Effect of Coiling Temperature on Microstructure and Properties of Large-Deformation (B+M/A) X80 Pipeline Steel (Postprint)

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Abstract

Through continuous HOP (heating on-line partitioning) coiling technology, X80 pipeline steel acquired a (B+M/A) dual-phase microstructure and large deformation capacity. The microstructural evolution behavior of (B+M/A) X80 pipeline steel under different coiling temperature conditions was investigated via mechanical property testing, microstructural analysis, and X-ray diffraction methods, and the influence of microstructure on mechanical properties was analyzed. The results demonstrate that with increasing coiling temperature, the bainite content and dislocation density decrease, while the retained austenite content increases, leading to reduced material strength and enhanced ductility. Under high coiling temperature conditions, carbide precipitation and retained austenite decomposition are the microstructural factors responsible for increased strength and decreased ductility. At a certain coiling temperature, the experimental steel exhibits a low yield ratio, high uniform elongation, and high strain hardening exponent, meeting the technical requirements for large-deformation pipeline steel.

Full Text

Effect of Coiling Temperature on Microstructure and Mechanical Properties of (B+M/A) X80 Pipeline Steel with Excellent Deformability

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Abstract

High deformability X80 pipeline steel with a microstructure composed of bainite and martensite/austenite (B+M/A) can be obtained through the coiling continuous partitioning process. The effect of coiling temperature on the microstructure evolution and mechanical performance of (B+M/A) X80 pipeline steel was investigated using microscopic analysis, X-ray diffraction, and mechanical property tests. The results show that as coiling temperature increases, the strength of the steel decreases while ductility increases due to the reduced bainite content and dislocation density, as well as the increased retained austenite content. At high coiling temperatures, both carbide precipitation and retained austenite decomposition lead to increased strength and decreased plasticity. With an appropriate coiling temperature, the produced steel with this (B+M/A) dual-phase structure exhibits comprehensive mechanical properties including a low yield-to-tensile strength ratio, high uniform elongation, and high strain hardening index, meeting the technical requirements for high deformability pipeline steel.

KEY WORDS metallic materials, (B+M/A) X80 pipeline steel with excellent deformability, coiling continuous partitioning process, coiling temperature, microstructure and properties

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1. Introduction

With increasing demand for oil and natural gas, extraction and transportation have gradually extended to remote and environmentally harsh regions. Long-distance pipelines inevitably traverse geologically complex areas such as active fault zones, earthquake-prone regions, permafrost zones, and loose loess areas. Under the action of moving strata, pipelines can experience large deformation failures such as buckling and ductile fracture due to external abnormal load interference. To enhance the safety of long-distance pipeline systems under large deformation conditions, a new research direction has emerged focusing on a novel online partitioning process (Heating on-line partitioning, HOP) to obtain a bainite + martensite/austenite (B+M/A) duplex microstructure, in addition to ferrite + bainite (F+B) dual-phase steels.

HOP technology was developed by Japan’ s JFE Corporation in the early 21st century. In this process, pipeline steel plate is accelerated-cooled to a temperature within the bainite transformation range, where cooling is terminated to retain some untransformed supercooled austenite. Online heating equipment then reheats the material to a partitioning temperature for holding, allowing carbon from the bainite to diffuse into the untransformed austenite. The carbon-enriched supercooled austenite mostly remains untransformed during subsequent cooling, with a small portion transforming to martensite, forming fine and uniform M/A constituents. The resulting microstructure after HOP treatment is (B+M/A). This duplex microstructure significantly reduces the yield-to-tensile ratio while markedly increasing uniform elongation and strain hardening index compared to conventional pipeline steels, thereby meeting the requirements for high deformability pipeline steel.

However, the HOP process requires heating equipment on the accelerated cooling production line, increasing production difficulty and cost. To address this limitation, a new coiling continuous HOP technology has recently been developed based on the isothermal HOP process. This approach utilizes the residual heat during coil cooling for non-isothermal continuous partitioning, enabling pipeline steel to obtain (B+M/A) duplex microstructure and excellent plastic deformation capacity. This study investigates X80 pipeline steel to explore the principles of coiling continuous HOP technology, revealing the microstructural transformation patterns and performance characteristics under different coiling temperatures, providing a foundation for microstructure control and performance optimization of high deformability pipeline steel.

2. Experimental Materials and Methods

The experimental material was a microalloyed X80 pipeline steel with a thickness of 18.4 mm. Its chemical composition is shown in . The measured bainite transformation start temperature (Bs) was 690°C, and the finish temperature (Bf) was 336°C.

