Effect of Pre-Mn Partitioning Treatment on Carbon Partitioning and Retained Austenite in Q&P Steel Postprint

Authors: Chen Liansheng, Zhang Jianyang, Tian Yaqiang, Song Jinying, Xu Yong, Shihong Zhang

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Abstract

Using low-carbon Si-Mn steel as the research material, the pre-Mn partitioning behavior was investigated via an intercritical annealing-quenching (IQ) process, and the partitioning phenomenon was characterized. The effects of pre-Mn partitioning treatment on C partitioning, retained austenite, and mechanical properties in low-carbon high-strength Q&P-treated steel were examined using quenching-partitioning (Q&P) and intercritical annealing-austenitizing-quenching-partitioning (I&Q&P) heat treatment processes. The results indicate that during intercritical annealing, C and Mn continuously diffuse into austenite, and after quenching, C and Mn exhibit significant enrichment in martensite (original intercritical austenite). After I&Q&P processing, Mn enrichment in the room-temperature microstructure remains pronounced, while C enriches between martensite laths. With increasing C partitioning time, the tensile strength of the experimental steel continuously decreases, while the elongation first increases and then decreases. At a C partitioning time of 90 s, the steel processed by I&Q&P achieves a product of strength and ductility of 23478 MPa • %. In the I&Q&P process, pre-Mn partitioning treatment enables the experimental steel to retain more austenite during the first quenching, and subsequent C partitioning promotes the diffusion of more C atoms into this austenite, thereby obtaining more retained austenite after the second quenching to room temperature. The volume fraction of retained austenite stabilized by the combined effect of C and Mn in the I&Q&P process increases by approximately 2.4% at most compared to that stabilized by C partitioning alone in the Q&P process under the same conditions.

Full Text

Effect of Mn Pre-Partitioning on C Partitioning and Retained Austenite in Q&P Steels

CHEN Liansheng[1], ZHANG Jianyang[1], TIAN Yaqiang[1], SONG Jinying[1], XU Yong[1],[2], ZHANG Shihong[2]
[1] Hebei Key Laboratory of Modern Metallurgy Technology, Hebei United University, Tangshan 063009, China
[2] Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China

Abstract

The chemical compositions of carbon and manganese exert strong influence on the stability of metastable retained austenite at room temperature. During intercritical annealing, manganese enhances austenite stability through partitioning from ferrite to austenite, and Mn enrichment in austenite can further affect carbon diffusion from martensite to retained austenite during the partitioning process. Building upon carbon partitioning, manganese partitioning can additionally improve the product of strength and elongation without compromising the weldability of low-carbon high-strength steel. This effectively resolves the traditional conflict between mechanical properties and weldability in conventional quenching-partitioning (Q&P) processes. Consequently, investigating the mechanism of Mn pre-partitioning and its influence on carbon partitioning and retained austenite in low-carbon high-strength steel holds significant scientific importance.

This study examined a low-alloy C-Si-Mn steel to investigate Mn pre-partitioning behavior and its effects on carbon partitioning and retained austenite stability through intercritical heating-quenching (IQ), Q&P, and intercritical heating-austenitizing-quenching-partitioning (I&Q&P) processes. The results demonstrated that during intercritical reheating, carbon and manganese continuously diffused from ferrite to austenite, becoming enriched in austenite upon process completion. In I&Q&P treated steel, Mn enrichment remained evident in the room-temperature microstructure, while carbon exhibited regular enrichment between martensite laths.

With increasing carbon partitioning time in both Q&P and I&Q&P processes, tensile strength continuously decreased while elongation initially increased then decreased. The I&Q&P process achieved a strength-elongation product of 23,478 MPa · % at a carbon partitioning time of 90 s. Pre-Mn partitioning in the I&Q&P process retained more austenite during the first quenching stage, subsequently enabling more carbon atoms to diffuse into this austenite during carbon partitioning, thereby stabilizing greater amounts of retained austenite after the final quenching to room temperature. Under identical conditions, the combined effects of carbon and manganese partitioning in the I&Q&P process increased the volume fraction of stabilized retained austenite by approximately 2.4% compared to carbon partitioning alone in the Q&P process.

