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Ultrafine ferrite formation through isothermal static phase transformation

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Abstract

A novel thermomechanical route has been developed to produce an ultrafine-grained structure through warm deformation of metastable austenite followed by isothermal static transformation to ferrite. The thermomechanical parameters influenced the evolution of ferrite phase transformation (i.e. nucleation and growth), resulting in different levels of ferrite grain refinement. For the first time grains as fine as 200 nm were produced through a traditional diffusional transformation of austenite to ferrite. The use of a model Ni–30Fe austenitic alloy showed that the strain has a strong effect on the nature of the intragranular defects developed throughout the microstructure. At a low strain, microbands were the dominant intragranular features. There was a transition strain above which a complex cell/subgrain substructure with high misorientation angle appeared in the vicinity of prior austenite grain boundaries. This region was extended with strain and promoted significant ferrite nucleation sites at an early stage of phase transformation, resulting in the local formation of nanosized ferrite grains near the prior austenite grain boundaries with ultrafine grains towards the interior of the original austenite grain.

Keywords: Ultrafine ferrite; Warm deformation; Isothermal phase transformation; Substructure

1. Introduction

One of the ongoing challenges in the steel industry is to increase the strength levels without sacrificing other properties, such as ductility and toughness. The strength of steel is controlled to a large extent by the grain size. It has been established that both the strength and ductility are markedly improved if the grain size can be reduced to 1–2 μm [1]. Conventional thermomechanical processing (e.g. controlled rolling) has been employed commercially to refine the ferrite grain size, although it approaches a limit of ~5 μm regardless of the applied strain in the austenite [2]. However, a number of techniques and approaches were recently developed to overcome this limitation, and successfully obtained a ferrite grain size of ~1 μm or less [3–18].

The major approaches can be categorized as either simple or complex thermomechanical methods. The latter involves techniques such as severe plastic deformation [3], the formation and subsequent processing of martensite/pearlite [4] and other multistage techniques [5]. In the former, most of the work is related to dynamic recrystallization of the austenite [6] or ferrite [7,8], and the concurrent deformation and ferrite phase transformation [9–18], hereafter called dynamic strain induced transformation (DSIT). Among the various approaches, the DSIT technique has received significant attention among research groups around the world due to its simplicity [9–18] and because it can be applied over a wide range of steel compositions [9,10]. In this technique, the deformation is applied in a critical temperature regime, i.e. between the Ar_3 and Ae_3 (the empirical and equilibrium austenite to ferrite transformation temperatures, respectively). This results in

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an extremely fine microstructure, consisting of an equiaxed ferrite grain of 1–3 μm with a uniform dispersion of second phase (e.g. carbide) [14].

The concurrent deformation and phase transformation in the DSIT process is believed to be necessary to obtain ultrafine ferrite-grained structure (UFF) in steels [9–18]. This process is, however, much more complex than conventional controlled rolling as the deformation is being applied in the two-phase region once transformation initiates. Even though the DSIT ferrite grains experience deformation, they mostly preserve their equiaxed morphology and do not elongate along the deformation direction [14]. There is still debate as to whether the DSIT ferrite grains undergo continuous dynamic recrystallization [19] or the deformation locks in a critical size for the DSIT ferrite grains depending on the thermomechanical condition [14]. Despite the current debate, it is generally believed that the dynamic nature of phase transformation sets up a condition, which significantly controls the evolution of ferrite phase transformation (i.e. nucleation and growth), resulting in extreme grain refinement.

Some attempts have been made to refine the ferrite grain size through a controlled rolling process in conjunction with an accelerated cooling technique [13,20]. Although it enabled a grain size of less than 2 μm to be obtained, other low-temperature phases were introduced in the microstructure due to the high cooling rate. Adachi et al. [21] more recently performed a critical set of experiments in which they successfully produced a ferrite grain size of ~1.5 μm through static transformation. They demonstrated that it is potentially possible to produce an ultrafine structure using warm deformation followed by static phase transformation and controlled cooling [21]. However, it is not clear (i) how the ferrite nucleation and growth were controlled through this process and (ii) whether the controlled cooling is necessary to obtain a UFF microstructure through this technique. The current research examines the role of the ferrite nucleation sites at an early stage of phase transformation and the evolution of the ferrite grains during transformation (i.e. growth) and their effects on the level of grain refinement using warm deformation followed by isothermal phase transformation (i.e. static transformation without controlled cooling).

