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MECHANICAL PROPERTIES OF A HIGH Si AND Mn STEEL HEAT TREATED BY ONE-STEP QUENCHING AND PARTITIONING

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In recent decade, there has been increasing interest in applying quenching and partitioning (Q&P) as a novel heat treatment for obtaining excellent combinations of mechanical strength and ductility in steel components. This process leads to microstructures containing martensite and carbon-enriched retained austenite in which martensite acts as a strengthening phase while retained austenite significantly contributes to the elongation due to the transformation-induced plasticity (TRIP) effect during the deformation. In this research, Q&P heat treatments in which the partitioning step is performed at a temperature equal to the quenching temperature were applied to a high Si and Mn steel, and the mechanical properties of the treated specimens were evaluated and discussed. According to the final results, considerable balances of strength and ductility were obtainable in Q&P treated specimens for application in the automotive industry such as B-pillar reinforcement, inner B-pillar, front floor side member, inner door panel, etc.
Keywords: *one-step quenching and partitioning, partitioning time, mechanical properties.*

Introduction. The application of high-strength steel components with good ductility in the car industry (a) leads to decrease in the car body weight, which reduces the fuel consumption and emissions [1], and (b) promotes passenger safety [2]. In 2003, Speer et al. [3] first proposed an approach designated as the Q&P process to exploit novel martensitic steels containing retained austenite (Q&P steel), based on the fact that carbon can diffuse from supersaturated martensite into neighboring untransformed austenite and stabilize it to room temperature.

The Q&P heat treatment sequence involves quenching from the austenization temperature to a temperature between the martensite-start (M_s) and martensite-finish (M_f) temperatures, followed by a partitioning treatment either at (called one-step Q&P), or above (called two-step Q&P) the initial quench temperature, and at this temperature carbon can diffuse from the supersaturated martensite into the surrounding austenite, thereby stabilizing retained austenite to room temperature [4]. Multiphase microstructures of martensite and residual austenite in the Q&P treated steels ensure their attractive mechanical properties of high strength along with high toughness. Martensite is a strengthening phase while residual austenite significantly contributes to the formability and energy absorption owing to the TRIP phenomenon during the deformation [5]. In this work, one-step Q&P cycles were applied to a high Si and Mn steel, and the trend of mechanical property changes in the treated specimens was investigated and discussed.

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TABLE 1. The Chemical Composition of the Investigated Material, wt.%

C	Si	Mn	Cr	Ni	Cu	Al	Pb	P	S
0.362	1.38	1.24	0.0973	0.0902	0.0711	0.03	0.025	0.0245	0.0202
W	Co	As	Sn	Mo	Nb	Ti	B	Zr	V
0.015	0.0101	0.0101	0.0095	0.005	0.0025	0.0023	0.002	0.002	0.002

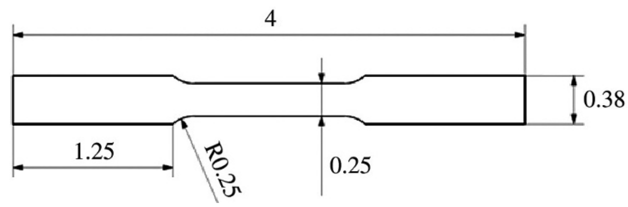

Fig. 1. The geometry of tensile test samples used in the present work (all dimensions are in inches).

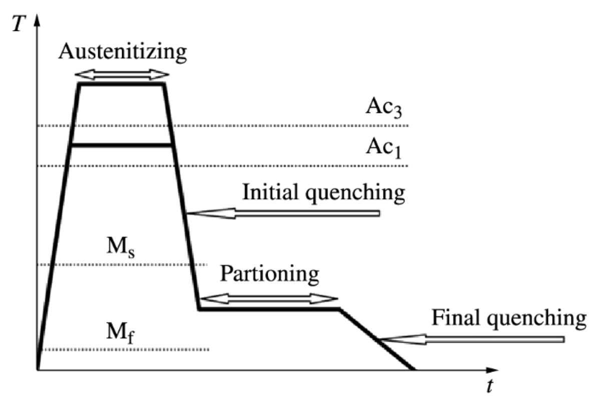

Fig. 2. Schematic of the one-step Q&P process applied in the present work.

