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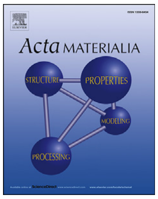

Full length article

Kinetics of the partitioning of carbon and substitutional alloying elements during quenching and partitioning (Q&P) processing of medium Mn steel

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A B S T R A C T

Quenching and partitioning (Q&P) processing of medium Mn steel is a new approach to produce formable ultra-high strength steel with a martensite + austenite microstructure. Carbon partitioning from martensite into austenite is essential for austenite stabilization during Q&P processing, and substitutional atom partitioning is usually considered not to occur. The present study provides a direct atomic-scale evidence for the partitioning of both interstitial carbon and substitutional Mn and Si, during the Q&P processing of medium Mn steel by means of 3-dimensional atom probe tomography. The experimental results were compared to results of a numerical simulation of the kinetics of carbon, Si and Mn partitioning during Q&P processing assuming an immobile martensite-austenite phase boundary. Both show that short range substitutional alloying element partitioning occurs during the partitioning stage in Q&P processing.

1. Introduction

Quenching and partitioning (Q&P) processing was originally proposed by Speer *et al.* [1] as a new approach to produce steel microstructures consisting of a martensitic matrix containing considerable amounts of retained austenite. Fig. 1 shows a schematic for Q&P processing. The austenitized steel is initially quenched to a quench temperature (T_Q) in the M_s to M_f temperature range, and the microstructure is partially transformed to primary martensite (α'_p). It is then partitioned at the partitioning temperature (T_P). During the partitioning stage, carbon diffuses from the supersaturated α'_p into the untransformed austenite. As a result of the segmentation of the austenite by the primary martensite and the carbon enrichment, the M_s temperature of the austenite is lowered. This leads to the stabilization of the untransformed austenite upon cooling to room temperature. If not enough carbon partitions to austenite, some of the austenite will transform to secondary martensite (α'_s) in the final quenching stage. The final microstructure after Q&P processing consists of carbon-enriched retained austenite in a low-carbon martensite matrix. The martensite provides a high strength level to the material and the carbon-enriched austenite enhances the elongation and the toughness. Recently, there has been increased interest in the development of Q&P steel grades, suitable for the production of structural parts of automotive body-in-white, due to their potential for superior mechanical properties. It is well documented that the application of Q&P processing to various advanced high strength steels (AHSS) leads to a higher strength level combined with an improved ductility [2–8].

Carbon partitioning from martensite into austenite is essential for austenite stabilization during Q&P processing. Speer *et al.* [9] showed that, under the constrained carbon equilibrium (CCE) condition, most of the carbon partitions from martensite into austenite during the partitioning treatment. The three main conditions for CCE are (1) the absence of cementite formation; (2) an identical chemical potential for carbon in martensite and austenite; (3) a stationary martensite/austenite phase boundary. Condition (2) applies only to carbon; it does not apply to substitutional solutes. These three conditions are unlikely to be satisfied during actual Q&P processing because the bainitic transformation and the carbide precipitation may not be suppressed during Q&P processing. The carbide precipitation in martensite is often observed during the partitioning stage, in low carbon steels [10,11], high carbon steel [12–14], and steels with a higher Si content [2,14]. In several earlier studies, the occurrence of a bainitic transformation during the

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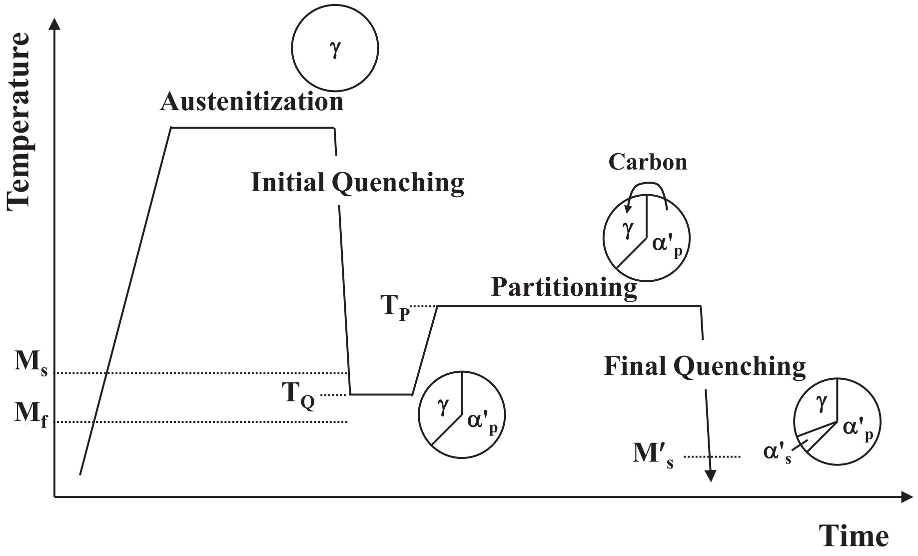

