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Effect of partial and full austenitisation on microstructure and mechanical properties of quenching and partitioning steel

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ABSTRACT

A novel high-strength steel has been made through thermo-mechanical controlled processing with the finish rolling temperature of 750 °C followed by air cooling. Subsequently, both partial austenitisation at 800 °C and fully austenitisation at 930 °C have been attempted for equal duration of 30 min prior to one step quenching and partitioning (Q&P) at 345 °C below M_S temperature (365 °C). As-rolled steel reveals ferrite-bainite-martensite microstructures with a good combination of strength and ductility. After Q&P, all the specimens have exhibited the multiphase microstructures comprising ferrite, lath microstructure (martensite and bainite), and retained austenite with the volume fractions of up to 10.50 wt%. It is evident that partitioning for 30 min leads to good carbon enrichment (> 1 wt%) of the austenite phase from the neighbouring martensite or bainite which might be due to fast partitioning kinetics and possible suppression of carbides through a combination of Si and Al additions. The attractive combination of tensile strength (921–922 MPa) and ductility (25–26% total elongation) along with low yield ratio (0.63–0.69) are attributed to ferrite and lath microstructures along with the thin film like carbon enriched retained austenite obtained after Q&P process.

1. Introduction

In recent years, there has been an increased emphasis on the development of new advanced high strength steels (AHSS) in order to reduce vehicle weight and consumption of raw materials as well as to maintain or even improve safety standards in the automobile industries. In this context, there has been increased demand for the development of complex phase or multiphase steels having ferrite-bainite-martensite microstructure with significant amount of retained austenite, thereby manifesting high combination of strength and ductility [1]. As a critical component of main commercial steels, a certain amount of retained austenite can potentially increase ductility [2,3] and toughness [4]. These are attributed to the transformation induced plasticity (TRIP) phenomenon of carbon-enriched retained austenite during plastic deformation [5]. To obtain a certain amount of carbon-enriched retained austenite in steel at room temperature, the traditional method is to increase the carbon content in steel to reduce the martensite start (M_S) temperature below room temperature [6]. However, high carbon content in steel is detrimental to ductility and weldability [7]. In this regard, a fundamentally new heat treatment named quenching and partitioning (Q&P) has been proposed [8,9] to create advanced high strength multiphase steels with a controlled amount of carbon-enriched retained austenite at room temperature. The quenching step was performed to form specific fraction of supersaturated martensite and retained austenite by fast quenching below the M_S temperature but above the martensite finish (M_f) temperature. A subsequent partitioning treatment at the quenching temperature below the M_S temperature (one-step treatment) or above the M_S temperature (two-step treatment) was employed to accomplish complete diffusion of carbon from martensite to retained austenite in the absence of carbide precipitation by alloying with appropriate amount of Si and/or Al. Finally, the carbon-enriched austenite was mostly retained at room temperature. It is well known that Si significantly restricts the formation of cementite because its solubility is incredibly low or even near zero in cementite phase [10]. However, alloying with certain amount of Si is ineffective to inhibit formation of epsilon carbide [11,12]. Therefore, it is possible to form lower bainite (bainitic ferrite plus ε-carbide) rather than carbide-free bainite during the partitioning process [13]. Al which is a typical alloying addition to transformation-induced plasticity (TRIP) steel, is employed to suppress carbide formation during partitioning and as a consequence, substantial fraction of carbon

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enriched retained austenite is produced [14]. According to Wang and Chang [15], Al also improves the anti-corrosion behaviour by forming Al_2O_3 layer on the surface.

However, experimental investigations with partial and fully austenitisation can improve our understanding of the Q&P process for adjusting and tailoring the required mechanical properties of Q&P steels. The studies on the relationship between microstructure and mechanical properties of high strength steels during the one-step Q&P process are limited [16]. It is reported that one step Q&P process is achieving high strength level of 700–2400 MPa with adequate ductility of 10–20% [16–18]. This combination of mechanical properties can be achieved by multiphase microstructure consisting of mostly lath martensite, bainite and retained austenite enriched with carbon. It appears that enough attention has not been paid to the fact that martensite being the matrix of steel makes a major contribution to the mechanical properties [19]. So investigation on the microstructure-properties relationship in Q&P steel is still open. The strategy of Q&P process is to make cost effective steel with high tensile strength and good ductility. However, to fulfil this requirement several processing parameters like austenitisation temperature (A_T), cooling rate (CR), quenching temperature (Q_T) and partitioning time (P_T) should be optimised.

In view of the above, steel with somewhat different chemistry from conventional TRIP-assisted steel was chosen for superior mechanical properties and corrosion resistance [20,21] by alloying with copper, nickel and cobalt for potential structural applications in motor vehicles, high-rise buildings, power plants, refineries, industrial sheds, ware houses etc. [22]. In addition, alloying with Si and Al was employed to achieve carbon depletion from supersaturated martensite to austenite by restraining carbide precipitation during partitioning process. The improved mechanical properties resulting from Q&P processing were discussed based on the multiphase microstructure along with retention of carbon enriched austenite and compared with the current generation Q&P steels.

