Journal of Magnetism and Magnetic Materials 362 (2014) 159–164

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

# Effects of high magnetic field on isothermal pearlite transformation and microstructure in a hypereutectoid steel

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ARTICLE INFO

*Article history:*
Received 11 December 2013
Received in revised form
27 February 2014
Available online 12 March 2014

*Keywords:*
Hypereutectoid steel
High magnetic field
Isothermal transformation
Growth rate
Interlamellar spacing
Low angle boundary

ABSTRACT

A high magnetic field was applied during the isothermal pearlite transformation of a hypereutectoid carbon steel at three different temperatures. It was found that the magnetic field applied can increase the transformation rate and the pearlite nodule growth rate, decrease the interlamellar spacing of pearlite and the amount of low angle boundary in ferrite lamella. The magnetic field effects are more obvious at high temperature. The mechanism of field-effect was discussed by analyzing the influences of high magnetic field on the eutectoid temperature, diffusion activation energy in austenite, Gibbs free energy of ferrite and dislocation mobility.



## 1. Introduction

The requirement to develop fully pearlitic steel filaments with higher strengths than those of the current filaments, while maintaining a low price, provides a strong motivation for the use of high carbon content (significantly greater than the eutectoid composition) in the wire drawing process. Fully pearlitic steel with hypereutectoid composition is an important choice for increasing the strength [1].

High magnetic field has a promising potential as a processing method for developing customized microstructure and enhanced performance. Recently, it was reported based on the theoretical calculation that the application of a high magnetic field can elevate the $A_1$ and $A_3$ lines of the Fe–C system [2,3]. Research on steels has shown experimentally that martensite transformation [4], bainite transformation [5], proeutectoid ferrite transformation [6–8], pearlite transformation [9,10], recrystallization [11,12] and carbide precipitation [13–15] can be influenced by the high magnetic field. Isothermal transformation in lead or other bath, i.e. patenting, is an important heating treatment for controlling microstructure during steel wire production. Application of high magnetic field in the patenting process of hypereutectoid steel may provide a new way to enhance mechanical properties by changing the pearlite transformation and microstructure.

Zhang [16] investigated the isothermal transformation in a Fe–C–Ni hypoeutectoid steel. However, much proeutectoid ferrite forms before the pearlite transformation during isothermal treatment in hypoeutectoid steel. The proeutectoid ferrite nucleates along the austenite grain boundaries which are also the nucleation sites for pearlite [17]. The ferrite with a much lower carbon content ejects carbon atoms and thus forms a carbon-rich region around the grain boundaries. Proeutectoid ferrite reduces the sites of nucleation for pearlite transformation and changes the local carbon content distribution both of which influence the pearlite transformation strongly. It is interesting to study the effect of magnetic field on the fully pearlitic transformation in a hypereutectoid steel.

A hypereutectoid steel was used in this study and isothermally transformed for various times in high magnetic field. The transformed fraction of pearlite, largest nodule sizes, and pearlite microstructure were systematically observed and measured to investigate the effects of magnetic field during the isothermal transformation.

## 2. Experimental procedures

The material used in this study is a hypereutectoid plain carbon steel with chemical composition (wt%) C 1.11%, Si 0.17%, Mn 0.28%, P 0.009%, S 0.007% and bal. Fe. Initial steel wire rod was machined into cylindrical samples with dimensions of 10 mm in height and 4 mm in diameter.

The samples were austenitized at 950 °C for 60 min and then swiftly transferred into the furnace placed in 10 T magnetic field at

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http://dx.doi.org/10.1016/j.jmmm.2014.03.006
0304-8853/

600, 650 and 700 °C for various times. After the isothermal holding, the samples were quenched into the water out of the magnetic field. The samples were heated as the same procedure but without magnetic field treated for comparison.

The samples were prepared by using the standard electro-polishing (10% perchloric acid in ethanol) procedure and then immersed into 4% nital etchant to reveal the microstructure. The microstructure evolution of samples for different holding times was observed and recorded with SEM (Tescan MIRA 3 LMH).

The fraction of pearlite was determined by employing the point counting method [18] and plotted against the holding time to present the transformation kinetics. The largest pearlite nodule sizes at different holding times were measured and plotted against the holding time to evaluate the growth rate. Since the pearlite nodules impinge each other at the later stage of transformation, and thus the data of the unimpinged pearlite nodule size were obtained at the early stage of isothermal transformation. The interlamellar spacing in the samples with complete pearlite transformation was an average value of the minimum observed interlamellar spacing measured by a linear intercept method [19]. The EBSD system of HKL Channel 5 was employed to characterize the orientation of samples and then reconstruct the boundary maps.