Experimental Details. The chemical composition of the base material is a significant subject that should be taken into account in Q&P process. The base material used in this research was a low alloy C–Mn–Si steel with chemical composition similar to conventional TRIP-assisted steels, as shown in Table 1. The carbon concentration of the base material was 0.362 wt.%, and the 1.24 wt.% manganese included in the chemical composition was used to retard ferrite, pearlite, and bainite formation and decrease the bainite start temperature, as well as to enhance the austenite stability. On the other hand, a silicon content of 1.38 wt.% was used to restrict carbide precipitation during the partitioning step [6]. The critical temperatures for the base material were M_s = 339°C, Ac_1 = 748.1°C, and Ac_3 = 841.5°C, respectively.

Tensile test samples were prepared from the base material according to ASTM E8-04 with a gage length of 25.4 mm. The geometry of the tensile samples is shown in Fig. 1. For one-step Q&P heat treatment, the samples in the tensile test and x-ray diffraction (XRD) were heated to 900°C at a heating rate of +5°C/sec in a furnace and held for 10 min for full austenitization, then quenched into an oil bath at 238°C (optimum quenching temperature) with a cooling rate of –220°C/sec. Then they were partitioned at this temperature for 10, 30, 100, 700, and 1000 sec, then finally water quenched to room temperature (Fig. 2).

After the heat treatments, the mechanical properties of the treated specimens such as mechanical strength and elongation were measured at room temperature at an extension rate of 0.5 mm/min using a GOTECH MACHINE-1220AJ-50K testing machine. The yield strength was measured as the 0.2% offset stress.

TABLE 2. The Microstructural Results Obtained for the Base Material during the One-Step Q&P Process

Partitioning time, sec	Volume fraction of retained austenite, %	Average carbon content of retained austenite, %	Carbide precipitation
10	11.83	1.5205	No
30	7.23	1.2886	No
100	10.85	1.4022	No
700	10.43	1.4318	Yes
1000	10.73	1.3932	Yes

TABLE 3. The Mean Crystallite Size and Dislocation Density of the Final Phases for Different Conditions of the One-Step Q&P Process

Partitioning time, sec	D_M, nm	D_γ, nm	$\delta_M \cdot 10^{-10}$, cm^{-2}
10	17.75	83.74	31.74
30	25.77	35.08	15.06
100	25.79	124.86	15.03
700	29.81	15.40	11.25
1000	39.48	87.27	6.42

In order to determine the mean crystallite size and dislocation density in the final phases of the treated specimens, XRD measurements were performed on a Bruker D8 diffractometer using CuKα radiation operating at 35 kV and 30 mA. Samples were scanned over a 2θ range from 10 to 90° with a dwell time of 1 sec and a step size of 0.05°. The mean crystallite size of the retained austenite and martensite phases was determined using Scherrer's equation (1) [7] by using the $(200)_\gamma$, $(220)_\gamma$ and $(200)_M$, $(211)_M$ peaks, and the dislocation density of martensite phase was calculated using Eq. (2) [8, 9]:

$$D = K\lambda/(\beta\cos\theta); \quad (1)$$

$$\delta = n/D^2, \quad (2)$$

where D is the mean crystallite size, K is Scherrer's constant (shape factor), λ is the x-ray wavelength, β is the width of the XRD peak at half height, θ is the Bragg angle, and δ is the dislocation density, and n is a constant; K and n are equal to 0.9 and 1, respectively, in this research.

Results and Discussion. The microstructural results obtained in this work were discussed in [10]. A summary of these results is shown in Table 2 and Fig. 3. Moreover, the mean crystallite size and dislocation density of phases were calculated for different conditions of the one-step Q&P process and are shown in Table 3.

The mechanical properties resulting from the one-step Q&P process according to the scheme of Fig. 2 are shown in Figs. 4 and 5. The ultimate tensile strength (UTS) and elongation were from 607 to 918 MPa and from 9.53 to 13.14%, respectively, for these values of the partitioning time.

