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Experimental and numerical analysis on formation of stable austenite during the intercritical annealing of 5Mn steel

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Abstract

Microstructure evolution during the intercritical annealing at 650 °C for various durations up to 144 h in 5 wt.% Mn-containing steel, from the initial martensitic microstructure to mainly ultrafine lamellar microstructures consisting of austenite laths and ferrite laths, was examined experimentally and analyzed numerically in this paper. Annealing for longer duration results in a larger volume faction of austenite and thicker γ laths with an enrichment of Mn, which significantly improves elongation and lowers the yield stress. The γ fraction increases almost linearly with the logarithm of annealing time until it is saturated after 12 h annealing. The thickening of the austenite lath was numerically simulated by DICTRA software and the MOB2 database under the local equilibrium. The simulation result is in fair agreement with the measurements, and also shows a proportional dependence on the logarithm of the annealing time up to 12 h. Furthermore, numerical simulations on growth of the austenite lath nucleated at the ferrite–cementite interface were also performed, and indicated that such growth should be very sluggish due to the slow dissolution of cementite. As a result, it is concluded that the growth of austenite nucleated at the ferrite lath boundaries, instead of the growth of austenite nucleated at the ferrite–cementite interface, plays a major role in the increase in austenite volume fraction during the annealing, which is controlled by the diffusion of Mn in both austenite and ferrite phases.

Keywords: Phase transformation kinetics; Intercritical annealing; Austenite; Ferrite; Numerical simulation

1. Introduction

It has been recognized that strain-induced martensitic transformation plays a major role in improving the mechanical balance (tensile strength × elongation) of transformation-induced plasticity (TRIP) steels, which are widely used in the automobile industry [1–5]. The enhanced plasticity is determined by both the phase fraction and the stability of the retained austenite [6]. In the 1970s, Miller firstly developed 0.1 wt.% C–5 wt.% Mn steel, in which 20–40% austenite was retained with optimized stability by intercritical annealing [7]. Recently, the present authors have made remarkable progress with modified compositions of 5Mn steel which contain more than 30% austenite in the microstructure and exhibit tensile strength of 1–1.5 GPa and total elongation of 31–44% [8]. The key process to achieve such outstanding properties is to heat the steel with the original martensitic microstructure to the intercritical region (the $\alpha + \gamma$ two-phase region), where part of the martensite is reversibly transformed to the austenite. During such transformation, nucleation and growth of the austenitic phase involves movement of the interface boundary into the ferrite phase and diffusion of the interstitial C and the substitutional Mn atoms in both the ferrite and austenite phases. This is much different from the phase transformation occurring during the hot rolling, accelerated cooling and continuous annealing etc. in commercial steel production lines, in which para-equilibrium is often considered since only diffusion of the interstitials is possible within the short period. During the long intercritical annealing duration, diffusion of both the interstitial and

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substitutional elements may occur in the submicrometer range, which determines both the phase fraction and the stability of the retained austenite. Therefore, it is crucial to know the quantitative relationship between the annealing process parameters and the microstructural features of the formed austenite, such as the phase fraction and composition, the latter influencing the chemical stability.

Intercritical annealing, which involves α-to-γ transformation in the martensitic/bainitic microstructures during heating, was intensively studied from the 1950s to the 1980s [9–13]. Hara et al. [14] summarized these relevant researches and made the following conclusions. There are two types of austenite grains formed at different nucleation sites during the intercritical annealing. One is globular austenite grains nucleated at the martensite packet boundaries, at prior austenite grain boundaries or at the dissolved cementite, and their growth is normally diffusion controlled and accompanied by the dissolution of cementite. The other is acicular austenite grains, or austenitic laths, nucleated at the boundaries of martensite laths. The acicular γ grains within any prior austenite grains have the same orientation and may coalesce on impingement, leading to a reconstruction of the original prior γ grain, which is called the γ grain memory effect. However, the method of formation of acicular γ grains is a subject of debate. Matsuda and Okamura [11] believed that acicular γ grains could be formed by reverse martensite transformation while keeping the Kurdijmov–Sachs orientation relationship with the martensite matrix. However, Plichata and Aaronson [13] reported that growth of acicular γ grains was controlled by diffusion rather than due to the shear mechanism.

In this paper, experimental observation of the formation of the austenite phase during intercritical annealing is presented. Moreover, numerical simulation on the growth kinetics of the γ lath, nucleated either on the retained austenite at the initial martensite lath boundaries or at the ferrite–cementite interface, are performed using DICTRA commercial software with its MOB2 database under the assumption of local equilibrium (instead of para-equalibrium assumption). The objective of this study is to explor, by experiments and simulations, the nucleation and thickening mechanism of austenite laths of 5Mn steel during the intercritical annealing process.

2. Experimental procedures

The steel studied, with a nominal composition of 0.2 wt.% C–4.72 wt.% Mn, was melted in an induction furnace under a vacuum and cast to a 50 kg ingot, which was then homogenized at 1250 °C for 2 h and forged into rods with diameters of 16 mm. These forged rods were austenized at 750 °C for half an hour, quenched in oil, intercritically annealing at 650 °C for various durations up to 144 h in a box furnace and finally air cooled to room temperature. The heating rate was estimated to be around 40–60 °C s^{-1} during the intercritical annealing. Dog-bone-shaped tensile specimens, subjected to various annealing durations, were machined with a gauge length of 25 mm and a diameter of 5 mm. Tensile tests were performed with a strain rate of 10^{-3} s^{-1} at room temperature using an Instron machine (WE-300) for measurements of the mechanical properties.

The microstructure evolution during the intercritical annealing was carefully examined by transmission electronic microscopy (TEM). Compositional analysis of the different phases was carried out by scanning transmission electronic microscopy (STEM) and energy-dispersive spectroscopy (EDS). Austenite volume fractions after different annealing durations were examined by X-ray diffraction (XRD).

Thin foils for TEM measurements were first mechanically ground down to ∼40 μm thickness, then twin-jet polished in a solution of 5% perchloric acid and 95% alcohol at about −20 °C. Samples for XRD measurements were ground and polished mechanically, then polished electrolytically in a solution of 10% chromic acid and distilled water to relieve stress. The volume fraction of the retained austenite was estimated by XRD using Cu Kα radiation. The calculations were based on the integrated intensities of $(2\,0\,0)_\alpha$, $(2\,1\,1)_\alpha$, $(2\,0\,0)_\gamma$, $(2\,2\,0)_\gamma$ and $(3\,1\,1)_\gamma$ diffraction peaks. The carbon content of the austenite was estimated by XRD from the measured lattice parameter of the austenite after excluding the influence of the measured Mn content in the austenite [15].

3. Experimental results

The martensite microstructure in the sample quenched after austenization at 750 °C for 30 min was characterized by TEM (Fig. 1). Three to four martensite packets were formed within each austenite grain. The thickness of the martensitic lath is about 0.1–0.15 μm. No precipitates were

Fig. 1. Microstructure of the 5Mn steel after austenization at 750 °C for 30 min and quenching in oil.