ELSEVIER

Physica B 234–236 (1997) 1027–1029

PHYSICA B

Neutron depolarization as a tool for studying phase transformations in steels

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Abstract

Neutron depolarization experiments of austenite to ferrite phase transformations in C60 steels are presented. The ferrite fraction and the average ferrite particle size, determined during a two-step isothermal transformation, are compared to numerical simulations.

Keywords: Neutron depolarization; Phase transitions; Domains; Nucleation

1. Introduction

The neutron depolarization (ND) technique with three dimensional (3D) polarization analysis of the polarized neutron beam after transmission through a sample is suitable for studying the magnetic structure of materials [1]. From the measured (3×3) depolarization matrix the magnetic fraction and average magnetic domain size can be calculated [2].

ND was used to study the (ferromagnetic) proeutectoid ferrite fraction f and average domain size (particle radius) δ during an isothermal phase transformation from supersaturated (paramagnetic) austenite in a medium carbon steel (in wt%: 0.66C, 0.19Cr, 0.69Mn) [3,4]. This phase transformation, which proceeds via nucleation and growth, is very important in controlling the structure and properties of construction and engineering steels.

2. Results

The temperature–time sequence imposed on the sample along with the results are given in Fig. 1. Initially,

f increases rapidly when cooled below 1013 K ($t = 48$ min). When the temperature is held at 1003 K, df/dt decreases, yet f does not reach its equilibrium value. δ increases approximately proportional to $\sqrt{t}$, as is expected for diffusional growth [5]. When the temperature is reduced to 998 K, f and δ both increase further with initially increased rates, yet df/dt is much smaller than at the beginning of the transformation.

In order to gain a better understanding of the results, the transformation and depolarization were simulated with a model in 3D space. The austenite grains are modelled by Voronoi cells with the corners as possible nucleation sites for ferrite. The nucleation follows a time-dependent S-shaped function. The growth of the individual ferrite particle is modelled using diffusional growth theory for finite media [5]. It is assumed that each ferrite particle contains only one magnetic domain and that the direction of the magnetization is determined by the sum of the applied field and the magnetic dipole interaction of near-neighbor particles. At time intervals during the simulated transformation the depolarization is calculated using the equations in Refs. [2,6].

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Fig. 1. The ferrite fraction f and average particle radius δ measured (data marks) and simulated (lines), and the sample temperature as a function of time. During the measurement the applied field was 780 A/m.

The experimental data for f and δ give rise to a linear relationship between the average particle volume and f around the transition from 1003 to 998 K. This means that the ferrite particle density is unchanged and the increase in f at the temperature change can be concluded to be due to growth only. For this reason, in the simulations, nucleation is allowed to take place only at the beginning of the phase transformation. Preliminary simulations of f and δ are also given in Fig. 1.

3. Discussion

Although there is a reasonable agreement between the measured and simulated δ , there is a large discrepancy in f . A possible cause of this discrepancy is that in determining the experimental f , it was assumed that the reduced magnetization $m = \langle M \rangle / M_s$ was constant ($m = 0.72$). In the simulations, as a result of the dipole interac-

tions, m varies from 0.75 to 0.55 as the fraction increases at the beginning of the transformation. Because there is good agreement between the mean direction cosines of the particle magnetizations determined (but not shown here) for the measurements and simulations, it can be expected that during the measurement m does indeed vary. However, also the quantity mf , cannot be simulated satisfactorily.

Increasing the particle density in order to have a good agreement in the beginning, results in f reaching its equilibrium value ($\approx 7\%$) at $t \approx 200$ min. Furthermore, the rate at which f increases during the second isothermal period at 998 K, becomes much too large.

Further refinement of the simulation model is required. In particular, the initial rapid increase in f , not accompanied by a similar increase in δ suggests that assumptions of homogeneous nucleation throughout the sample might not be correct.

Acknowledgements

The authors thank the Dutch Technology Foundation (STW) for financial support and P.D.M. van Zoest for experimental assistance.

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