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Preliminary study on kinetics of carbon partitioning in a high Ni Q&P steel

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ABSTRACT

Quenching and Partitioning (Q&P) treatment is a novel process to produce advanced high-strength steel. It is relatively difficult to investigate kinetic processes of the partitioning which normally complete after tens of seconds. Since the Mf (martensitic transformation finish temperature) of medium-carbon steels with high Ni content (9.8 wt%) is under room temperature, the kinetics of carbon partitioning can be studied around room temperature. In this study the carbon partitioning for a high Ni steel was investigated by means of Differential Scanning Calorimetry (DSC), Dynamic Mechanical Analyzer (DMA) and X-ray Diffraction (XRD). The activation energy of carbon partitioning estimated from the DSC is 1.02 eV (98 kJ/mol) which is comparable with DMA result. The frequency dependence anelastic peaks observed in DMA measurement was also discussed in correlation with Snoek-Koster-like relaxation in high strength steels containing considerable residual austenite and martensite phases.

1. Introduction

Advanced High-Strength Steel (AHSS) has been developed as the requirement of fuel efficiency and occupant safety in automobile manufacturing. One important way is to develop multiphase steel, such as, transformation-induced plasticity (TRIP) steels, nanobainitic steels [1] and Quenching and Partitioning (Q&P) [2] or quenching–partitioning–tempering (Q–P–T) [3] steels. The main character of these steels is containing a significant fraction of retained austenite in the steels. The martensite (ferrite in nanobainite) provides strength and the retained austenite improves ductility. As a certain amount of austenite is required to improve the ductility, one method is partitioning the elements, such as C, Mn [4], Ni into austenite to stabilize austenite (lower the Ms), so larger fraction of austenite can be remained to room temperature. Q&P steels exhibit excellent combination of strength and ductility. The key issue of the novel Q&P process is the introduction of partitioning during the stay at a medium temperature (200–400 °C). However, there is still controversy of kinetics of carbon partitioning in the partitioning process. The direction of interface migration between martensite and austenite [5,6] during the partitioning step is not determined and the theoretical estimation retained austenite fraction at room temperature in Q&P steels is quite different from the experimental result [7]. These problems are closely related to the kinetics of carbon partitioning, which is however not well known yet.

A high Ni steel is designed for the study of kinetics of carbon partitioning. Considerable fraction of residual austenite can be obtained at room temperature since the nickel decreases the Ms of steels, while migration of interstitial carbon is possible at room temperature because the carbon is movable even at sub-zero temperature [8].

Dynamic Mechanical Analyzer (DMA) is one type of internal frication techniques and it is indeed very sensitive to a wide range of phenomena related with defect mobility in materials, in particular the interactions between interstitial atoms and dislocations. Internal friction has been successfully used to study the carbon diffusion in steel for the tempering and aging process [9]. Here DMA measurement was applied to study the partitioning behavior of carbon element in a high Ni steel.

2. Experimental procedures

The chemical composition of studied alloy was shown in Table 1. An ingot was prepared by vacuum induction melting, then reheated to 1250 °C and hot-rolled to 10 cm thickness plate. Then individual specimens were austenitized at 730 °C for 5 min and quenched into water at room temperature. Dynamic Mechanical Analyzer (DMA, TA Q800), Differential Scanning Calorimetry (DSC), and X-ray Diffraction (XRD, Rigaku D/max-2550/PC, Cu K_α) were used to investigate the steels.

3. Experiment results

3.1. Carbon partitioning observed in differential scanning calorimetry test

Specimens of water quenching from 730 °C were heated from 50 to 600 °C at constant heating rates of 30, 40, 60 and 100 °C per minute in DSC furnace. Two distinct peaks were observed in DSC tests shown in Fig. 1(a). The low temperature peaks appeared at about 260 °C while the high temperature peaks were at about

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Table 1
The chemical composition of the alloy.