Because the strength of the retained austenite is very low and the volume fraction of this phase was not more than 12 vol.% in this study, the strength level and volume fraction of the martensite phase were the two dominant parameters in determining the final strength of the treated samples. On the other hand, the strength of the martensite phase is derived from various strengthening mechanisms such as: (1) dislocation strengthening of the martensite, (2) precipitation strengthening

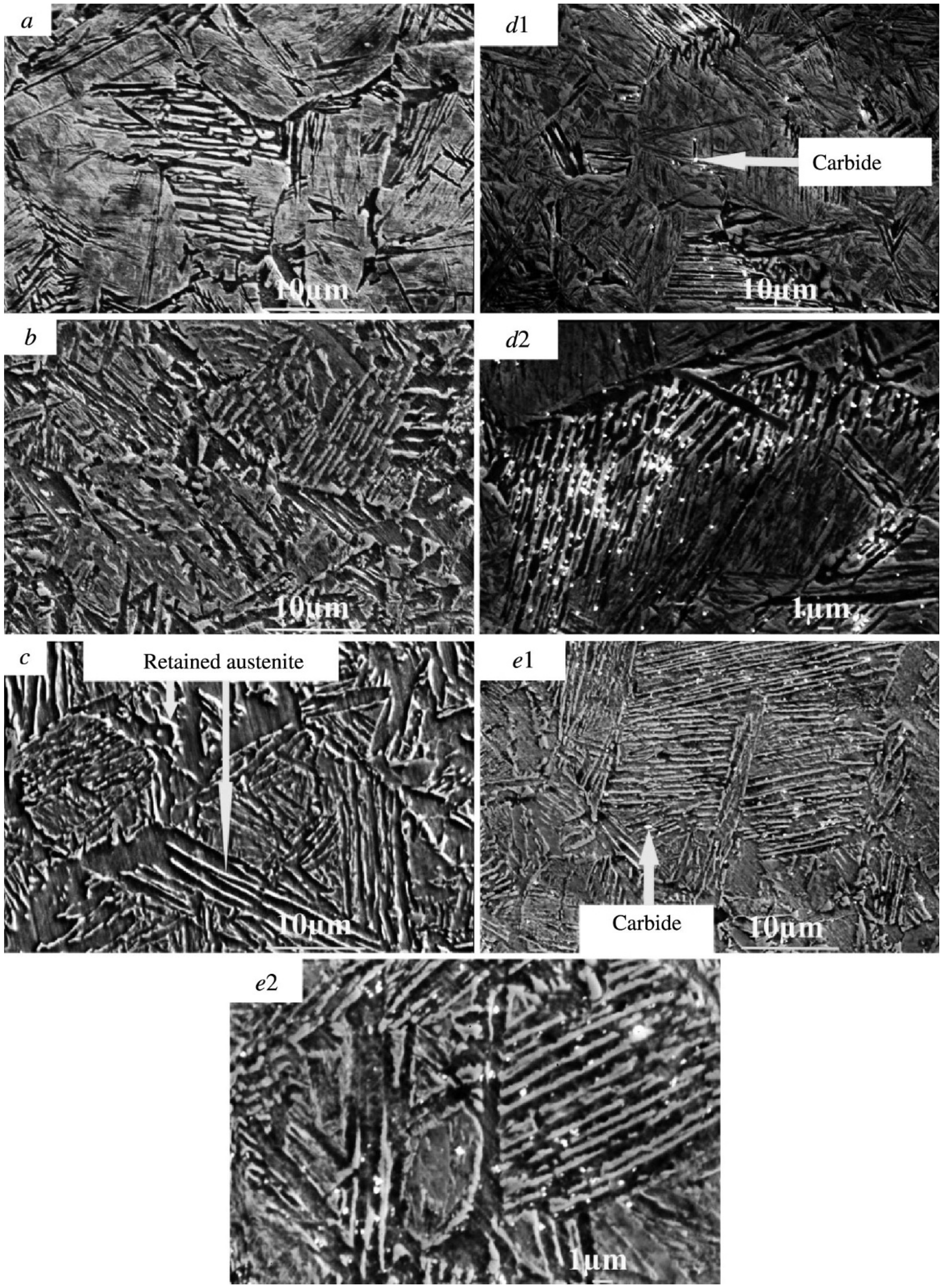

Fig. 3. SEM micrographs of the treated specimens: fully austenitized at 900°C, quenched to 238°C, partitioned at 238°C for 10 (*a*), 30 (*b*), 100 (*c*), 700 (*d*), and 1000 (*e*) sec, and finally water quenched to room temperature.

