

Analysis of the $\gamma \rightarrow \alpha$ Transformation in a C-Mn Steel by Phase-Field Modeling

M.G. MECOZZI, J. SIETSMA, S. VAN DER ZWAAG, M. APEL, P. SCHAFFNIT,
and I. STEINBACH

This article deals with the austenite (γ) decomposition to ferrite (α) during cooling of a 0.10 wt pct C-0.49 wt pct Mn steel. A phase-field model is used to simulate this transformation. The model provides qualitative information on the microstructure that develops on cooling and quantitative data on both the ferrite fraction formed and the carbon concentration profile in the remaining austenite. The initial austenitic microstructure and the ferrite nucleation data, derived by metallographic examination and dilatometry, are set as input data of the model. The interface mobility is used as a fitting parameter to optimize the agreement between the simulated and experimental ferrite-fraction curve derived by dilatometry. A good agreement between the simulated α - γ microstructure and the actual α -pearlite microstructure observed after cooling is obtained. The derived carbon distribution in austenite during transformation provides comprehension of the nature of the transformation with respect to the interface-controlled or diffusion-controlled mode. It is found that, at the initial stage, the transformation is predominantly interface-controlled, but, gradually, a shift toward diffusion control takes place to a degree that depends on cooling rate.

I. INTRODUCTION

IN the recent years, there has been a strong development in modeling solid-state transformations in steels and alloys, mainly because of the strong dependence of the final properties of the material on the microstructural evolution during processing. In C-Mn steels, the austenite (γ)-to-ferrite (α) transformation during cooling is the most important transformation, since it determines to a large extent the microstructure and, therefore, the properties of the final product. In the literature, the kinetics of the γ -to- α transformation is often modeled assuming that the carbon diffusion in austenite is the rate-controlling process and the interface mobility is high enough not to affect the transformation kinetics (the *diffusion-controlled transformation mode*).^[1,2,3] The other extreme is to assume that the transformation kinetics is controlled only by the interface mobility and that the carbon diffusivity in austenite is large enough to maintain a homogeneous carbon concentration in austenite (the *interface-controlled mode*).^[4,5] In reality, both processes will influence the transformation kinetics, and the transformation is of a mixed-mode character.^[6,7]

The effect of both the interface mobility and the carbon diffusion is considered in the phase-field modeling of solid-state transformations, and, therefore, the phase-field approach can be considered as a mixed-mode model. The phase-field model was originally proposed to simulate the dendritic

growth in pure undercooled melts^[8-11] and, later, it was extended to the solidification of alloys with a single solid phase^[12,13,14] or with two solid phases.^[15,16] The models developed for describing the alloy solidification may be divided into two groups, depending on the definition of the free-energy density of the interfacial region, which is of finite thickness (η). Among the first group of models is that proposed by Wheeler, Boettinger, and McFadden (the WBF model),^[12] in which any point within the interfacial region is assumed to be a mixture of the liquid and solid phase with the same composition. The problem in this model is that it produces a chemical interface energy that depends on the interface thickness. Steinbach and co-workers, on the other hand, propose a model with a different definition of the free-energy density in the interface^[18,19] (the multi-domain model). In their model, the interfacial region is assumed to be a mixture of liquid and solid phase with different compositions, defined by a constant ratio for each element. This model was augmented by Kim *et al.*^[17] by a thermodynamic-consistent derivation, and it can be used for general multiphase and multicomponent problems.

Few studies are present in the literature on the application of the phase-field model to simulate the γ -to- α transformation. Yeon *et al.*^[20] simulated the isothermal austenite-to-ferrite transformation in an Fe-Mn-C system under paraequilibrium (only C redistributes during transformation, while the Mn content remains equal in ferrite and austenite) using the WBF model. Pariser *et al.*^[21] applied the model of Steinbach and co-workers for modeling the austenite-to-ferrite transformation in an ultra low-carbon steel and in an interstitial-free steel during cooling at a medium cooling rate.

In this article, the phase-field model derived by Steinbach and co-workers^[18,19] is used to simulate the γ -to- α transformation during controlled cooling of a 0.10 wt pct C-0.49 wt pct Mn steel. The transformation kinetics was experimentally investigated at three different cooling rates using dilatometry: a low rate (0.05 K/s), a medium rate (0.4 K/s), and a high rate (10 K/s). Phase-field simulations

M.G. MECOZZI is with the Netherlands Institute for Metals Research, Rotterdamseweg 137, 2628 AL Delft, The Netherlands, and the Department of Materials Science and Engineering, Delft University of Technology, Rotterdamseweg 137, 2628 AL Delft, The Netherlands. Contact e-mail: m.g.mecozzi@tnw.tudelft.nl J. SIETSMA, Ph.D., is with the Department of Materials Science and Engineering, Delft University of Technology. S. VAN DER ZWAAG, Professor, is with the Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands. M. APEL, P. SCHAFFNIT, and I. STEINBACH, Ph.Ds., are with Access eV, Intzestasse 5, D-52072 Aachen, Germany.

Manuscript submitted May 14, 2004.