribution at the austenite side during continuous cooling transformation are illustrated in [Figure 1: see original paper]. In the schematic, x_0 represents the austenite/ferrite interface position, L denotes the carbon diffusion length, C_γ and C_α are the equilibrium carbon concentrations at the austenite and ferrite sides of the interface, respectively, C_0 is the initial bulk carbon concentration, C_m is the carbon concentration at the center of the austenite grain after soft impingement occurs, X marks the center position of the austenite grain, and T_1-T_7 indicate temperature evolution. During continuous cooling transformation, the austenite-proeutectoid ferrite interface migrates from the austenite grain boundary toward the grain center. In the early stage, the carbon diffusion length at the austenite side does not reach the grain center, so the carbon concentration at the austenite grain center remains at the initial value. As transformation proceeds, the diffusion length eventually contacts the grain center, marking the onset of the soft impingement stage, during which the carbon concentration at the austenite grain center begins to change.

1.1 Carbon Concentration Distribution at the Austenite Side of the Interface

The carbon concentration profile $C(x)$ at the austenite side of the interface can be approximated by a parabolic function [5], where the relationship between the carbon diffusion curve and interface position x satisfies:

$$C(x) = A_1 + A_{2x} + A_{3x}^2$$

where A_1, A_2, and A_3 are determined by boundary conditions. For isothermal transformation or extremely slow cooling rates, the carbon concentration at the austenite side of the interface can reach the equilibrium concentration C_γ. However, at higher cooling rates, the equilibrium concentration changes rapidly with temperature, making it difficult for the interface carbon concentration to achieve the equilibrium value corresponding to the instantaneous temperature within the short available time. Therefore, a correction factor for the carbon concentration at the austenite side of the interface is introduced:

$$A = 1 - a\phi^b$$

where ϕ is the cooling rate, and a and b are material-dependent constants.

1.2 Stage Before Soft Impingement

In this stage, the carbon concentration at the austenite grain center remains at C_0, and the concentration gradient at the end of the diffusion field is zero. The boundary conditions are expressed as:

$$C(x_0) = C_\gamma^*$$

$$C(x_0 + L) = C_0$$

$$\left.\frac{dC}{dx}\right|_{x=x_0+L} = 0$$

Combining equations (1)-(4) yields the carbon concentration distribution before soft impingement:

$$C(x) = C_0 + \frac{(C_\gamma^* - C_0)}{L^2}(x_0 + L - x)^2$$

The carbon concentration redistribution must satisfy mass conservation:

$$\int_{x_0}^{x_0+L} C(x)dx = C_{0L}$$

From equations (5) and (7), the diffusion length L is determined by:

$$L = \frac{2(C_\gamma^* - C_0)}{C_\gamma^* - C_\alpha} \cdot \frac{dx_0}{dt}$$

where $S = \frac{C_\gamma^* - C_0}{C_\gamma^* - C_\alpha}$.

Additionally, since the carbon diffusion flux at the interface is zero, we have:

$$D\left.\frac{dC}{dx}\right|_{x=x_0} = -(C_\gamma^* - C_\alpha)v$$

where v is the interface migration velocity and D is the carbon diffusion coefficient in austenite.

For continuous cooling transformation, equation (9) gives:

$$v = \frac{dx_0}{dt} = \frac{dx_0}{dT}\cdot\frac{dT}{dt} = -\phi\frac{dx_0}{dT}$$

Combining equations (5), (8), and (10) yields the relationship between interface position and temperature:

$$\frac{dx_0}{dT} = -\frac{D}{\phi L}$$

where T is the temperature during austenite transformation and T_s is the transformation start temperature.

1.3 Stage After Soft Impingement

During the soft impingement stage, the carbon concentration at the austenite grain center no longer remains constant at C_0 but varies with temperature:

$$C(x_0 + L) = C_m(T)$$

where $L = X - x_0$.

In continuous cooling transformation, the equilibrium carbon concentrations in austenite and ferrite continuously change with decreasing temperature. To investigate interface position evolution and carbon concentration distribution at the austenite side, the equilibrium carbon concentrations at various temperatures must first be determined. In this work, equilibrium carbon concentrations were calculated using thermodynamic equations for phase transformation, while the carbon diffusion coefficient in austenite was computed using the formula given by Ågren [23].

The interface position before soft impingement can be obtained from equation (11). The transformation process after soft impingement can be treated as a superposition of isothermal processes at temperature T with time increment dt. By combining equations (13), (15), and (16), the interface position, carbon concentration distribution at the austenite side, and carbon concentration at the austenite grain center can be determined.

2. Model Validation

The proposed model for austenite transformation during continuous cooling was used to calculate the evolution of ferrite volume fraction (ratio of interface position to austenite grain radius) with temperature in Fe-0.17C alloys (mass fraction, %) with an initial austenite grain size of 17 m at various cooling rates. The results were compared with calculations by Kumar et al. [24], as shown in [Figure 2: see original paper]. The coefficients in the expression $A = 1 - 0.01\phi^{0.85}$ were obtained by regression fitting of ferrite volume fraction evolution at cooling rates of 1 and 80 °C/s. The model predictions show good agreement with literature results, demonstrating that the proposed model accurately captures the transformation kinetics of austenite during continuous cooling.

The correction factor A for carbon concentration at the austenite side of the interface decreases with increasing cooling rate, indicating that at higher cooling rates, the interface carbon concentration deviates more significantly from the equilibrium value.

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3. Simulation Results and Discussion

This work focuses exclusively on proeutectoid ferrite transformation, with the lower temperature limit set at 600 °C [25]. To investigate the effects of austenite grain size, cooling rate, and carbon content on ferrite transformation, simulations were conducted for austenite grain sizes of 15 and 30 m, cooling rates of 1 and 5 °C/s, and initial carbon contents of 0.1%, 0.3%, and 0.5%.

