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Effect of retained austenite on the dynamic tensile behavior of a novel quenching-partitioning-tempering martensitic steel

Qingguo Hao [a], Shengwei Qin [a], Yu Liu [a], Xunwei Zuo [a,*], Nailu Chen [a], Wen Huang [b], Yonghua Rong [a]

[a] School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] College of Civil Engineering, Shenzhen University, Shenzhen 518060, China

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ABSTRACT

The dynamic tensile test with a strain rate of 500 s^{-1} and the quasi-static tensile test with a strain rate of $5.6\times10^{-4}\,s^{-1}$ were performed for a novel Fe-0.20C-1.49Mn-1.52Si-0.58Cr-0.05 Nb (wt%) quenching-partitioning-tempering (Q-P-T) martensitic steel with high amount of retained austenite, respectively. This low carbon steel was also treated by the traditional quenching and tempering (Q&T) process, and the same experimental tests were performed for the low carbon Q&T martensitic steel with little retained austenite to understand the effect of the retained austenite on the dynamic tensile behavior. The results indicate that compared with the quasi-static tensile test, the high strain rate in the dynamic tensile test raises the strength of the Q-P-T steel. However, the elongation slightly decreases. These results differ from the enhancement in both the strength and elongation of the Q&T steel in the dynamic tensile test. The increase in the strength of the Q-P-T steel in the dynamic tensile test is attributed to the strain rate hardening effect. The slight decrease in the elongation stems mainly from that the suppression of the dislocation absorption of the retained austenite (DARA) effect existing in the quasi-static tensile test, moreover, such a suppression is not effectively complemented by the adiabatic softening of the martensitic matrix in dynamic tensile test. The marked increase in the elongation of the Q&T steel in the dynamic tensile test is only attributed to the adiabatic softening of the martensite matrix because there is no DARA effect in the Q&T steel with little retrained austenite.

1. Introduction

Advanced high strength steels (AHSSs) are extensively applied in modern vehicles. Due to their excellent combination of strength and ductility, these steels reduce weight and improve fuel efficiency without sacrificing passenger safety. Extensive studies have focused on several types of low alloying Fe-Mn-Si based AHSSs, including dual-phase (DP) steels [1], transformation-induced plasticity (TRIP) steels and quenching and partitioning (Q&P) steels [2–7]. During the development of the AHSSs, investigators have been concerned with maintaining the ductility of the AHSSs at sufficient levels. Therefore, studies focused on the soft-phase retained austenite in the AHSSs. Novel processes were proposed to obtain maximum amounts of the retained austenite. For example, in the Q&P process proposed by Speer et al. [6], a Si-containing steel is used for quenching from the austenitizing temperature to a temperature (T_q) between the start temperature (M_s) and finish temperature (M_f) of martensitic transformation. This is followed by a “carbon partitioning” treatment either at T_q for the one-step Q&P process or above T_q for the two-step Q&P process. During this “partitioning”, the carbon diffuses from the supersaturated martensite phase to the untransformed austenite phase. This makes the carbon-enriched retained austenite be stable during the subsequent cooling to the room temperature. In the case of low or medium carbon Q&P steels, the T_q is usually much higher than room temperature [8,9]; thus, considerable amounts of the retained austenite can be obtained. Based on the “constrained carbon paraequilibrium” (CCE) theory of Q&P process proposed by Speer et al. [6], the formation of carbides is not permitted during the Q&P process, which excludes precipitation strengthening. For this reason, Hsu [10] proposed the quenching-partitioning-tempering (Q-P-T) process in 2007, and in the Q-P-T steels, additional carbide forming elements are added. The addition of these elements leads to stable carbides formation and grain refinement for precipitation strengthening and refined-grain strengthening [11]. As the Q-P-T process absorbs the core idea of the Q&P process, the quenching temperature (T_q) is determined by a combination of the CCE theory and the K-M equation [6]. The Q-P-T martensitic steels

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[*] Corresponding author.
E-mail address: jeepling@sjtu.edu.cn (X. Zuo).

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also have considerable amounts of the retained austenite compared to the traditional quenching and tempering (Q&T) steels. Research interest in the effects of the retained austenite on the ductility enhancement in high strength steels can be traced back to the 1960 s. Zackay et al. proposed TRIP effect in 1967 [12], in which the strain-induced martensitic transformation from the retained austenite relaxes the stress concentration and redistributes stresses during the plastic deformation [13]. This delays the necking up to the high strain region accompanying with a uniform increase in elongation. In 1968, Webster studied the effect of the retained austenite on the toughness of the high strength steels and proposed that the retained austenite can block crack propagation (BCP) [14]. Recently, using X-ray diffraction line profile analysis (XLPA) [15,16], we found a new effect of retained austenite on ductility enhancement based on the measurement of average dislocation densities in both martensite and retained austenite in the Q-P-T martensitic steels. This is termed the DARA (dislocation absorption by retained austenite) effect [9], that is, the dislocations in the martensite can move into the nearby retained austenite through the martensite-retained austenite interfaces, and these dislocations are absorbed by the retained austenite [17,18]. DARA effect was in succession observed in medium carbon and low carbon Q-P-T steels [9,17] as well as bainitic steel [19]. This effect is indirectly verified by transmission electron microscope (TEM) observation of dislocations athwart from martensite to retained austenite at their interfaces [9,17]. Molecular mechanics simulation in the Cu-Nb bi-layer film theoretically verifies the possibility of dislocations transmitted from the bcc-phase into the fcc-phase [20]. Since the retained austenite flakes absorb the dislocations moving from the nearby martensite laths, the DARA effect makes the martensite exist in a “softening” state in deformation, and thus the deformation ability of hard phase martensite is intensified.