The (B+M/A) duplex microstructure was obtained through coiling continuous HOP technology. As shown in [Figure 1: see original paper], after austenitization at 920°C, the experimental steel was cooled at 30°C/s to different coiling temperatures (380°C, 410°C, 440°C, 470°C, 500°C) between Bs and Bf, where cooling was terminated to retain some untransformed supercooled austenite and produce appropriate amounts of bainite and austenite. Subsequent slow cooling at the coiling cooling rate (0.68°C/s) provided continuous partitioning treatment. During this slow cooling process below the coiling temperature, carbon from the bainite diffused into the austenite, enriching the untransformed austenite with carbon to enhance its stability. Less stable austenite transformed to martensite during continued cooling, while more stable austenite was retained to room temperature, forming M/A constituents. Thus, the final microstructure after coiling continuous HOP treatment was (B+M/A) duplex structure. In this process, coiling temperature is a critical parameter that serves both as the final cooling temperature, determining the proportions of bainite and austenite before partitioning, and as the initial partitioning temperature, affecting the final partitioning effect during continuous coil cooling. Unlike isothermal HOP where final cooling and partitioning temperatures can be controlled independently, in coiling continuous HOP both are controlled by the coiling temperature. Previous studies have demonstrated that the residual heat from coiling continuous cooling is sufficient to ensure carbon diffusion from bainite to austenite, meeting the requirements for forming (B+M/A) duplex microstructure during coiling.

Coiling continuous HOP experiments were conducted on a Gleeble-3500 thermal simulator using transverse specimens measuring $ $11 mm × 80 mm and 11 mm × 11 mm × 60 mm, all taken from the mid-thickness of the plate. After HOP treatment, specimens were machined into tensile specimens ($ $10 mm × 65 mm) and Charpy impact specimens (10 mm × 10 mm × 55 mm) for mechanical testing. Tensile tests were performed on an MTS-880 universal testing machine according to ASTM A370, while impact tests were conducted on a JBC-300 instrumented impact tester following ASTM E23.

Microstructural analysis specimens were ground, polished, and etched with 3% nital solution for examination using a JSM-6390A scanning electron microscope. TEM specimens were mechanically thinned to 50 m and twin-jet electropolished in a solution of 10% perchloric acid + 90% acetic acid, then examined using a JEM-200CX transmission electron microscope. Phase analysis was performed using a DMAX 2500PC X-ray diffractometer (XRD) with Cu target, step size of 0.02°, voltage of 40 V, current of 150 mA, scanning range of 40°–95°, speed of 4°/min, precisely measuring diffraction angle 2 and integrated intensity I to calculate retained austenite volume fraction according to GB/T 8362-87.

2. Results and Discussion

2.1 Strength and Ductility The stress-strain curves of X80 experimental steel at different coiling temperatures are shown in [Figure 2: see original paper]. All curves exhibit a round-house shape with smooth profiles and high strain hardening tendency, indicating strong deformation strengthening capability. A flat region near maximum load covers a large strain range, demonstrating substantial uniform deformation capacity.

The strength and ductility variations after continuous HOP treatment at different coiling temperatures are presented in [Figure 3: see original paper]. With increasing coiling temperature, both yield strength and tensile strength gradually decrease, though tensile strength shows an increase at higher coiling temperatures. Conversely, uniform elongation and total elongation increase with coiling temperature, but total elongation decreases at higher temperatures.

The large deformation characteristic parameters of the experimental steel after HOP treatment at different coiling temperatures are summarized in . At all coiling temperatures, the yield ratio is below 0.80, uniform elongation exceeds 9%, and the strain hardening index is greater than 0.11, demonstrating excellent plasticity levels that meet the technical requirements for high deformability pipeline steel.

2.2 Impact Toughness The impact toughness test results for X80 steel after HOP treatment at different coiling temperatures are shown in [Figure 4: see original paper]. As coiling temperature increases, impact toughness values vary within only 2–5%, and all exceed 340 J across the temperature range, indicating high toughness levels and demonstrating that online coiling partitioning treatment has a positive effect on pipeline steel toughness.

2.3 General Microstructural Characteristics SEM images of X80 pipeline steel microstructure after HOP at different coiling temperatures are presented in [Figure 5: see original paper]. All specimens exhibit (B+M/A) duplex microstructure, with dark gray bainite matrix and bright white M/A constituents distributed within or between bainite regions. Since both final cooling and partitioning temperatures are controlled by coiling temperature, the proportions of bainite and M/A vary with processing conditions. At higher coiling temperatures, carbide precipitation in the matrix becomes observable, with more distinct carbide morphology visible at higher magnification, as shown in [Figure 6: see original paper].

