



Kinetics of austenite decomposition in manganese-based steel

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Abstract

In this work, pearlite formation in undeformed and deformed austenitic manganese-based steel is investigated by means of in situ magnetization measurements and optical and scanning electron microscopy. The metastable austenitic microstructure partially transforms to pearlite upon isothermal aging in the temperature range 500–600 °C on a time scale of tens of hours. The observed transformation kinetics and microstructure development are interpreted in terms of the nucleation and growth of pearlite colonies. Preferential nucleation sites for pearlite formation are grain boundaries, and prior plastic deformation increases the density of nucleation sites. Manganese partitioning between the ferrite and cementite lamellae in pearlite appears to control the growth rate, and is the underlying reason for the slow transformation kinetics.

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1. Introduction

In order to improve safety and fuel economy, the use of advanced high-strength steels in the automotive industry has increased significantly in the last decade. One of the latest developments is austenitic manganese-based steels, which combine high strength with high ductility [1]. These superior mechanical properties are a result of deformation mechanisms involving twinning- or plasticity-induced transformation [2–6] related to the austenite (γ) stability. The austenitic phase in manganese-based steel with 14% manganese is metastable at room temperature, and is seen to transform to martensite by means of stress-induced $\gamma \rightarrow \varepsilon \rightarrow \alpha'$ martensitic transformations [7–10]. The observation that the austenite can transform into martensite implies that the fully austenitic microstructure is not stable

at room temperature, but metastable [11]. Manganese contents below approximately 20% form the basis for this metastability at room temperature, allowing the study of a broad domain of deformation and temperature conditions [12]. Whereas the metastable austenite transforms by martensitic mechanisms upon mechanical loading, diffusional decomposition of austenite into pearlite is expected when the material is annealed at temperatures below the A_1 temperature. This diffusional growth of pearlite has been the subject of research for steels with relatively low manganese contents (<1.8%) [13,14], studying the role of manganese during austenite to pearlite transformation, in particular manganese partitioning between pearlitic cementite and ferrite. The present work investigates the austenite decomposition at intermediate temperatures into pearlite in manganese-based steels with 14% manganese.

Pearlite nucleates preferentially at prior austenite grain boundaries, compared to the grain interior, due to the interfacial energy [15]. Plastic deformation increases the stored energy within the austenite grains and of the austenite grain boundaries, enhancing the density of effective nucleation sites [16]. According to Xiao et al. [16],

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isothermal transformation of austenite results from the combined effect of short-distance Fe diffusion across the interface and long-distance C diffusion, with plastic deformation predominantly accelerating the latter.

Plastic deformation introduces microstructural defects such as dislocations, twin boundaries and deformation bands within the austenite grains which are preferential nucleation sites for ferrite [12,15–18] and pearlite [18,19]. The number density of potential nucleation sites therefore increases with prior plastic deformation. Beladi et al. suggest that this process is static, providing more favourable nucleation conditions, but not affecting the transformation process itself [12]. In the present work, using in situ thermomagnetic techniques and ex situ optical microscopy and scanning electron microscopy, the nucleation and growth of the pearlite colonies in undeformed and deformed condition are systematically investigated. From observations on the pearlite fraction and the size distribution and number density of pearlite colonies, the characteristics of the austenite-to-pearlite transformation are derived.

2. Experimental

The as-received material is a 1.7 mm thick manganese-based steel grade in cold-rolled and recrystallized condition. At room temperature the as-received material is austenitic. The composition and yield strength are listed in Table 1. The material was investigated in the as-received condition and after 10% tensile deformation at room temperature. The limited tensile deformation is small enough to avoid recrystallization of the austenite in the applied heat treatments.

For the magnetization experiments samples of approximately 2 mm × 2 mm × the sheet thickness were machined from the sheet material using an electrodischarge machine. All magnetic measurements were performed in a Lake Shore 7307 vibrating sample magnetometer (VSM), which includes a furnace for experiments at elevated temperatures. Before the experiments the VSM was calibrated with a standard NIST nickel specimen. Two types of experiments were performed. Firstly, in situ thermomagnetic experiments at 500, 550 and 600 °C in a magnetic field of 1.0 T, which is high enough to reach the saturation magnetization [20]. The fraction of ferromagnetic phases in the microstructure is derived from the saturation magnetization by:

$$f(\alpha) = \frac{M_s}{x_{Fe}M_{s,Fe}}, \quad (1)$$

where M_s is the sample magnetization, $M_{s,Fe}$ is the saturation magnetization of pure iron and x_{Fe} represents the Fe fraction in the material. The saturation magnetizations are dependent on the measurement temperature. Secondly, ex situ measurements of magnetic hysteresis curves were performed at room temperature, varying the field from −1.5 to +1.5 T [20]. Pearlite is the ferromagnetic component forming in the microstructure and its fraction is calculated using Eq. (1).

Thermodynamic calculations were performed using ThermoCalc software (TCW version 4, TCS Steels/Fe-Alloys database version 6) to calculate the equilibrium phase fractions as a function of temperature for the composition shown in Table 1.

Scanning electron microscopy (SEM) was performed on a Zeiss Ultra 55 field emission gun scanning electron microscope to characterize the microstructure. The undeformed microstructure is fully recrystallized, with an equiaxial austenite grain size of ~5 μm [8]. The microscope was equipped with an in-lens electron optical system. Specimens were mounted in Polyfast resin, which is electrically conductive with low emission in the vacuum chamber during examination. All micrographs were obtained using a 15 keV electron beam.

The samples for optical microscopy were mechanically polished and electropolished, followed by electroetching. Optical bright-field images were taken on a Polyvar microscope. A matrix of 4(x) × 5(y) fields was scanned with a motorized stage, resulting in a total scanned area of 2.6 × 2.4 mm². The area fractions were determined by Leica QWin Pro (version V3.5.1) automatic quantitative image analysis software in combination with QUIPS (Quantimet Interactive Programming System). The minimum feature area was 1 μm²; no maximum feature area was set. An in-house routine was used to determine the area fraction.

3. Results

Fig. 1a shows the mass fraction of phases in equilibrium as calculated by ThermoCalc. Above 700 °C, the equilibrium microstructure consists entirely of austenite. At lower temperatures, ferrite and cementite are present in equilibrium with austenite. Below 400 °C, the equilibrium fraction of austenite appears to stabilize at ~5%.

Fig. 1b shows the manganese concentration as a function of temperature in the ferrite, austenite and cementite phases, as calculated by ThermoCalc. The equilibrium manganese concentration in ferrite does not exceed 5% in the temperature range below 600 °C, whereas carbides are strongly enriched in manganese. A strong tendency for manganese partitioning between ferrite and carbides is therefore expected to occur in the formation of ferrite and carbides from austenite, requiring manganese diffusion. The diffusion rate of manganese will be of significant importance for the transformation process. ThermoCalc calculations also show that the almost 3% aluminium in

Table 1
Composition and yield strength of the manganese-based steel grade

C [wt%]	Si [wt%]	Mn [wt%]	Al [wt%]	$\sigma_{0.2}$ [MPa]
0.71	0.07	14.55	2.93	508

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