## 3. Experimental results

In Fig. 1(a) through (c) is plotted the fraction of pearlite against the holding times at three temperatures. The curve shows a steeper slope for the samples with magnetic field treated at 700 °C, which means magnetic field increases the transformation rate. The difference of transformation rate between non-field and field treated samples is weaker at 650 °C and almost disappears at 600 °C. Besides that, the magnetic field presents a similar influence on the incubation time of isothermal transformation. The change of incubation time becomes stronger with the increasing transformation temperature.

Fig. 2 shows the largest pearlite nodule radii against the holding times at different isothermal temperatures. The solid line is determined through the least square method. The growth rates of pearlite nodule are 0.66 and 2.10 μm/s for samples transformed at 700 °C without and with magnetic field treated. For transformation at 650 °C, the growth rates are 2.05 and 2.81 μm/s respectively for samples without and with magnetic field treated. The growth rates in non-field and field treated samples at 600 °C are 2.60 and 3.00 μm/s respectively. The growth rates are larger with the transformation temperature decreasing regardless of magnetic field condition, which is due to the larger undercooling and stronger transformation driving force at the lower temperature. It is also seen clearly that the high magnetic field increases the pearlite growth rate. The effect of magnetic field on pearlite growth rate is more obvious at the higher transformation temperature.

The pearlite microstructure of samples transformed at 700 °C is shown in the Fig. 3. The interlamellar spacing is decreased by the magnetic field at 700 °C. The interlamellar spacings of samples transformed at different temperatures are plotted in Fig. 4. The interlamellar spacing is increased by high magnetic field at 700 and 650 °C, but almost becomes invariant at 600 °C.

The boundary map of ferrite lamella is shown in Fig. 5 for samples transformed completely at 700 °C. It is seen that the amount of low angle boundary (2–10°) is dramatically decreased by the high magnetic field. The effect of magnetic field on the low angle boundary diminishes with the decreasing temperature.

## 4. Discussion

### 4.1. Effect of magnetic field on the pearlite transformation rate

Nucleation rate or growth rate influences the pearlite transformation rate strongly. The following discussion of field-effect on the

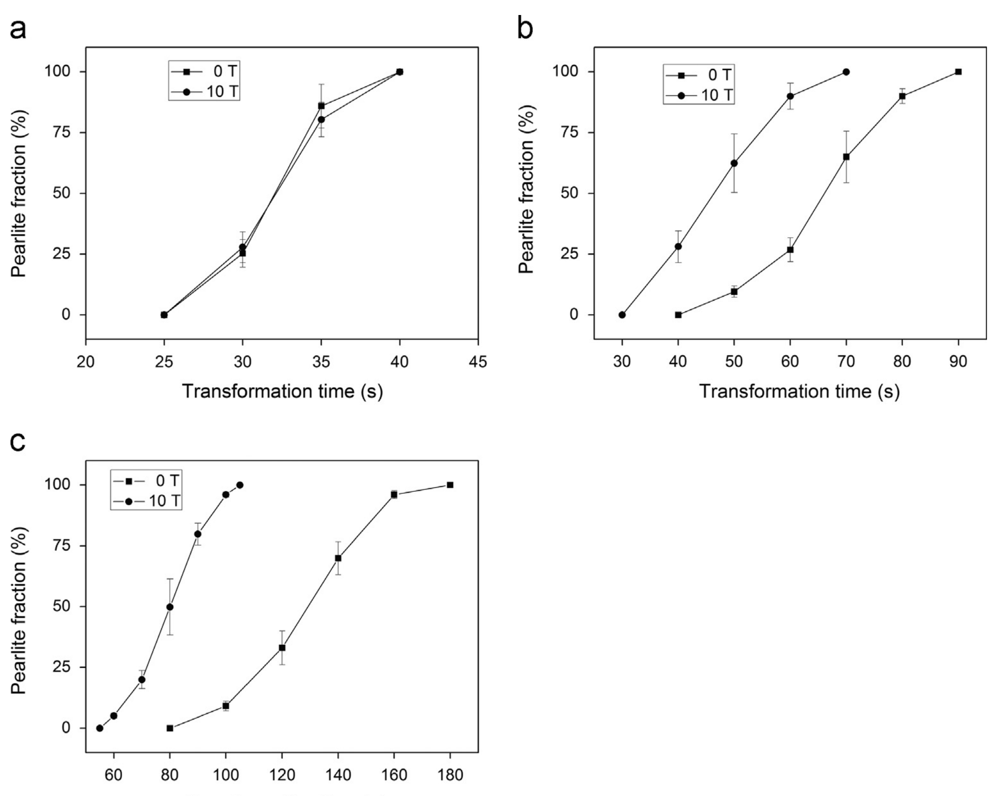


**Fig. 1.** Variations of pearlite fraction against holding time at 600 °C (a), 650 °C (b) and 700 °C (c). (2-column).