Sample	C	Si	Mn	P	S	Ni
Q	0.39	1.56	2.00	<0.005	0.0022	9.84

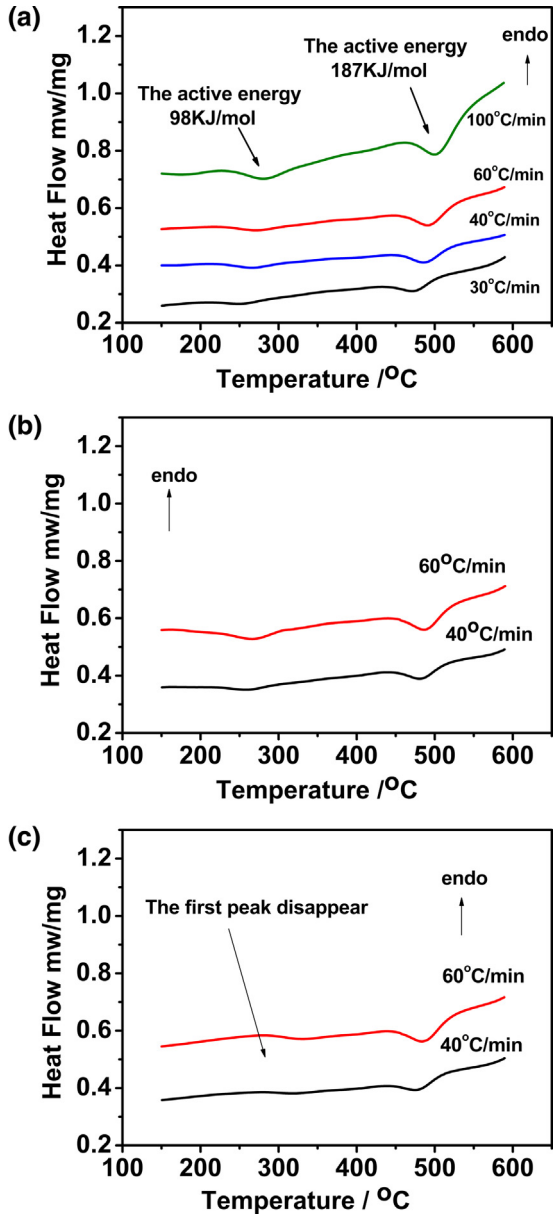

Fig. 1. DSC results of specimens after different heat treatments (a) 730 °C*5 min + water quenching; (b) 730 °C*5 min + water quenching + 190 °C*10 s (salt bath); (c) 730 °C*5 min + water quenching + 300 °C*10 s (salt bath).

480°C. The activation energy of two kinds of peaks was estimated from Kissinger-type kinetic analysis based on the Eq. (1) [10]:

$$ln\frac{T_f^2}{\phi} = \frac{E}{RT_f} + ln\left(\frac{E}{R}\right) - ln(A) \quad (1)$$

Where E is the activation energy, A is the pre-exponential factor, T_f is the peak temperature corresponding to a certain fraction (f) of the transformation (or other applicable process), and ϕ is the heating rate. The activation energies for low and high temperature peaks are 98 kJ/mol (1.02 eV) and 187 kJ/mol (1.95 eV), respectively.

De Moor [11] have reported that the activation energy of carbon partitioning and austenite decomposition was 92 kJ/mol and 172 kJ/mol in Q&P samples. So the low temperature DSC peaks shown in Fig. 1(a) were concluded to be associated with carbon partitioning from supersaturated martensite to retained austenite. The high temperature DSC peaks were related to retained austenite decomposition.

Two different samples were prepared to look into the origin of low temperature DSC peaks around 260 °C. One of the quenched samples was annealed at 190 °C and the other at 300 °C for 10 s, i.e., one is below 260 °C and the other is above 260 °C, followed by water quenching. No obvious influence was observed for both the low temperature peak and the high temperature peak for specimens annealed at 190 °C for 10 s (Fig. 1(b)). However for specimens annealed at 300 °C for 10 s (Fig. 1(c)), the low temperature peak disappeared or became indistinct in the DSC test, which implies that the carbon partitioning completed after annealing at 300 °C for 10 S.

XRD results of specimens after different heat treatments were presented in Fig. 2. The retained austenite fraction was estimated around 14–16%. The phase fraction of the specimens after different heat treatment was nearly fixed. The slight difference of XRD profiles for these specimens after treatments between room temperature and 300 °C might be resulted from the carbon portioning or dislocation migration. So the slight change of XRD profile may also suggest carbon partitioning and/or dislocation migration.

3.2. Snoek-Koster-like peaks observed in Dynamic Mechanical Analyzer (DMA)

Internal frication widely used in solid-state physics, physical metallurgy and materials science to study structural defects and their mobility, transport phenomena and phase transformations in solids. The internal friction can generally be written as [12]:

$$Q^{-1}(\omega\tau) = \boldsymbol{\Delta}\frac{\omega\tau}{1+(\omega\tau)^2} \quad (2)$$

Where ω denotes the angular frequency of the stress sequence, Δ is the relaxation strength, and τ is the relaxation time depending on temperature according to an Arrhenius law:

$$\tau = \tau_0 exp\left(\frac{H}{kT}\right) \quad (3)$$

Where τ_0, H and k are the pre-exponential factor (fundamental relaxation time of the process), the activation energy and the Boltzmann constant, respectively.

The effective activation enthalpy ("apparent activation energy") H and the "limit relaxation time" (reciprocal "attempt frequency")

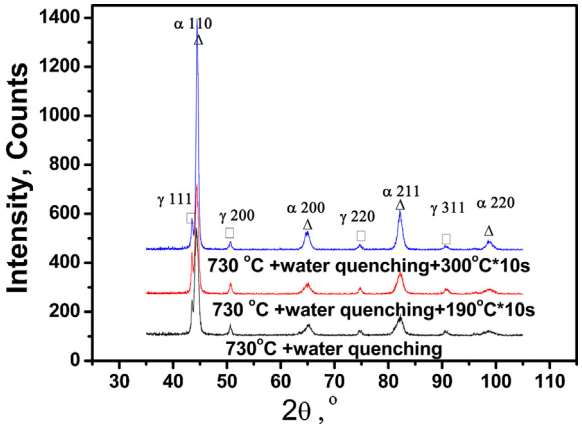

Fig. 2. XRD profiles of specimens after different heat treatments.