Keywords: Mn partitioning, C partitioning, retained austenite, product of strength and elongation

Introduction

With continuous advancement in steel metallurgy technology and rapid development of the automotive industry, modern steel grades must achieve high strength while simultaneously maintaining high ductility. Researchers [1,2] developed the quenching-partitioning (Q&P) heat treatment process, which produces a composite microstructure of martensite and retained austenite. During deformation, the martensite matrix provides ultra-high strength, while strain-induced martensitic transformation of retained austenite contributes to sustained ductility, representing the primary mechanism for achieving high strength and toughness in advanced high-strength steels.

Studies [3~7] have shown that controlling the retained austenite phase is the key factor determining the strength-ductility product in Q&P-processed steels. To obtain more retained austenite, the conventional approach involves increasing carbon content. However, elevated carbon content promotes extensive twinning during austenite-to-martensite transformation, increasing hardness while reducing ductility and toughness [8,9]. Excessive carbon also causes carbide precipitation, which reduces the carbon content in retained austenite and leads to its decomposition, representing another important cause of low ductility [10~12]. Furthermore, high carbon content increases hardenability, enlarging the heat-affected zone during welding and promoting weld cracking, thereby degrading weldability [13,14]. Conversely, reducing carbon content decreases the stability of retained austenite at room temperature [15].

Therefore, to ensure Q&P-processed steels possess both excellent mechanical properties and good weldability, investigating the use of other alloying elements to obtain more stable retained austenite, along with corresponding high-strength steel processing parameters, has become an urgent scientific challenge. Research [16~21] has found that Mn diffusion into austenite during intercritical annealing plays a significant role in enhancing austenite stability. For conventional Q&P processes, the intercritical heating-austenitizing-quenching-partitioning (I&Q&P) process, which incorporates pre-Mn partitioning, can significantly increase both the content and stability of retained austenite through combined carbon and manganese partitioning [22~24]. However, detailed investigations of Mn partitioning behavior and its effects on carbon partitioning and retained austenite in low-carbon high-strength steels remain limited.

Consequently, this work employed a low-carbon Si-Mn steel to investigate pre-

Mn partitioning behavior and characterize the partitioning extent using the intercritical heating-quenching (IQ) process. Comparative experiments using Q&P and I&Q&P heat treatments were conducted to clarify the influence of pre-Mn partitioning on carbon partitioning behavior, retained austenite morphology and content, and to reveal the synergistic effects of carbon and manganese in stabilizing retained austenite, providing a practical foundation for developing low-carbon high-strength high-ductility steels.

Experimental Procedures

The experimental steel had a chemical composition (mass fraction, %) of: C 0.17, Si 1.58, Mn 1.83, P 0.0032, S 0.0014, with Fe as balance. The material was melted in a 50 kg vacuum furnace, forged into 80 mm thick billets, homogenized at 1200 °C for 2 h in an RX3-90-12 high-temperature box furnace, then hot-rolled. The rolling began at 1100 °C with three passes to 55 mm thickness. After cooling to 950 °C, the material was further rolled in seven passes to a final thickness of 5 mm. Using dilatometry on a DIL805A/D high-temperature phase transformation analyzer, the near-equilibrium transformation temperatures were determined as $Ac_3 = 871$ °C, $Ac_1 = 730$ °C, and Ms = 330 °C (where Ac_3 is the temperature at which all pro-eutectoid ferrite transforms to austenite during heating, Ac_1 is the start temperature of pearlite-to-austenite transformation, and Ms is the start temperature of martensitic transformation during cooling).

[Figure 1: see original paper] presents schematic diagrams of the three different heat treatment processes. To investigate Mn diffusion behavior between ferrite and austenite during pre-Mn partitioning, samples were heated to 770 °C and held for 1800 s, then water-quenched to room temperature (IQ process, Fig. 1a). To study carbon partitioning behavior and its effect on retained austenite in the Q&P process, samples were austenitized at 900 °C for 180 s, rapidly salt-bath quenched to 220 °C (between Ms and Mf, where Mf is the final martensite transformation temperature) and held for 10 s, then reheated to 350 °C and held for various times (30, 90, and 180 s). During this holding period, carbon partitioning occurred, followed by final water quenching to room temperature (Q&P process, Fig. 1b). To investigate the effect of pre-Mn partitioning on carbon partitioning and retained austenite in Q&P steel, samples were first heated to the intercritical temperature of 770 °C for 1800 s to enable Mn partitioning from ferrite to austenite, then austenitized at 900 °C for 180 s. Subsequent processing followed the Q&P procedure (I&Q&P process, Fig. 1c) for direct comparison with the Q&P process.