2. Experimental procedure

The composition of the steel examined in this study was 0.26C–1.96Si–2Mn–0.31Mo (in wt.%). The composition was designed based on the previous work [21] on 0.2C–2Si–2Mn steel, where an UFF structure was formed through static transformation followed by controlled cooling. The addition of C and Mo in the present composition further enhances the quench hardenability and lowers the ferrite (Ar_3), bainite (B_s) and martensite (M_s) starting transformation temperatures of the steel [22]. Mo also retards recrystallization through the solute drag effect [23]. This provides a condition in which the UFF structure can be produced through the isothermal phase transformation. The continuous cooling transformation (CCT) diagram of the steel was determined to characterize the evolution of the austenite transformation during continuous cooling using a Material Measuring Corporation dilatometer. The samples were reheated up to 1000 °C at a rate of 5 °C s^{-1} and held for 300 s resulting in an average austenite grain size of 55 μm. The samples were cooled at rates ranging from 100 to 0.3 °C s^{-1}. The analysis of the volumetric variation of the samples during cooling and the final microstructures were used to determine the phase boundaries on the CCT diagram. The steel had high quench hardenability (Fig. 1). The ferrite nose in the continuous cooling transformation diagram appears at a long elapsed time, with the incubation time for ferrite transformation at the nose being more than 1 h. The Bs and Ms temperatures were approximately 500 and 350 °C, respectively (Fig. 1).

An as-received billet was reduced in thickness to 12 mm by hot rolling at temperatures between 1200 and 1000 °C. Compression samples with a height of 15 mm and a diameter of 10 mm were machined out of the hot-rolled plate with their longitudinal axis perpendicular to the rolling direction. The samples were reheated at 5 °C s^{-1} to 1000 °C and held for 300 s to obtain a fully austenite microstructure. They were then cooled down to 570 °C (i.e. above the Bs and Ms temperatures) and held for 10 s to obtain a uniform temperature throughout the sample. The metastable austenite was then deformed at different strains (i.e. 0.3, 0.6 and 1) at a strain rate of 0.1 s^{-1}. The warm deformed samples were reheated to 650 °C at 10 °C s^{-1} and held for different holding times, from 0 to 180 min, followed by water quenching to monitor static ferrite phase transformation evolution. The reason behind the current thermomechanical route was to significantly enhance intragranular defects in the metastable austenite through deformation at relatively low temperature (i.e. 570 °C).

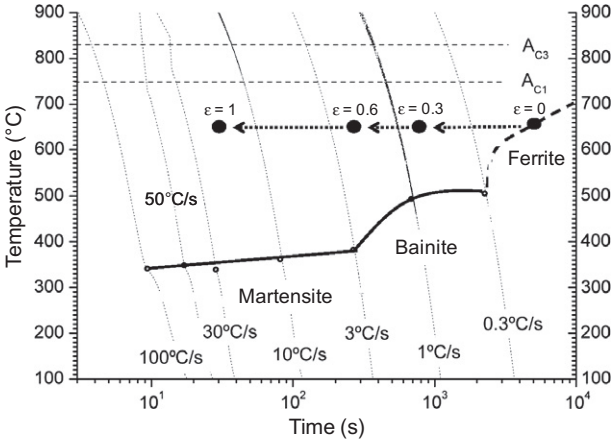

Fig. 1. Continuous cooling phase transformation diagram for a 0.26C–1.96Si–2Mn–0.31Mo (wt.%) steel. Solid circles represent the start of ferrite phase transformation for the steel deformed at different strains at 570 °C followed by isothermal holding at 650 °C, based on metallography observation.