



# Influence of alloying elements on the microstructure evolution and mechanical properties in quenched and partitioned steels

N. Maheswari<sup>a</sup>, S. Ghosh Chowdhury<sup>b</sup>, K.C. Hari Kumar<sup>a</sup>, S. Sankaran<sup>a,\*</sup>

<sup>a</sup> Department of Metallurgical and Materials Engineering, Indian Institute of Technology Madras, India

<sup>b</sup> CSIR – National Metallurgical Laboratory, Jamshedpur, India

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## ABSTRACT

Quenching and partitioning (Q&P) is one of the most promising heat treatment processes to produce microstructure in steels which contains martensite and high fraction of retained austenite. In the present study, three newly designed steels (A–C) were produced by casting with varying amounts of C, Mn, Si and Al and then subjected to the quenching and partitioning (Q&P) treatment. Microstructural investigation revealed that all the three steels were characterized by two phase microstructure comprising of lath martensite and austenite (interlath film and blocky morphology) as constituents. All the three steels contained almost similar volume fraction of retained austenite in it (0.15–0.18) irrespective of variation in the alloying content. The microstructure of the steel with lowest amounts of C, Si and highest amount of Mn (steel C) contained the finest martensite laths, high fraction of interlath austenite films with high austenite contiguity ratio in comparison with the other two steels (A and B). It also exhibited best strength (882 MPa)–toughness (188 MJ) combination. Austenite fraction analysis on the tensile tested samples suggested that in all three steels a significant percentage (35–50) from the total retained austenite undergo strain induced transformation to martensite. The study suggests that the Q&P steels are very sensitive to small variation in the chemical composition with respect to microstructural features and consequently mechanical properties, although fraction of microstructural constituents does not change significantly.

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## 1. Introduction

Processing of steels with low density, high strength with improved ductility has been increasingly important in automobile industries for the past few decades. In order to meet these demands there have been attempts to arrive at new alloy design and processing methods which are different from the processing routes of producing advanced high strength steels (AHSS) that include dual phase, TRIP, TWIP steels, etc. Speer et al. introduced one of the most promising heat treatment process called “quenching and partitioning (Q&P)” to improve the strength without adversely affecting ductility of high strength steels by producing the steel microstructure with martensite and high fraction of retained austenite [1]. The process involves quenching the fully/partially austenitized steel at a temperature between martensite start ( $M_s$ ) and martensite finish ( $M_f$ ) temperature, followed by the carbon partitioning treatment at a temperature which is slightly below the  $M_s$  temperature. Hence, by selecting the appropriate

heat treatment cycle the desired final microstructure can be obtained.

In the conventional tempering process of the quenched steel the martensite and the retained austenite decompose to ferrite and carbide [2]. In Q&P steels the final desired microstructure constituents are martensite and austenite. Strength–ductility combination is decided by their relative amounts and morphology. While martensite is beneficial for strength, austenite promotes ductility. Keeping this in view, most Q&P steels contain Mn (0.3–3.5 wt%), C (0.17–1 wt%), Al (0.006–1.9 wt%), and Si (0.3–3 wt%) as alloying elements [1–10]. Since Mn and C are austenite stabilizers and they significantly lower the  $M_s$ , presence of these will ensure sufficient retained austenite in these steels. Presence of alloying elements such as Si and Al inhibit the formation of carbides, instead they promote diffusion of carbon from the martensite to the retained austenite thus enhances the stability of the latter. However, if the silicon content is very high (> 2 wt%) it may result in promoting transition carbides [11].

The primary reason for the carbon migration from martensite to retained austenite is its high solubility in the latter [3,4]. Bhadeshia and Mujahid studied the thermodynamics of the carbon partitioning from a supersaturated ferrite to austenite phase by

\* Corresponding author.

E-mail address: [ssankaran@iitm.ac.in](mailto:ssankaran@iitm.ac.in) (S. Sankaran).

considering the paraequilibrium between the two phases [5]. Later a model called ‘constrained carbon equilibrium’ (CCE) was developed by Speer et al. [1], to describe the endpoint of partitioning of carbon from supersaturated ferrite to retained austenite. It was suggested that (i) only carbon atoms diffuse faster through an immovable (constrained) interface between martensite and austenite as compared to the substitutional atoms, and (ii) at the end of partitioning the chemical potential of carbon in two phases becomes equal and the fraction of the two phases is conserved [1,6].

Cai et al. reported a high tensile strength (1050 MPa) with high elongation (25%) in quenched and partitioned alloy steel containing C, Si, Mn, Al, P and S [12] after full austenitization. Santofimia et al. studied the effect of quenching and partitioning treatment after intercritical annealing in a low carbon (0.2 wt%) steel by varying the Si and Al content and keeping the Mn content constant [10]. The partitioning effect was studied in bainite microstructure on TRIP steels [13]. The steels with strength varying from 800 to 1000 MPa and 10% to 25% elongation were studied by Moor et al. [14]. However, effect of alloying elements on the microstructure and resulting mechanical properties of Q&P steels is still not clear.

In the present work, three different steel compositions were chosen as shown in Table 1 based on the chemistry of reported Q&P steels [1–10], keeping in mind the physical metallurgy aspects as discussed above. One of the aims in the present study is to identify the alloy chemistry with minimum number of alloying elements (C, Si, Mn and Al) that retains highest fraction of austenite and gives best combination of strength and ductility. The mechanical properties were evaluated through tensile tests and the microstructure–mechanical properties relationships are reported.