Heat-treated samples were machined into flat tensile specimens with a gauge length of 25 mm and dimensions of 4 mm × 9.6 mm × 59 mm. Tensile testing was conducted according to national standard GB/T228-2002 on an INSTRON5969 universal testing machine at a strain rate of 10^{-3} s^{-1}. Microstructural observation was performed using an SSX-550 scanning electron microscope (SEM) on samples that were sectioned, ground, polished, and etched with 4%

nital solution (volume fraction). Carbon and manganese distributions in the room-temperature microstructure were examined using a JXA-8230 electron probe microanalyzer (EPMA) at 20 kV with a secondary electron resolution of 5 nm. Retained austenite morphology was characterized using a JEM-2010 transmission electron microscope (TEM). The volume fraction and average carbon content of retained austenite in the multiphase steel were analyzed using a D/MAX2500PC X-ray diffractometer (XRD) with Cu Kα radiation, scanning from 40° to 100° at 40 kV, 150 mA, a step size of 0.02°, and a scanning rate of 0.3°/min. To minimize texture effects and improve measurement accuracy, the five-peak method [25] was employed, selecting the austenite (200)γ, (220)γ, (311)γ and ferrite (200)α, (211)α diffraction peaks. The integrated intensities of these peaks were calculated to determine the volume fraction of retained austenite. The carbon content in austenite was calculated from the XRD data using the lattice constants a(200)γ, a(220)γ, and a(311)γ corresponding to each austenite diffraction peak, according to the following equation [26]:

$$\omega(\mathrm{C})\gamma = (\mathrm{a}\gamma - 0.35467) / 0.00467$$

where $\omega(\mathrm{C})\gamma$ is the mass fraction of carbon in austenite and aγ is the lattice constant of austenite for each peak (nm). Notably, the effects of Mn and Si on the austenite lattice constant are much smaller than that of carbon and were therefore neglected in this calculation.

Results and Discussion

3.1 Distribution of Carbon and Manganese After IQ Process

[Figure 2: see original paper] shows the initial microstructure of the hot-rolled experimental steel, consisting of pearlite (gray-white raised regions) distributed along ferrite grain boundaries within a ferrite matrix (black depressed regions). The pearlite colonies exhibited polygonal shapes with grain sizes of approximately 3 m.

[Figure 3: see original paper] presents the microstructure and EPMA maps of carbon and manganese distribution after IQ processing. As shown in Fig. 3a, the microstructure consists of martensite (raised regions) and ferrite (depressed regions), where the martensite formed from austenite generated during intercritical holding followed by rapid cooling. Figures 3b and c reveal the distribution of carbon and manganese, respectively, demonstrating significant partitioning of both elements into the austenite phase during holding at 770 °C for 1800 s. This austenitization process occurs in two stages: first, austenite forms within pearlite regions until complete dissolution, involving only carbon diffusion; second, the initially formed austenite grows by consuming surrounding ferrite until two-phase equilibrium is reached, involving diffusion of both carbon and manganese [20].

[Figure 4: see original paper] illustrates the compositional variation curves of carbon and manganese between the two phases after IQ processing. Carbon diffusion controls the transformation to para-equilibrium, resulting in average carbon contents of approximately 0.280% in austenite and 0.004% in ferrite. The average manganese contents in austenite and ferrite were approximately 2.8% and 1.2%, respectively.

3.2 Microstructure After Q&P and I&Q&P Processing

[Figure 6: see original paper] shows SEM images of the experimental steel after Q&P processing with different carbon partitioning times. The microstructure exhibits typical lath martensite. At a partitioning time of 30 s, well-defined martensite laths arranged in parallel packets are observed, with small misorientations between laths making the packet structure prominent (Fig. 6a). With increasing partitioning time, the straight lath morphology gradually transforms to a lenticular shape, lath tips change from perpendicular to acute angles, laths become disordered and significantly shorter, and lath boundaries become indistinct (Figs. 6b and c). This occurs because prolonged partitioning leads to carbide precipitation, consuming carbon atoms and weakening the carbon partitioning effect. Consequently, unstable retained austenite transforms to martensite during final quenching, and these newly formed martensite plates located between original laths increase impingement and collision, resulting in disordered and unclear lath structures [27].

