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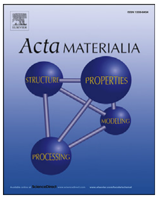

Full length article

The significance of multi-step partitioning: Processing-structure-property relationship in governing high strength-high ductility combination in medium-manganese steels

S. Liu [a, b], Z. Xiong [a], H. Guo [a], C. Shang [a, *], R.D.K. Misra [b]

[a] Collaborative Innovation Center of Steel Technology, University of Science and Technology Beijing, 30 Xueyuan Road, Beijing, 100083, China
[b] Laboratory for Excellence in Advanced Steel Research, Materials Science and Engineering Program, Department of Metallurgical, Materials and Biomedical Engineering, University of Texas at El Paso, 500 W. University Avenue, El Paso, TX 79968, USA

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ABSTRACT

Intercritical annealing, flash process and tempering were innovatively combined to obtain high strength-high ductility combination in 0.12C–4.89Mn-1.57Al steel. The process referred as multi-step partitioning (MSP) was designed to accomplish the following objectives: (a) enrichment of austenite with Mn to enhance the stability of retained austenite, (b) transformation hardening during quenching in the flash process and (c) stress relaxation and carbon enrichment of retained austenite. The tensile strength of steel increased from ~667 MPa in intercritically annealed steel to ~986 MPa in flash processed steel. The product of strength and elongation of flash steel and tempered steel were 23.2 GPa•% and 24.9 GPa•%, respectively and higher than the intercritically annealed steel (21.3 GPa•%). The high ductility, especially the uniform elongation of flash steel (16.2%) and tempered steel (19.4%) is attributed to ~15–19% by volume of Mn-rich stable retained austenite and efficient TRIP (transformation induced plasticity) effect. Thermodynamic calculations enabled us to understand the partitioning behavior of alloying elements in MSP. C, Mn and Al reverse partitioning during the flash process led to increased stability of retained austenite. The unique distribution of chemical constituents contributed to two types of martensitic transformation during the flash process: (a) austenite → α'-martensite transformation dominated at high temperature and contributed to the formation of stacking faults and ε-martensite transformation and (b) austenite → ε-martensite → α'-martensite phase transformation dominated at lower temperature. The stability of retained austenite and interaction with stress concentration contributed to highly efficient TRIP effect in flash processed and tempered steel. The experiment findings were consistent with the diffusion-controlled transformation simulation analysis.

1. Introduction

The motivation to increase strength and ductility of steels is driven by increased demand in automotive and mechanical sector. Excellent mechanical properties can be obtained through TRIP/TWIP (transformation-induced plasticity/twinning-induced plasticity) effect and is now widely acknowledged [1–11]. Intercritical annealing was used to obtain stable austenite in medium-Mn steel [1–3]. In our previous studies [4–6], two step intercritical annealing was used to obtain stable austenite in low alloy steel through enrichment with austenite stabilizing elements. However, the decrease in strength induced by annealing for longer times was difficult to compensate. Quenching and partitioning (Q&P) treatment enabled high strength martensite matrix and stable retained austenite in 0.2–1.0-wt.% carbon steel, while the stability of retained austenite was ensured by carbon during the partitioning process [7–9]. Long term isothermal heat treatment at bainite transformation temperature [10,11] utilized carbon partitioning concept to obtained stable retained austenite in very strong bainite steel. Both Q&P steel and very strong bainite were successful in improving the strength. However, the stability of retained austenite can be significantly enhanced via intercritical annealing by enriching austenite with C, Mn and Ni during intercritical annealing, at relatively higher temperatures. In this regard, we propose

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* Corresponding author.
E-mail addresses: cjshang@ustb.edu.cn (C. Shang), dmisra2@utep.edu (R.D.K. Misra).

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here a new heat treatment process that combines intercritical annealing, flash process and tempering to accomplish the following objectives: (a) enrich austenite with Mn to enhance the stability of retained austenite, (b) utilize the benefit of transformation hardening by quenching in the flash process and (c) relax stress and enrich retained austenite with carbon. The approach was applied to 0.12C-4.89Mn-1.52Al (wt.%) experimental steel, and excellent mechanical properties were obtained. The flash process involves rapid heating and cooling and has been used before [12–14], but heating and cooling rates were lower, and the objective was different.

The combination of intercritical annealing and flash process led to inhomogeneous distribution of alloying elements, such that the phase transformation during the flash process was significantly different from phase transformation during traditional quenching. Two types of martensite were observed in flash processed and tempered steels because two types of martensite transformation occurred. Thermodynamic calculations and DICTRA were used to study the partitioning behavior of alloying elements during the flash process and tempering. The simulated results are in a good agreement with the experimental findings. Stacking fault energy was calculated to further understand the phase transformation mechanism. The unique distribution of alloying elements and interaction with stress concentration led to an efficient TRIP effect.