## 2. Experimental

### 2.1. Casting of steels and Q&P treatments

The three selected steels were induction melted and casted in the form of ingots. The compositional analysis was carried out on the as-cast samples using inductively coupled plasma optical emission spectrometer (ICP-OES). From the as-cast ingot, small specimens with dimensions of 25 × 25 mm<sup>2</sup> were cut-out for Q&P heat treatment.

The upper critical temperature ( $A_{e3}$ ) for the three steels was calculated using the MatCalc software in combination with a Gibbs energy database for steels [15]. While the  $M_s$  temperature of the three steels was calculated using an empirical relation (Eq. (1)), the austenite fraction in the quenched steels was calculated using the Koistinen–Marburger relationship (Eq. (2)) [8].

$$M_s(^\circ\text{C}) = 539 - 423C - 30.4\text{Mn} - 7.5\text{Si} + 30\text{Al} \quad (1)$$

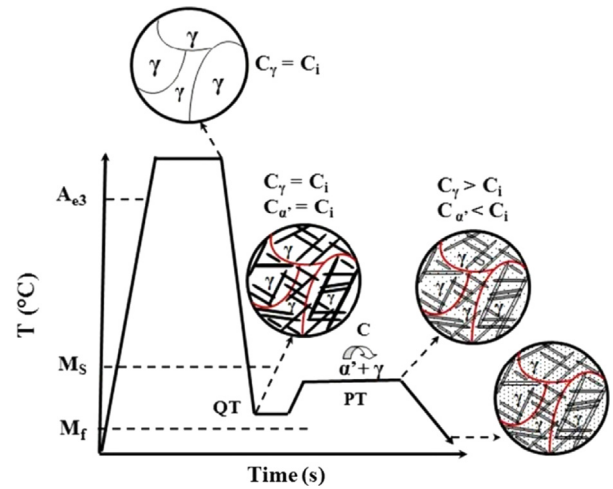
$$f_m^{\text{QT}} = 1 - e^{-1.1 \times 10^{-2}(M_s - \text{QT})} \quad (2)$$

The three steels with different chemical composition are designated as Q&P steel–A, B, and C. These were fully austenitized in a tubular furnace at 1060/1000 °C for 1 h and all the austenitized steel

**Table 1**  
Chemical composition (wt%) and critical temperatures of Q&P steels.

Notation	C	Mn	Si	Al	$A_{e3}$ (°C)	$M_s$ (°C)
Steel A	0.29	1.22	1.65	1.62	1028	416
Steel B	0.26	1.57	1.06	0.98	910	403
Steel C	0.22	1.85	0.41	1.46	950	430

$A_{e3}$  – upper critical temperature;  $M_s$  – Martensite start temperature by using Eq. (1) [8].



**Fig. 1.** Schematic of Q&P heat treatment schedule.  $C_i$ ,  $C_{\alpha'}$ ,  $C_\gamma$  are the carbon concentrations in the initial alloy, martensite and austenite respectively. QT – quench temperature; PT – partitioning temperature.

specimens were quenched in a salt bath furnace at 240 °C for 20 s. The partitioning treatment was carried out by reheating the steels in another muffle furnace to 350 °C for 1 min in order to promote the carbon partitioning. Finally the steels were water quenched. The schematic of the heat treatment schedule is shown in Fig. 1. It is important to note that most previous studies [7,9–14] involved intercritical annealing prior to Q&P treatment; the microstructure would consist of ferrite and cementite in addition to austenite–martensite phases. Therefore, in our present study the Q&P heat treatment was scheduled only after full austenitization to make sure the resulting microstructure contains only retained austenite and martensite.

### 2.2. Microstructural characterization

The X-ray diffraction (XRD) analysis was performed using the X’Pert Pro PANalytical machine, on the three polished Q&P steel (A, B, and C) specimens and the three tensile tested Q&P specimens with the  $2\theta$  scan range from 35° to 105° with the step size of 0.05° using Cu-K $\alpha$  radiation. The Reitveld refinement method in the X’Pert High Score Plus software was used to estimate the volume fraction of retained austenite from the XRD data.

The Q&P steel specimens were polished through standard metallographic techniques and etched with 2% Nital solution for the field emission scanning electron microscope (FEI QUANTA-400 FESEM) studies. Quantitative metallographic studies on the microstructures were performed using the procedures given in Eqs. (3)–(5) [16]. The average martensite colony size or mean intercept length  $\bar{L}_\alpha$ , was calculated by the line intercept method (Eq. (3)). The grain boundary surface area per unit volume of the martensite–martensite ( $S_V$ )<sub>M–M</sub> and austenite–austenite ( $S_V$ )<sub>A–A</sub> boundaries was estimated by using Eq. (4). The contiguity ratio or connectivity between austenite boundaries ( $C_A$ ) was calculated using Eq. (5) and it varies between 0 and 1.

$$\bar{L}_\alpha = 2P_p/P_L \text{ (}\mu\text{m)} \quad (3)$$

$$S_V = 2P_L \text{ (}\mu\text{m}^{-1}\text{)} \quad (4)$$

$$C_M = \frac{2(P_L)_{M-M}}{(P_L)_{A-M} + 2(P_L)_{M-M}} \quad (5)$$

where  $P_L$  is the number of intersections per unit length ( $\mu\text{m}^{-1}$ ).

For the transmission electron microscope (TEM) investigation the Philips-CM 12 TEM machine operating at 120 kV was employed.

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