[Figure 3: see original paper] shows the interface position evolution with temperature for Fe-0.1C, Fe-0.3C, and Fe-0.5C alloys with different austenite grain sizes at cooling rates of 1 and 5 °C/s. The solid lines represent calculations considering soft impingement, while dashed lines represent calculations without soft impingement, and circles indicate the onset of soft impingement. The results demonstrate that interface position during continuous cooling depends on initial carbon concentration, austenite grain size, and cooling rate. As initial carbon concentration, austenite grain size, and cooling rate increase, the rate of interface position change with temperature decreases. Neglecting soft impingement leads to unrealistically rapid interface migration to the austenite grain center, suggesting complete ferrite transformation, which contradicts actual transformation behavior and introduces significant errors.

After soft impingement occurs, the carbon concentration at the austenite grain center and the carbon diffusion length become two critical parameters describing ferrite transformation. [Figure 4: see original paper] shows the evolution of carbon diffusion length at the austenite side and carbon concentration at the grain center with temperature for Fe-0.3C alloy with an austenite grain size of 30 m at a cooling rate of 1 °C/s. Before soft impingement, diffusion length increases continuously with interface migration, while the carbon concentration at the grain center remains unaffected at the initial value. After soft impingement, diffusion length begins to decrease while the grain center carbon concentration increases progressively. Thus, soft impingement onset can be identified by monitoring changes in either diffusion length or grain center carbon concentration.

Carbon profile evolution in the austenite phase for Fe-0.3C alloy with a grain size of 15 μm under cooling rates of 1 and 5 °C/s is shown in [Figure 5: see original paper]. The carbon concentration at the ferrite side of the interface changes only slightly, while the carbon concentration at the austenite side increases continuously.

3.1 Effect of Initial Carbon Concentration

[Figure 6: see original paper] presents the evolution of interface position and carbon diffusion length with time for different initial carbon concentrations under the same austenite grain size and cooling rate. Increasing carbon concentration delays the onset of soft impingement. However, due to reduced interface migration velocity, the distance traveled by the interface toward the austenite center at the end of transformation decreases, indicating smaller ferrite volume fraction and ferrite grain size. When austenite grain size is small or cooling rate is low, carbon concentration has minimal effect on diffusion length before soft impingement, as shown in [Figure 6: see original paper]a–c.

3.2 Effect of Cooling Rate

[Figure 7: see original paper] shows the interface position evolution with temperature for Fe-0.3C alloy with an austenite grain size of 15 μm at cooling rates of 1 and 5 °C/s. Higher cooling rates result in lower ferrite transformation start temperatures and smaller carbon diffusion coefficients, leading to slower interface position change with temperature.

3.3 Effect of Austenite Grain Size

[Figure 8: see original paper] illustrates the evolution of interface position and carbon diffusion length with time for different initial austenite grain sizes at the same carbon concentration and cooling rate. Larger initial austenite grain size delays soft impingement onset. Due to faster interface migration, the distance traveled by the interface toward the austenite center at the end of transformation increases.

3.4 Relationship Between Carbon Diffusion Length and Interface Position

For isothermal austenite transformation, the correction factor A in equation (8) equals 1 and the equilibrium carbon concentration remains constant, so S stays constant and the carbon diffusion length before soft impingement increases linearly with interface position. During continuous cooling transformation, however, the equilibrium carbon concentration continuously changes, causing S to vary. [Figure 9: see original paper] shows the relationship between carbon diffusion length and interface position for Fe-0.1C, Fe-0.3C, and Fe-0.5C alloys with a grain size of 30 m at different cooling rates. At low cooling rates, diffusion length before soft impingement can be approximated as increasing linearly with interface position [Figure 9: see original paper]a. At high cooling rates, diffusion length varies approximately linearly with interface position in the early stage but deviates progressively from linearity as transformation advances [Figure 9: see original paper]b. Although increasing carbon concentration delays soft impingement onset, the interface position at which soft impingement occurs remains similar.

3.5 Interface Position Evolution with Time

For isothermal austenite transformation, the interface position before soft impingement follows the relationship [5]:

$$x_0 = \lambda\sqrt{t}$$

where λ is a constant. Equation (17) indicates a linear relationship between interface position and $t^{1/2}$. After soft impingement, this linear relationship no longer holds due to increasing carbon concentration at the austenite grain center.

[Figure 10: see original paper] shows interface position versus $t^{1/2}$ for Fe-0.1C, Fe-0.3C, and Fe-0.5C alloys with different grain sizes and cooling rates, where circles mark soft impingement onset. When austenite grain size is small or cooling rate is low, interface position before soft impingement can be approximated as linear with $t^{1/2}$ [Figure 10: see original paper]a–c. Unlike isothermal transformation, the relationship deviates from linearity even before soft impingement at high cooling rates [Figure 10: see original paper]d, due to continuous changes in carbon diffusion coefficient and equilibrium carbon concentration with temperature.

Conclusion

Based on carbon diffusion theory for austenite-to-proeutectoid ferrite transformation, a kinetic model for austenite transformation during continuous cooling has been established. The effects of initial carbon concentration, austenite grain size, and cooling rate on transformation kinetics were analyzed. These three factors critically influence austenite transformation during continuous cooling. Only when austenite grain size is small or cooling rate is low can the interface position before soft impingement be approximated as linear with $t^{1/2}$. At high cooling rates, the carbon concentration at the austenite side of the interface cannot be approximated by the equilibrium value, requiring a cooling-rate-dependent correction factor. The model calculations satisfactorily reflect the kinetic behavior of austenite transformation during continuous cooling.

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