2. Experimental procedure

The nominal chemical composition of multi-phase steel was Fe-0.12C-4.89Mn-1.52Al (in wt.%). The steel was alloyed with C and Mn to increase strength and stability of retained austenite, while Al was added to prevent cementite precipitation. Low carbon design was selected from the viewpoint of welding. There is, however, a need to optimize Mn-content since 5 wt% Mn increases the carbon-equivalent by 0.82. The volume fraction of BCC (body centered cubic) and FCC (face centered cubic) phases and concentration of alloying elements in FCC with temperature in the experimental steel were calculated by Thermo-calc to facilitate the design of heat treatment (Fig. 1). As shown in Fig. 1a, Ac_3 temperature of experimental steel was 900 °C. Austenitization and flash temperatures were selected based on Ac_3. Between 500 °C and 900 °C, the volume fraction of austenite increased with temperature. In this temperature range, the concentration of Al in austenite increased with temperature and Mn decreased with temperature, while C concentration peaked at ~650 °C, decreased with temperature above 650 °C, and increased with temperature below 650 °C (as shown in Fig. 1b). Thus, 650 °C was selected as the intercritical annealing temperature. At this temperature, 23.8% of austenite and 76.2% of ferrite were obtained after holding for a long time, while Mn, Al and C concentration in austenite were 11.5%, 0.85% and 0.5% (Fig. 1b).

The experimental steel was melted in vacuum and cast into ingots of ~80 mm thickness. The ingots were homogenized at 1200 °C for 2 h, and hot rolled to 12 mm thick strip using several passes with minimum reduction of 20% per pass. Using these homogenization temperature and time conditions, C- and Mn-segregation was not observed. Tensile samples were machined parallel to the rolling direction. The experimental heat treatment process simulates the actual hot strip condition and therefore can be widely used. A schematic of the heat treatment process is presented in Fig. 2 and consisted of austenitization at 960 °C for 30 min and water-quenched (Q), intercritical annealing at 650 °C for 6 h and quenching in water (L), reheating to 900 °C (at heating rate of 10 °C/s) then quenching in water (named flash process, F), tempering at 300 °C for 30 min (T). A low heating rate was used to ensure complete homogenization of carbon. Thus, the designed multi-step partitioning treatment essentially consisted of 3 steps namely intercritical annealing, flash process and tempering. First, austenitization and quenching led to lath-martensite matrix. The

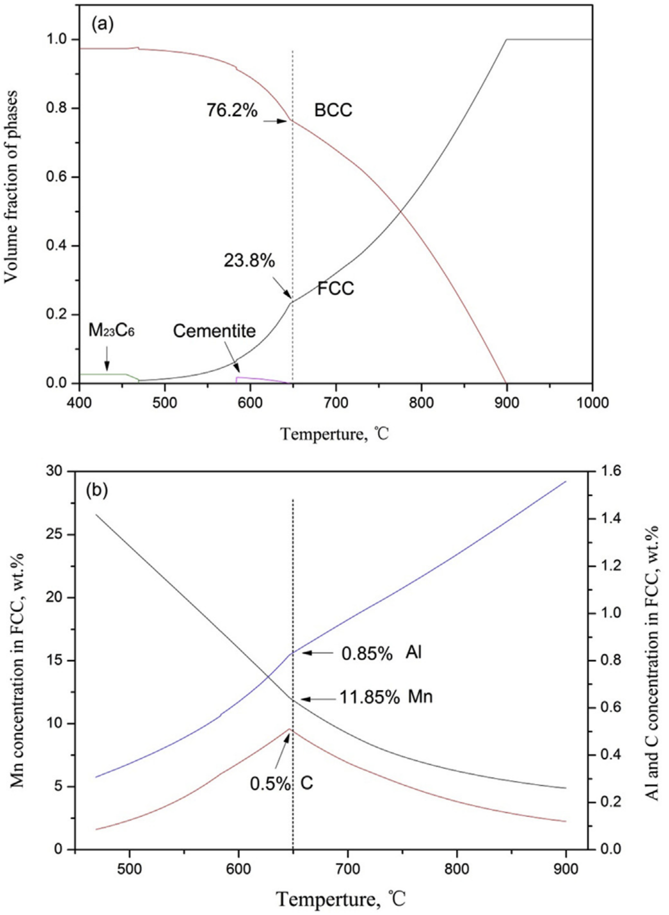

Fig. 1. (a) Temperature-volume fraction phase diagram, and (b) concentration od alloying elements (Mn, Al and C) in FCC as calculated by Thermo-calc.

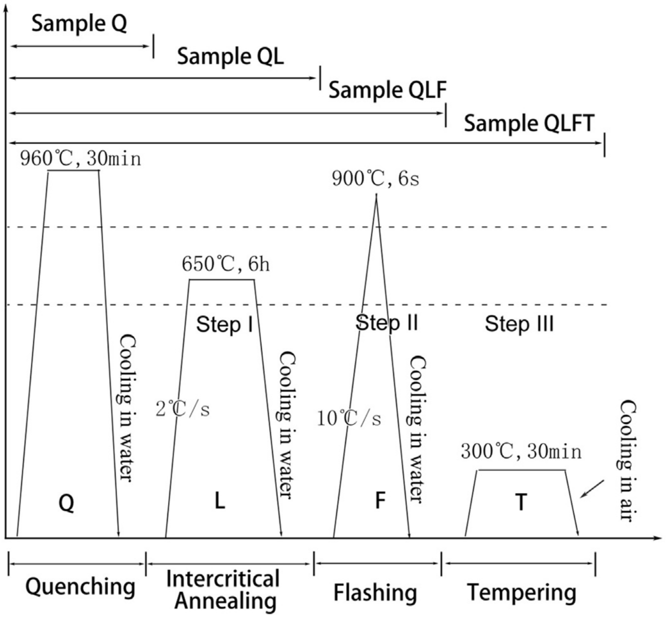

Fig. 2. Schematic diagram of the heat treatment.