[Figure 7: see original paper] presents SEM images after I&Q&P processing with varying carbon partitioning times. With increasing partitioning time, the parallel arrangement of martensite lath packets gradually disappears, lath length decreases, and boundaries become indistinct. Compared to Q&P-processed steel, blocky retained austenite appears in the I&Q&P microstructure, dispersedly distributed within the martensite matrix (Fig. 7a). At a carbon partitioning time of 90 s, the blocky retained austenite content reaches its maximum. This likely occurs because Mn enrichment in austenite significantly depresses the martensite start temperature (Ms), allowing Mn-rich regions to be retained after quenching to 220 °C. During carbon partitioning at 350 °C, these retained austenite regions become progressively enriched in carbon. At 90 s, the carbon content reaches its maximum, stabilizing the maximum amount of retained austenite at room temperature. Further increasing partitioning time leads to carbide precipitation, reducing carbon content in retained austenite and decreasing the amount of stabilized blocky retained austenite.

3.3 Retained Austenite and Mechanical Properties

[Figure 8: see original paper] shows TEM images and corresponding selected-area electron diffraction (SAED) patterns after Q&P and I&Q&P processing at a carbon partitioning time of 90 s. The microstructure consists of typical lath martensite and film-like retained austenite. In the Q&P-processed steel, the film-like retained austenite has a thickness of approximately 80 nm, with relatively sharp and straight interfaces between martensite and retained austenite. In contrast, the I&Q&P-processed steel exhibits film-like retained austenite with an average thickness of approximately 100 nm, significantly greater than that in the Q&P steel. Manganese is an austenite-stabilizing element that inhibits coarsening of martensite laths during carbon partitioning. In I&Q&P-processed steel, Mn segregation stabilizes more retained austenite [28] and suppresses migration of martensite-austenite interfaces, preventing decomposition of retained austenite and resulting in thicker retained austenite films. Additionally, carbon readily diffuses into Mn-rich regions, which is related to stacking faults in the structure. Increased Mn content promotes stacking faults in the fcc structure, and carbon atoms as interstitial solutes tend to segregate at stacking fault regions [29,30]. Therefore, regions with higher Mn content experience more extensive carbon diffusion, enabling more carbon to partition into retained austenite and stabilize larger amounts.

The experimental steel contained 1.58% Si (mass fraction), which increases carbon diffusivity, and contained no strong carbide-forming elements such as Nb or V, allowing more carbon to partition into retained austenite for stabilization.

[Figure 9: see original paper] shows XRD spectra of experimental steels after Q&P and I&Q&P processing with different partitioning times. The calculated retained austenite contents are listed in . For both processes, the volume fraction of retained austenite initially increases then decreases with partitioning time. For each process, the maximum retained austenite content occurs at 90 s, because increasing partitioning time raises carbon content and homogenization in retained austenite, improving its stability. At 90 s, the carbon content reaches its maximum, stabilizing the greatest amount of retained austenite. At 180 s, carbon homogenization is complete, and carbide precipitation consumes carbon in retained austenite, reducing its stability and causing partial transformation to martensite during final quenching, thereby decreasing retained austenite content. At 90 s, the Q&P-processed steel contained 11.2% retained austenite, while the I&Q&P-processed steel reached 13.6%, demonstrating that pre-Mn partitioning yields more retained austenite under identical carbon partitioning conditions.

presents the mechanical properties and retained austenite volume fractions after Q&P and I&Q&P processing at partitioning times of 30, 90, and 180 s. For each process, increasing partitioning time decreases tensile strength but increases then decreases elongation. During partitioning, carbon continuously diffuses from lath martensite to retained austenite, while small amounts precipitate as carbides. Research [31] indicates that martensite strength depends primarily on carbon content and supersaturated carbon in martensite; thus, carbon reduction softens martensite and decreases tensile strength. However, more carbon partitioning into retained austenite stabilizes more carbon-enriched retained austenite at room temperature, increasing elongation. Extended partitioning leads to carbide precipitation, reducing the volume fraction of stabilized retained austenite and decreasing elongation. At 90 s, the Q&P steel exhibited a tensile strength of 1326 MPa, elongation of 16.7%, and a maximum strength-elongation product of 22,144 MPa·%. The I&Q&P steel showed a tensile strength of

1319 MPa, elongation of 17.8%, and a maximum strength-elongation product of 23,478 MPa·%. Thus, under identical carbon partitioning time, I&Q&P processing yields lower tensile strength but higher elongation, resulting in superior strength-elongation product. Pre-Mn partitioning significantly improves the comprehensive properties of Q&P-processed steel.