2. Experimental procedures

A laboratory scale 25 kVA air induction furnace was used to manufacture the steel with the chemical composition as shown in Table 1. After cropping the top section of the ingot containing shrinkage/pipes, the remaining portion of 200 mm × 50 mm × 50 mm size was hot forged down to about 19 mm × 19 mm cross section. After that, the Ac_1, Ac_3 and M_S temperatures were measured as 725 °C, 830 °C and 365 °C respectively, by a Gleeble 1500D LVDT type dilatometer using cylindrical hollow samples of 1 mm wall thickness. At first the samples were heated at a heating rate of 10 °C/s at 1000 °C and soaked for 5 min, and then cooled under constant rate of 20 °C/s to room temperature. The experiments were carried out under argon atmosphere. The complete dilatometric curve of investigated steel is shown in Fig. 1. The T_{NR} temperature of the investigated steel had been experimentally measured to be as 933 °C [21].

The forged bars were soaked at 1200 °C and subsequently subjected to TMCP with 750 °C finish rolling temperature (FRT) according to the laboratory scale schedule as mention in Fig. 2 using two-high rolling mill (10 HP) and finally the rolled plates

Table 1
Chemical composition (wt%) of the investigated alloy.

C	Mn	Si	Al	Cu	Ni	Co	S	P	Fe
0.20	1.65	1.40	1.50	1.30	1.05	1.07	0.006	0.014	Bal.

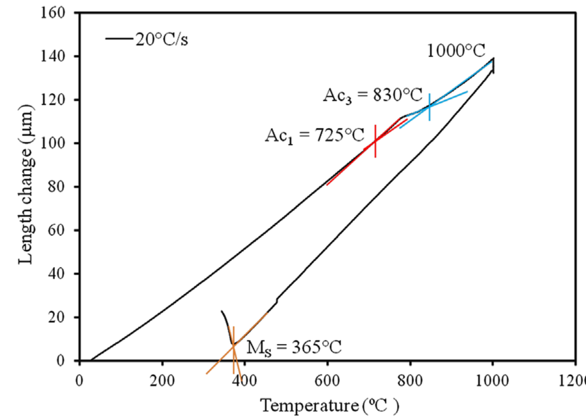

Fig. 1. Complete dilatometric curve of the investigated steel showing Ac_1, Ac_3 and M_S temperatures.

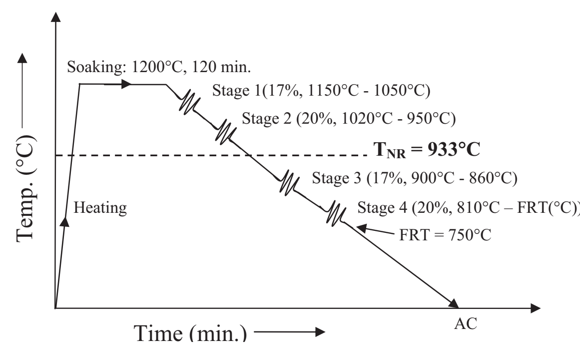

Fig. 2. Schematic illustration of Thermo-Mechanical Controlled Processing (TMCP) schedule. FRT stands for Finish Rolling Temperature.

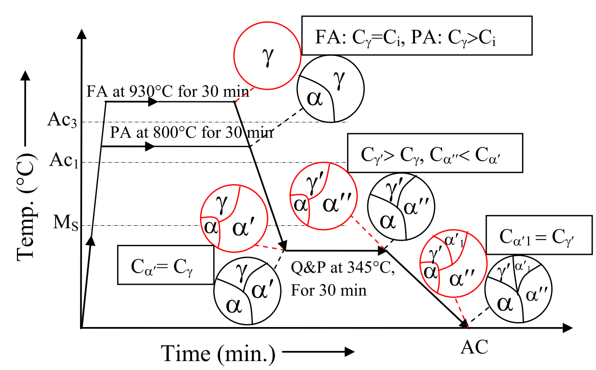

Fig. 3. Schematic illustration of the thermal profile and phase transformation behaviour of Q&P steel. C_i, C_γ, $C_{\alpha'}$, $C_{\gamma'}$, $C_{\alpha''}$ and $C_{\alpha'1}$ represent the carbon concentrations of the initial alloy, austenite, martensite, retained austenite, partitioned martensite and martensite formed during cooling after partitioning, respectively. FA and PA stand for full austenitisation and partial austenitisation.

($\approx$ 8 mm) were allowed to air cooling (AC). The TMCP samples were treated by Q&P processes, as shown in Fig. 3. All samples were subjected to partial austenitisation (PA) at 800 °C and full austenitisation (FA) at 930 °C temperatures with the same holding time of 30 min, followed by rapid quenching in a salt bath maintained at 345 °C below M_S temperature (365 °C) and partitioning at the same temperature for 30 min. After partitioning treatment, all specimens were air cooled to room temperature. In this context, it is noteworthy that the earlier researchers followed the partitioning time less than one minute to avoid formation of bainite as well as epsilon carbide during Q&P treatment, thereby getting maximum retained austenite. Bhadeshia et al. [23] reported that