effect from the carbide particles within the martensite phase (3), and high degree of carbon supersaturation in virgin martensite. According to Fig. 4, the highest UTS and yield strength in this study were 918 and 782 MPa, respectively, which were obtained for the shortest partitioning time in this study (10 sec). This can be related to the strong strengthening mechanism due to the high dislocation density in the martensite phase ($31.74 \cdot 10^{10}$ cm^{-2}). The yield strength and UTS decreased to 723

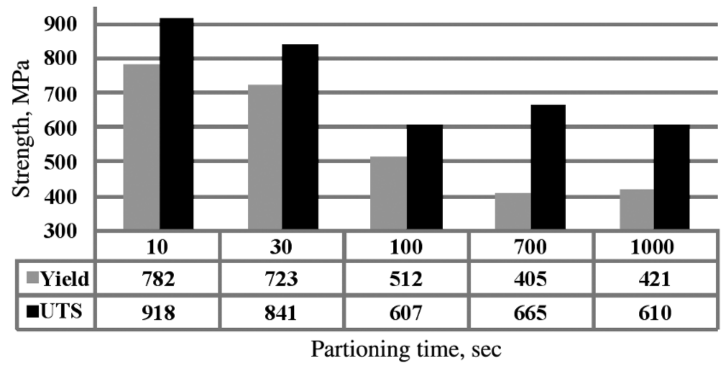

Fig. 4. Effect of partitioning time on strength of samples treated by the one-step Q&P process.

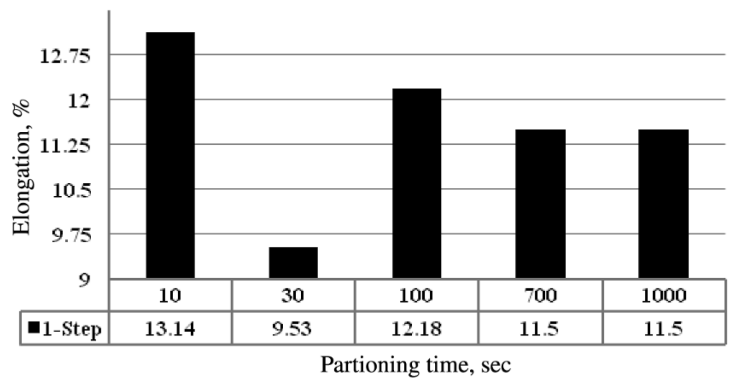

Fig. 5. Effect of partitioning time on elongation of samples treated by the one-step Q&P process.

and 841 MPa, respectively, with increase in partitioning time from 10 to 30 sec. Despite the decrease in strength, the strength level in this condition was higher than that at longer partitioning times, which can be due to the maximum volume fraction of the martensite phase and the higher dislocation density in this phase ($15.06 \cdot 10^{10}$ cm^{-2}). Also, the minimum average carbon content of retained austenite in this condition (1.2886%) means a higher degree of carbon supersaturation in the virgin martensite phase for samples treated for a partitioning time of 30 sec. The presence of the lower volume fraction of the martensite phase in addition to the lower degree of carbon supersaturation in the virgin martensite phase than that treated for a partitioning time of 30 sec and the lack of a strong strengthening mechanism in this condition led to the minimum UTS (607 MPa) in samples partitioned at 100 sec. The carbide particle precipitation during partitioning for 700 and 1000 sec provided a considerable precipitation strengthening effect, which resulted in an increase in the UTS but a decrease in the yield strengths in these conditions compared with a partitioning time of 100 sec and which can be related to lower dislocation densities in these partitioning times ($11.25 \cdot 10^{10}$ and $6.42 \cdot 10^{10}$ cm^{-2}).

