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MODELING OF STRAIN-INDUCED PRECIPITATION KINETICS IN Nb MICROALLOYED STEELS

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On the basis of the thermodynamic calculation of precipitation and considering the effect of strain on the precipitation behavior and chemical composition (Si and Mn), the kinetics of precipitation from austenite has been investigated for different temperatures and strains. Nucleation theory and the solubility product of niobium, carbon, and nitrogen in austenite have been used to derive equations for the start time of precipitation as a function of temperature and composition. The value of n in Avrami equation was determined using the available experimental data from the published reports, which indicated that n is a constant independent of temperature and the end time of precipitation is a function of n and the start time of precipitation. The values of the start time and end time of precipitation predicted by the new model are compared with the experimental values and a good agreement was obtained between both.

KEY WORDS *strain-induced precipitation; start time of precipitation; end time of precipitation; precipitation kinetics*

1. Introduction

It is well established that the precipitation of carbides or carbonitrides in microalloyed steels containing one or more of transition metals such as Nb, Ti, and/or V play a critical role in determining the properties of steel. The precipitation not only retards recrystallization kinetics but also greatly influences

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the microstructural evolution of austenite during the thermo-mechanical processing, resulting in precipitation hardening in the final matrix and consequently determining the final mechanical properties. Therefore, it is difficult to determine precisely the start time and end time of the strain-induced precipitation. Dutta and Sellars[1] proposed a model to calculate the start time of precipitation. However, these models are not accurate enough to calculate complex precipitation volume fraction in a lot of situations, and the effect of Si and Mn contents cannot be taken into considerated.

The purpose of the present study is to develop models to calculate the start time and end time of precipitation and the precipitation kinetics, in which the effect of Si and Mn contents has been considered.

2. Mathematical Modeling

Dutta and Sellars[1] established that the start time for precipitation ($t_{0.05}$), corresponding to a partial precipitation of 5% was correlated to the content of microalloying elements and applied strain was applied in accordance with the following expression

$$t_{0.05}=A[\mathrm{Nb}]^{-1}\varepsilon^{-1}Z^{-0.5}\exp\frac{Q_d}{RT}\exp\frac{B}{T^3(\ln k_s)^2} \tag{1}$$

where A is a constant, the ideal value being 3×10^{-6}, [Nb] denotes the weight percentage of Nb, ε denotes the strain applied during hot rolling, Z denotes the Zener-Hollomon parameter, which can be determined using Eq.(2), and Q_d the diffusion activation energy of Nb in austenite is about 266500J/mol[2], T the deformation temperature in Kelvin, and R denotes the gas constant. The effect of strain rate on precipitation time is accounted for by the Zener-Hollomon parameter. k_s denotes the supersaturation ratio, which can be described by Eq.(3)[3]

$$Z=\dot{\varepsilon}\exp\frac{375000}{RT_{def}} \tag{2}$$

where $\dot{\varepsilon}$ is the strain rate and T_{def} is the deformation temperature.

$$k_s=\frac{10^{-6770/T_{rh}+2.26}}{10^{-6770/T_{def}+2.26}} \tag{3}$$

where T_{rh} is the reheating temperature.

Eq.(1) can be further modified to take into account the effect of Mn and Si level on the start time of precipitation during hot-strip rolling. The addition of Si increases the activities of C and N and decreases the solubility of Nb(CN), resulting in additional supersaturation, and increases the driving force to accelerate the kinetics of precipitation. Moreover, Si addition increases the diffusivity of Nb in austenite over a wide temperature range. Researchers showed that Mn has an opposite effect on Nb diffusivity compared with Si[4-6]. Therefore, Eq.(1) should be replaced by Eq.(4), which considers the effect of Si and Mn.

$$t_{0.05}=\frac{t_{0.05}^{DS}}{10^{(-0.26-0.90[\mathrm{Mn}]+2.85[\mathrm{Si}])}} \tag{4}$$

where [Mn] and [Si] are the weight percentages of Mn and Si, respectively. $t_{0.05}^{DS}$ is the model of Dutta