Fig. 1. Schematic of the heat treatment cycle for the Q&P processing. γ, α'_p, and α'_s are retained austenite, primary martensite, and secondary martensite, respectively.

partitioning stage was reported to occur during Q&P processing [2,15,16]. Having said this, there is also clear evidence for carbon partitioning from martensite into austenite during the Q&P processing. Bigg *et al.* [17] suggested that the austenite lattice dilatation which they observed during the partitioning stage by *in situ* neutron diffraction measurements clearly indicated that the carbon partitioned from martensite into austenite in a 0.64C-4.57Mn-1.3Si steel (wt. %). Gouné *et al.* [18] also reported the carbon partitioning from martensite into austenite during the Q&P processing of 0.4C–25Ni steel (wt. %). Recently, Toji *et al.* [13] provided atomic scale evidence of carbon partitioning from martensite to austenite in a 0.59C–2Si–3Mn steel (wt. %) during the partitioning stage. This was accompanied by the carbide precipitation inside the martensite which was observed by means of field-emission electron probe micro analysis (FE-EPMA) and 3-dimensional atom probe tomography (3D APT).

The CCE condition ignores the partitioning of iron or substitutional alloying elements during the partitioning stage in Q&P processing. From a fundamental point of view, this corresponds to the assumption that the martensite/austenite interface is kinematically stationary. This assumption is based on the fact that as Q&P processing is carried out at a relatively low temperature (350 °C - 450 °C), the diffusivities of the substitutional alloying elements are too low to partition between martensite and austenite. Most studies on Q&P processing do therefore not consider the possibility of the partitioning of substitutional alloying elements. However, Toji *et al.* [12] recently observed the Mn partitioning from martensite into austenite by means of 3D APT in a 0.59C–2Si–3Mn steel (wt. %) partition-treated at 400 °C for 300 s.

The present study provides a direct atomic-scale evidence of the partitioning of carbon and substitutional alloying elements between martensite and austenite during the Q&P processing of a medium Mn steel by means of field-emission transmission electron microscopy (FE-TEM) and 3D APT. A one-dimensional explicit finite differences model was used to calculate the kinetics of the partitioning of carbon during the Q&P processing under CCE condition. This model was also applied to the partitioning kinetics of substitutional alloying elements during the partitioning treatment. A comparison between the experimental results and the model calculation confirmed the partitioning of substitutional elements.

2. Experimental procedure

The chemical composition of the steel used in the present study was Fe-0.21C-4.0Mn-1.6Si-1.0Cr (in wt. %). The M_s temperature of the steel was 273 °C. The microstructure of the industrially cold-rolled sheet steel prior to Q&P processing was complex, containing both deformed pearlite and martensite. The Q&P processing was carried out in a Bähr 805 pushrod dilatometer either in vacuum or in a He atmosphere. The specimens with dimensions of $10 \times 5 \times 1.2$ mm^3 were heated at a heating rate of +10 °C/s to 850 °C, fully austenitized for 240 s at 850 °C, initially quenched to a quenching temperature T_Q of 210 °C and held at 210 °C for 10 s. Subsequently, the specimen was reheated to a partitioning temperature T_P equal to 450 °C using a heating rate of +20 °C/s, held at T_P for 300 s, and finally quenched to room temperature. Both the initial and final quenching were done using He gas to obtain a cooling rate of −50 °C/s.

Based on previous studies [3], the quenching temperature T_Q which yields the maximum volume fraction of retained austenite was identified as 210 °C. The reason for the selection of this T_Q was that the formations of bainite and secondary martensite were not observe. If there had been a bainite transformation during the partitioning stage, this would have made it difficult to distinguish the contribution of the carbon enrichment from the bainitic ferrite into austenite during the bainite transformation, from the enrichment caused by the carbon partitioning from martensite. The optimum T_P and partitioning time t_P were also identified by means of dilatometry. The procedure is shown in Fig. 2. Fig. 2(a) shows the dilatometry traces for Fe-0.21C-4.0Mn-1.6Si-1.0Cr (in wt. %) quenched from 850 °C to 230 °C, and partition treated at a T_P temperature in the range of 250 °C–550 °C for 180 s. The volume expansion during the final quenching stage was due to the formation of secondary martensite. The secondary M_s temperature is indicated by the departure from the dotted line in Fig. 2(a). It is clear that the secondary M_s temperature was lowest for $T_P = 450$ °C. This suggests that the amount of carbon partitioned to retained austenite during the partitioning stage was highest for $T_P = 450$ °C. Selection of another T_P would result in a lower austenite stability, and a lower retained austenite fraction after Q&P processing. The selection of the optimal partitioning time t_P is illustrated in Fig. 2(b), which shows the relative sample length change in the final