

Atomic-scale analysis of carbon partitioning between martensite and austenite by atom probe tomography and correlative transmission electron microscopy

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Abstract

Carbon partitioning between ferritic and austenitic phases is essential for austenite stabilization in the most advanced steels such as those produced by the quenching and partitioning (Q&P) process. The atomistic analysis of the carbon partitioning in Q&P alloys is, however, difficult owing to the simultaneous occurrence of bainite transformation, which can also contribute to carbon enrichment into remaining austenite and hence overlap with the carbon partitioning from martensite into austenite. Therefore, we provide here a direct atomic-scale evidence of carbon partitioning from martensite into austenite without the presence of bainite transformation. Carbon partitioning is investigated by means of atom probe tomography and correlative transmission electron microscopy. A model steel (Fe–0.59 wt.% C (2.7 at.% C)–2.0 wt.% Si–2.9 wt.% Mn) with martensite finish temperature below room temperature was designed and used in order to clearly separate the carbon partitioning between martensite and austenite from the bainite transformation. The steel was austenitized at 900 °C, then water-quenched and tempered at 400 °C. Approximately 8 vol.% retained austenite existed in the as-quenched state. We confirmed by X-ray diffraction and dilatometry that austenite decomposition via bainite transformation did not occur during tempering. No carbon enrichment in austenite was observed in the as-quenched specimen. On the other hand, clear carbon enrichment in austenite was observed in the 400 °C tempered specimens with a carbon concentration inside the austenite of 5–8 at.%. The results hence quantitatively revealed carbon partitioning from martensite to austenite, excluding bainite transformation during the Q&P heat treatment.

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1. Introduction

Fundamental research on advanced steels is confronted with an increasing demand for realizing high-strength alloys that enable the design of highly fuel-efficient vehicles with maximum passive passenger safety [1,2]. One essential high-strength steel for applications in car bodies is the transformation-induced plasticity (TRIP) grade [3]. These steels contain retained austenite and hence show excellent

ductility. However, the tensile strengths of conventional low-carbon TRIP steels with microstructures consisting of ferrite, carbide-free bainite, retained austenite and small amounts of martensite generally do not exceed 1100 MPa [3–6]. This limitation is due to the fact that their ferrite volume fraction is normally too high so as to accumulate a sufficient amount of carbon into austenite during intercritical annealing and following austempering to obtain stable retained austenite. In order to achieve a higher strength level above 1100 MPa while maintaining high ductility, several novel steels that utilize retained austenite have been developed in the last decade, such as nanocrystalline

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bainitic steel (or super bainite) [7,8], maraging-TRIP steel [6,9,10] and quenching and partitioning (Q&P) steel [11,12].

Q&P steels yield an excellent balance of high tensile strength and good elongation with similar chemical compositions as conventional TRIP steels [12]. They are produced via the Q&P process which consists of a quenching and a partitioning step. In the quenching step, fully austenitized or intercritically annealed steels are quenched to temperatures (hereafter referred to as the “quench temperature”) below the martensite start (M_s) temperature but above the martensite finish (M_f) temperature in order to form a controlled volume fraction of martensite. The quenched steels are then held at the same or higher temperatures than the quench temperature during the subsequent partitioning step. Austenite that prevails after quenching is considered to be stabilized through carbon partitioning from martensite into the austenite during the partitioning treatment. The resultant microstructures of the steels mainly consist of tempered martensite and retained austenite so that a higher strength can be achieved as compared to conventional TRIP steels.

Carbon partitioning between ferritic and austenitic phases is essential for all austenite stabilization phenomena in most advanced steels such as those encountered in the Q&P process. The atomistic analysis of carbon partitioning in Q&P alloys is, however, challenging owing to the overlap of several competing phenomena during the partitioning step. It has been suggested that the carbon partitioning from martensite into austenite is controlled by the constrained carbon equilibrium (CCE) criterion [11]. This criterion aims at predicting the carbon concentration in austenite under the condition that (1) an identical carbon chemical potential exists in both ferrite (or martensite) and austenite; and that (2) the atomic balancing proceeds under the assumption that the interface between ferrite and austenite does not migrate. Therefore, this model does not account for the volume expansion frequently observed during the partitioning step [13–17]. Possible reasons, as mentioned by Santofimia et al. [16], to explain the volume expansion are the bainite transformation [15–18] or the migration of martensite/austenite interface [14–16,19,20], in cases where the partitioning temperature is above the M_s temperature. The bainite transformation can also contribute to carbon enrichment into the remaining austenite if carbide precipitation is suppressed, for example, through the addition of Si [21]. The migration of the martensite/austenite interface should also have some influence on carbon enrichment into austenite [20]. Therefore, it is essential to separate the contributions to the carbon enrichment into austenite during the Q&P heat treatment caused by the carbon partitioning from martensite (addressed in this work) from that caused by the other possible mechanisms mentioned above (excluded from this work). Such knowledge is not only important for the further understanding of the Q&P process but also for the more precise prediction of microstructures and

resultant mechanical properties of other advanced high-strength steels.

The Q&P process has mainly been applied to steels with chemical compositions similar to those of conventional TRIP steels [12,15]. In such steels, bainite formation is practically unavoidable [15] as the chemical compositions are designed to promote bainite formation during austempering in the same temperature range as the partitioning step. This makes it difficult to distinguish the contributions to carbon enrichment into austenite during the partitioning step caused by the bainite transformation from that caused by the carbon partitioning from martensite. Recently, Santofimia et al. [16] tried in an elegant study to address this point by separating the contributions of these two phenomena using a high Ni and Cr containing steel to avoid bainite transformation. The data, however, seem to indicate that the face-centered cubic (fcc) to body-centered cubic (bcc) transformation could not be entirely suppressed during partitioning as a slight volume expansion of the specimens was observed. Bigg et al. [22] reported on carbon enrichment into austenite without the occurrence of bainite transformation by means of in situ neutron measurement during reheating an as-quenched martensite containing ~30 vol.% austenite. However, up to now there is no direct atomic-scale evidence of carbon partitioning from martensite into austenite without the interference of bainite.

Therefore, this study aims at providing direct atomic scale evidence of carbon partitioning from martensite into austenite during a Q&P heat treatment excluding the bainite transformation. Carbon partitioning is investigated in detail by means of atom probe tomography (APT) [23–32] and correlative transmission electron microscopy (TEM), conducted directly on APT samples.

2. Experimental procedure

2.1. Model alloy design and processing

For separating carbon partitioning between martensite and austenite from bainite transformation and/or interface migration, a chemical composition with M_s and M_f temperatures, respectively, above and below room temperature was selected. Fig. 1 shows the comparison between (a) the heat treatment applied in this study and (b) a general Q&P heat treatment. The bottom figures schematically show the relationship between partitioning time and retained austenite (γ) volume fraction as measured by, for instance, X-ray diffraction (XRD) at room temperature after cooling from the partitioning temperature (PT). In the case of the general Q&P heat treatment (Fig. 1b), the remaining austenite at the quench temperature (QT) is unstable at room temperature so that the retained austenite volume fraction before partitioning treatment, which is measured at room temperature, is almost zero. Therefore, the exact amount of austenite remaining at the quench temperature can generally not be measured and hence has to be estimated, for instance, by using the Koistinen–Marburger

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