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Controlling the work hardening of martensite to increase the strength/ductility balance in quenched and partitioned steels

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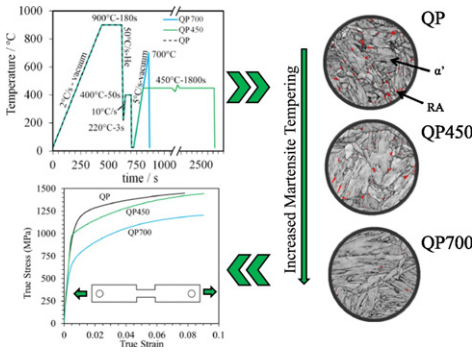
HIGHLIGHTS

- Martensite tempering was varied in a quenched and partitioned steel.
- Work hardening behavior at small strains depends on martensite dislocation density.
- Tensile ductility is impacted by small strain work hardening rate in Q&P steels.
- The strength of martensite in Q&P steels is reduced due to carbon partitioning.

GRAPHICAL ABSTRACT



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ABSTRACT

The role of retained austenite on tensile behavior in quenched and partitioned (Q&P) steels has been studied extensively, but the deformation behavior of martensite, which comprises the majority of Q&P microstructures, has received less attention. In this investigation, martensite properties were varied through heat treatment in a low carbon Q&P steel consisting of retained austenite and martensite. Additional conditions were produced by reheating the Q&P steel to 450 °C for 30 min or to 700 °C followed immediately by quenching. The reheated microstructures contained similar fractions of retained austenite as the non-reheated Q&P microstructures, but reheating tempered the martensite, thereby decreasing martensite dislocation density. The reheated conditions had a lower yield stress and initial work hardening rate than the non-reheated Q&P condition. However, the reheated conditions had a greater work hardening rate at larger strains and greater uniform strain due to less stable retained austenite. Furthermore, the tensile strength of the condition reheated to 450 °C was nearly equal to the non-reheated condition. In addition to retained austenite to martensite transformation, the early stage work hardening rate of martensite is critical to ductility and is dependent on martensite dislocation density, which can be decreased through tempering.

1. Introduction

Combinations of retained austenite and martensite have been predicted and experimentally shown to produce properties desired for third generation advanced high strength sheet steels (AHSS) [1].

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Matlock et al. [1] showed that austenite stability is also a critical factor in flow behavior through a composite model that incorporated austenite and martensite fractions as well as austenite stability. The model assumes isostrain conditions and sufficient interfacial bonding between the phases to avoid debonding. The work hardening behavior of the composite, controlled by increases in dislocation density and retained austenite to martensite transformation, results in a larger uniform strain than that achieved in the harder martensite by itself. The result is enhanced combinations of strength and ductility, specifically uniform elongation.

Uniform elongation is related to the work hardening rate through the instability criterion for necking:

$$\frac{d\sigma}{d\varepsilon} = \sigma \tag{1}$$

where σ is true stress and ε is true strain. Matlock et al. [1] noted the importance of strain hardening rate as a function of strain on uniform elongation. A high strain hardening rate at low strains has a similar effect as a high yield strength; both result in reaching the instability criterion at lower strain values, i.e. lower ductility. Therefore, it is advantageous for ductility to maintain high strain hardening rates at large strain values. Retained austenite stability directly influences the strain hardening rate as a function of strain, in turn affecting the uniform elongation that can be achieved. The high initial work hardening rate in martensite is also an important factor in composite austenite-martensite microstructures but has not yet been considered in great detail.

Microstructures containing mixtures of austenite and martensite can be produced through the quenching and partitioning (Q&P) process [2,3]. The process is performed by first austenitizing and then quenching to a temperature below the martensite start temperature to form a mixed austenite-martensite microstructure. Then, a holding step at the quench temperature or a slightly elevated temperature allows for carbon partitioning from martensite to austenite and stabilization of the remaining austenite before a final quench. The resulting microstructure consists of austenite, martensite that formed during the initial quench and was subsequently tempered in the partitioning stage, and martensite that formed during the final quench. Carbon partitioning to austenite is critical to stabilize austenite before the final quench and also to provide increased stabilization against mechanical formation of martensite during plastic deformation [3–9]. Since austenite stability is one factor that controls uniform elongation, much of the research on the Q&P process has focused on optimizing the fraction and stability of retained austenite through variations in the quench and partitioning step temperatures and times [10–14].