3.4 Effect of Pre-Mn Partitioning on Carbon Partitioning in Q&P Steel

[Figure 10: see original paper] shows the average carbon content in retained austenite after Q&P and I&Q&P processing with different carbon partitioning times. For both processes, carbon content in retained austenite increases markedly with partitioning time and stabilizes, indicating carbon diffusion from martensite to retained austenite at 350 °C until reaching saturation, after which remaining carbon precipitates as carbides. At identical partitioning times, the carbon content in retained austenite is significantly higher in I&Q&P steel than in Q&P steel, demonstrating that pre-Mn partitioning facilitates carbon diffusion into retained austenite. Combining [Figure 9: see original paper] and [Figure 10: see original paper], when partitioning time increases from 90 s to 180 s, retained austenite content decreases from 11.2% to 9.0% in Q&P steel and from 13.6% to 10.4% in I&Q&P steel. However, the retained austenite exhibits the highest carbon content (0.92% in Q&P steel and 1.28% in I&Q&P steel), confirming that carbon-rich retained austenite possesses higher stability and only the highest-carbon retained austenite survives final quenching, while carbon-depleted austenite transforms to martensite.

3.5 Effect of Pre-Mn Partitioning on Retained Austenite Volume Fraction

Pre-Mn partitioning influences the stability of retained austenite in Q&P steel. Based on experimental results, Mn partitioning in austenite within the intercritical region affects austenite stability, which can be characterized by the martensite start temperature (Ms). The relationship between Ms and alloy content is given by [32]:

$$Ms = 539 - 423[C] - 30.4[Mn] - 7.5[Si] \quad (2)$$

where [C], [Mn], and [Si] represent mass fractions of carbon, manganese, and silicon, respectively.

The volume fraction of retained austenite (fRA) generated when quenching from the austenitizing temperature to a temperature T below Ms can be calculated using the Koistinen-Marburger (KM) formula [33]:

$$fRA = \exp[-0.011(Ms - T)] \quad (3)$$

Using equations (2) and (3), the relationship between retained austenite volume fraction and Mn content in austenite when quenching to 220 °C was calculated, shown as curve L0 in [Figure 11: see original paper]. The results indicate that retained austenite volume fraction increases with Mn content in austenite. Points P1 and P2 represent the relationship between retained austenite volume fraction and Mn content for Q&P and I&Q&P processes, respectively (the brief austenitization in I&Q&P prevents diffusion of enriched Mn, maintaining an enrichment level of approximately 2.8%, corresponding to point P2). Comparison of points P1 and P2 shows that retained austenite volume fraction increases with Mn content under identical carbon partitioning conditions. The actual measured trend matches theoretical predictions, though measured values at 90 s exceed theoretical calculations because the theoretical model considers only Mn effects, neglecting carbon' s contribution to retained austenite stability. Therefore, pre-Mn partitioning effectively increases retained austenite volume fraction in Q&P steel.

Conclusions

1. During the intercritical heating-quenching (IQ) process, the initial ferrite-pearlite microstructure transformed to ferrite-martensite. Carbon and manganese continuously diffused into austenite during intercritical holding, resulting in significant enrichment of both elements in martensite (originally intercritical austenite) after quenching. After I&Q&P processing, Mn enrichment remained evident in the room-temperature microstructure, while carbon enriched between martensite laths.
2. At identical carbon partitioning temperatures, increasing partitioning time decreased tensile strength and initially increased then decreased elongation in both Q&P and I&Q&P processes. Compared with Q&P processing, I&Q&P processing yielded lower tensile strength but higher elongation. At 90 s partitioning time, the I&Q&P steel achieved a strength-elongation product of 23,478 MPa • %.
3. Pre-Mn partitioning in the I&Q&P process retained more austenite during quenching to 220 °C. Subsequent carbon partitioning at 350 °C enabled more carbon diffusion into this austenite, stabilizing greater amounts of retained austenite after final quenching to room temperature. The combined effects of carbon and manganese partitioning in the I&Q&P process increased the volume fraction of stabilized retained austenite by approximately 2.4% compared to carbon partitioning alone in the Q&P process (from 11.2% to 13.6%), resulting in superior mechanical properties.

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