In addition to the quasi-static (10^{-5}–10^{-1} s^{-1}) loading rates, the structural components of automobiles are also subjected to dynamic loading rates (10^{1}–10^{3} s^{-1}), such as those in a car collision or in sheet metal formation. Hence, it is imperative to understand the material behavior under these loading rates. Dynamic loading differs from quasi-static loading because the features of dynamic loading include both the strain rate hardening effect and the adiabatic softening effect, as revealed in studies of the DP steels and the TRIP steels [21–26]. Studies reported the dynamic mechanical properties of the Q&P 980 steel (consisting of ferrite, martensite and retained austenite) in the low alloyed Fe-Mn-Si based AHSSs but do not investigate the influences of strain rates or retained austenite on the dynamic mechanical behavior [27,28]. Our interesting refers to the effect of the retained austenite on the dynamic mechanical behavior, and thus we investigate the following: 1) the effect of the high strain rate on the DARA effect, 2) the effect of adiabatic heating on the TRIP effect and 3) the effect of the retained austenite on the ductility of the Q-P-T martensitic steel in the dynamic tensile test compared with that in the quasi-static tensile test.

This paper examines the above issues by comparing the dynamic tensile/quasi-static tensile experiments of a novel low carbon Q-P-T martensitic steel with those of the traditional Q&T martensitic steel with the same composition.

2. Experimental procedure

2.1. Material

The chemical composition of the steel designed was measured by the chemical analysis as Fe-0.20C-1.49Mn-1.52Si-0.58Cr-0.05 Nb (wt%). The design principles of composition for the steel include the addition of Mn and Cr is to stabilize the retained austenite and to provide adequate hardenability and the addition of Si to inhibit the formation of brittle Fe_3C carbide. The addition of Nb further raises the strength by precipitation strengthening and refined-grain strengthening [29,30].

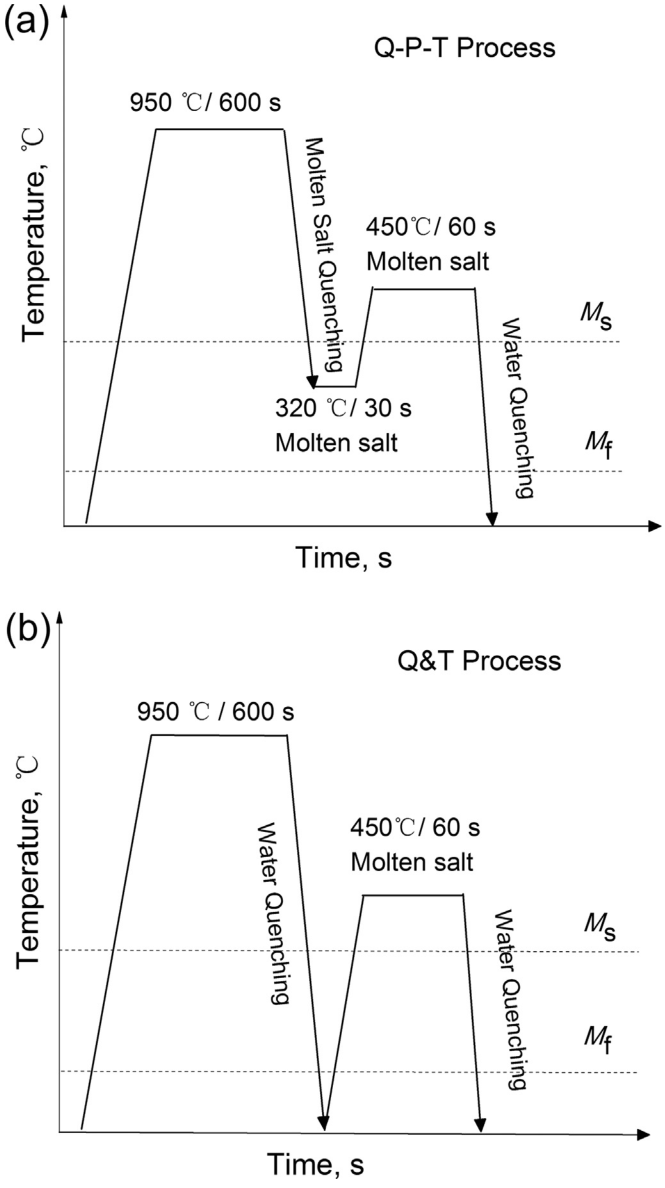

Fig. 1. Schematic illustration of the Q-P-T (a) process and the Q&T (b) process.

The steel was melted in a medium frequency induction furnace, and then a hot-rolled plate with 20-mm thickness was prepared by the Central Iron and Steel Research Institute (Beijing, China). The specimens with 4-mm thickness were cut from the hot-rolled plate. After cutting, they were respectively subjected to the Q-P-T process and the Q&T process, as shown in Fig. 1. The samples treated by the Q-P-T process were austenitized at 950 °C for 600 s, followed by quenching into a salt bath at 320 °C for 30 s, subsequently partitioned / tempered at 450 °C for 60 s in molten salt, and finally fast quenched to water. The difference between the Q-P-T process and the Q&T process only is in the quenching temperature (T_q) used. For the Q-P-T process the T_q is 320 °C, while for the Q&T process the T_q is the room temperature.