Tempering after the final quench is another route that can modify the austenite-martensite microstructure. Most of the work on tempering of Q&P steels has been performed on alloys with microalloy additions to obtain precipitate strengthening during the tempering step; it is proposed that these carbides can also be used to control carbon distribution [14–18]. Tempering can also change the deformation behavior and strength of the microconstituents, especially the martensite. Changes in the strength of the martensite and austenite would be expected to result in changes in the composite flow behavior. Additionally, tempering could promote diffusion of carbon from martensite to austenite as well as austenite decomposition into ferrite and carbides. These and other changes in the microstructure can have prominent effects on deformation and flow behavior.

This paper explores the effects of reheating or tempering heat treatments on tensile properties of a quenched and partitioned steel, with a focus on the possibility of engineering the strain hardening rate of martensite to alter tensile deformation response, while the initial amount of retained austenite does not vary significantly between conditions. In a previous study by Koopmans et al. [19,20] aiming to analyze the thermal stability of retained austenite in Q&P steels, a steel was subjected to various Q&P treatments and then reheated to temperatures up to 700 °C and quenched immediately. For some of the Q&P heat treatments, the reheating step resulted in little change in retained austenite volume fraction and austenite lattice parameter, implying that the austenite carbon concentration may not have significantly changed during these post Q&P heat treatments [19,20]. Thus, the alloy studied by Koopmans and the specific Q&P heat treatments that lead to minimal variations in the characteristics of the retained austenite upon heating are well suited to study the effect of tempering on martensite microstructure and its impact on tensile behavior.

2. Experimental methodology

2.1. Material and heat treatments

The composition of the steel alloy used in this study is provided in Table 1. The steel was produced using a laboratory vacuum induction furnace. After casting, the steel was hot rolled to a final thickness of 4 mm and then air cooled. Specimens with the geometry shown in Fig. 1a were machined for dilatometry heat treatments and tensile testing.

Heat treatments were performed with a Bähr 805 DIL A/D dilatometer. A type S thermocouple spot-welded on the surface was used to monitor and control temperature. A vacuum on the order of 10^{-4} mbar was used during heating or isothermal segments, and helium was used as the cooling gas. The dilatometer can be configured to heat treat a specimen as shown in Fig. 1 for subsequent tensile testing. The heat treatments are summarized in Table 2.

The baseline quench and partitioning heat treatment, labeled QP220, was previously shown [19,20] to result in a microstructure consisting of retained austenite, tempered martensite, and less than 2% as-quenched martensite; the retained austenite volume fraction was approximately 9%. Fig. 1b shows the complete thermal history. The target quench temperature of 220 °C, which varied by ±5 °C, is below the measured M_s temperature, which is 325 °C. After the heat treatment, there was 91 ± 3 vol% of martensite in the final microstructure.

Two different reheating treatments were performed on specimens initially heat treated with the QP220 heat treatment. The objective of the heat treatments was to alter the tempering conditions of the martensite while keeping the fraction of retained austenite similar to the QP220 heat treatment. One heat treatment, labeled QP220-700, consisted of the application of the heat treatment in Fig. 1b followed by a ramp in temperature to 700 °C at a rate of 5 °C/s, and then an immediate quench to room temperature. The peak temperature of 700 °C is above the Ae_1 temperature, which is approximately 637 ± 12 °C in this alloy. This heat treatment was shown by Koopmans to result in a 1–2% decrease in the fraction of retained austenite including the complete disappearance of the larger and blockier retained austenite grains [19,20]. Furthermore, the austenite lattice parameter was similar to the QP220 condition. This latter result indicates the chemical composition of the retained austenite in the QP220 and QP220-700 conditions are similar. Significant tempering of the martensite presumably occurred during the 700 °C reheating step. There is also the possibility of ferrite to austenite reversion during reheating since the peak temperature is above the A_{e1} temperature. However, the dilatometry results do not indicate any significant formation of austenite upon heating or austenite to martensite formation upon quenching from the peak temperature.

An alternative reheating treatment, labeled QP220-450 was performed as indicated in Fig. 1b and was designed to provide tempering of the martensite but to a lesser extent than the QP220-700 condition.

Table 1
Composition, in wt%, of the steel alloy used in the study.

C	Mn	Si	Mo	Al	S	P	Fe
0.20	3.51	1.525	0.509	0.03	0.0079	0.006	Balance