Retained austenite plays a key role in plasticity enhancement. As has been pointed out in [11], interlath film-like austenite can impede generation and propagation of cracks and in turn improve toughness. Furthermore, both interlath and island-like austenite can partially transform to martensite and show the TRIP effect during deformation, thus eliminating stress concentration and retarding necking [12], which results in an increase in elongation. With an increase in retained austenite volume fraction, more martensitic transformation owing to the TRIP phenomenon during deformation occurs, and this leads to an increase in steel sheet elongation and formability.

According to Fig. 5, the greatest elongation in this study was 13.14%, which was obtained in samples partitioned for 10 sec, and this was due to the maximum volume fraction of retained austenite in this condition (11.83%) and the pres-

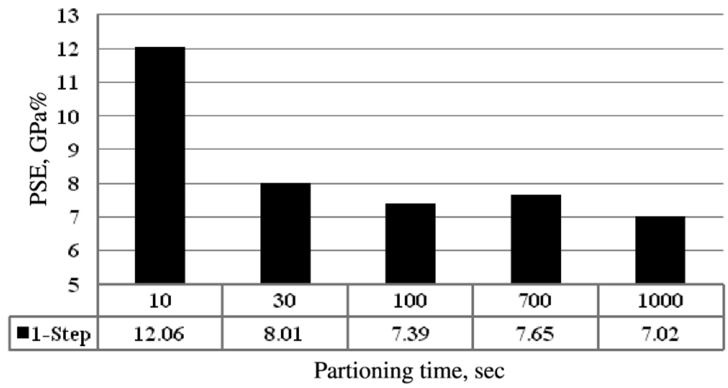

Fig. 6. The products of tensile strength to total elongation of Q&P processed base material.

ence of the thicker austenitic films and a lot of austenitic islands with sizes much larger than a micrometer in microstructure. Due to the minimum volume fraction of retained austenite (7.23%) and high strength level in samples partitioned for 30 sec, the elongation decreased markedly to a minimum value (9.53%). The increase in partitioning time from 30 to 100 sec resulted in an increase in elongation from 9.53 to 12.18%, which can be related to the increase in retained austenite volume fraction from 7.23 to 10.85% and the presence of more austenitic films with greater thickness and elongation in the microstructure than those for a partitioning time of 30 sec. The negligible decrease in retained austenite volume fraction from 10.85 to 10.43% and the decrease in thickness and elongation of austenitic films in samples partitioned for 700 sec led to a decrease in the elongation from 12.18 to 11.5%, and this value was retained for a partitioning time of 1000 sec.

The product of strength and elongation (PSE) indicates the balance of strength and ductility for advanced high-strength steels (AHSS) in engineering applications [13]. The products of tensile strength to total elongation (UTS×El) of Q&P processed base material were calculated and are given in Fig. 6. It can be observed that the UTS×El of Q&P processed base material is from 7.02 to 12.06 GPa%, and these values are considerable when compared with similar heat treatments such as austempering and conventional quenching and tempering for industrial applications.

Conclusion. In this study, Q&P heat treatments in which the partitioning step is performed at a temperature equal to the quenching temperature were applied to a high Si and Mn steel:

1. The change in strength with partitioning time in treated samples was described based on strengthening mechanisms, including: the dislocation strengthening of the martensite, the precipitation strengthening effect from the carbide particles within martensite phase, the high degree of carbon supersaturation in virgin martensite, etc.

2. Retained austenite plays a key role in plasticity enhancement. The interlath film-like austenite can impede generation and propagation of cracks, which in turn improves toughness. Furthermore, both interlath and island-like austenite can partially transform to martensite and show the TRIP effect during deformation, thus eliminating stress concentration and retarding the occurrence of necking, which results in increasing the elongation.

3. The products of tensile strength to total elongation of Q&P processed base material in this research were from 7.02 to 12.06 GPa%, and this range is considerable when compared with similar heat treatments such as austempering and conventional quenching and tempering for industrial applications.

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