2.4 Detailed Microstructure and Its Effect on Properties The use of residual heat from coil cooling for non-isothermal continuous partitioning produces a (B+M/A) duplex microstructure in X80 pipeline steel. Coiling temperature characterizes and controls both the final cooling temperature for carbon partitioning and the initial partitioning temperature. Therefore, coiling temperature not only determines the amounts of bainite and austenite before partitioning but also influences the partitioning effectiveness during continuous cooling. Additionally, changes in coiling temperature alter the morphology, substructure of bainite and M/A, and the retained austenite within M/A, thereby affecting mechanical properties.

2.4.1 Bainite The (B+M/A) duplex microstructure obtained through coiling continuous HOP contains bainite whose morphology significantly influences mechanical properties. The effect of coiling temperature on bainite morphology is shown in [Figure 7: see original paper]. At low coiling temperatures near the bainite transformation finish temperature, bainite forms at lower temperatures, resulting in fine bainite laths with multiple orientations. As coiling temperature increases, the bainite transformation temperature rises, causing bainite lath widening.

During coiling, the dislocation configuration in bainite also undergoes significant changes, as shown in [Figure 8: see original paper]. Since bainite has a larger specific volume than austenite, low coiling temperatures promote shear and volume expansion that generate numerous mobile dislocations, forming dense tangles within the matrix [Figure 8a: see original paper]. With increasing coiling temperature, the higher transformation temperature and increased carbon diffusion to untransformed austenite reduce carbon solubility in bainite, decreasing dislocation density. At even higher coiling temperatures, the bainite matrix undergoes tempering during slow cooling, with dislocation recovery forming cellular structures that further reduce dislocation density [Figure 8b: see original paper]. These changes—bainite lath widening and dislocation density reduction—contribute to decreased steel strength with increasing coiling temperature.

The mechanical property variations are also affected by bainite content, which increases with lower coiling temperatures, leading to higher strength and lower plasticity. Bainite content was measured using the grid point counting method from GB/T 1547-2008 and Office software to quantify M/A constituent content, with results shown in . As coiling temperature increases, bainite content decreases, causing strength reduction and plasticity improvement.

During coiling continuous HOP treatment, carbon partitioning and carbide precipitation reduce carbon content in the bainite matrix, decreasing solid solution strengthening effects, reducing lattice distortion, and relieving transformation stresses. This softening of the bainite matrix leads to gradually decreasing yield strength with increasing coiling temperature [Figure 3: see original paper], while tensile strength shows an upward trend at higher coiling temperatures (470°C) due to pronounced carbide precipitation [Figure 9: see original paper]. As a microalloyed steel containing Nb, V, and Ti—strong carbide-forming elements—fine and dispersed alloy carbides precipitate during high-temperature partitioning, enhancing dislocation pinning and providing precipitation strengthening that increases strength. Further increasing coiling temperature causes carbide coarsening, diminishing this strengthening effect.

2.4.2 M/A Constituent In the (B+M/A) duplex microstructure obtained through coiling continuous HOP, the M/A constituent serves as an important structural unit whose distribution, size, and content significantly influence mechanical properties. At different coiling temperatures, various M/A morphologies are distributed between bainite laths and prior austenite grain boundaries. In SEM images, M/A islands appear bright white and blocky or granular [Figure 5: see original paper], while TEM reveals black blocky, strip, and film morphologies [Figure 10: see original paper]. [Figure 11: see original paper] shows bright-field, dark-field images and selected-area electron diffraction patterns of M/A at 440°C, with typical M/A sizes below 2 mm, beneficial for strength and ductility improvement.

In (B+M/A) microstructure, bainite strength primarily affects yield strength, while tensile strength depends on both bainite strength and M/A characteristics. Under applied stress, soft bainite grains with favorable orientations slip first, activating dislocation sources in adjacent grains or making sessile dislocations mobile, producing initial yield extension. When dislocations encounter hard M/A phases, stress concentrations in soft regions reach levels required for hard phase deformation, causing M/A yielding and releasing stress concentrations in soft regions. This delays necking formation and improves load-bearing capacity. As a hard phase distributed in the matrix, M/A increases flow stress, enabling sustained deformation even at high strain levels and maintaining high instantaneous n-values while increasing relative deformation before fracture, thereby improving uniform elongation.

During partitioning at different coiling temperatures, M/A volume content changes, as shown in [Figure 12: see original paper], increasing with coiling temperature. Studies indicate that when M/A volume fraction exceeds 5%, steel exhibits reduced yield ratio and good deformation performance.

2.4.3 Retained Austenite In coiling continuous HOP, coiling temperature controls both the final cooling temperature and initial partitioning temperature, thereby regulating retained austenite content in M/A. Based on online coiling partitioning principles and parameter control, a certain amount of retained austenite can be preserved to improve material plasticity.

TEM bright-field, dark-field images and diffraction patterns of retained austenite at different coiling temperatures are shown in [Figure 13: see original paper]-[Figure 15: see original paper]. At low coiling temperatures, the low final cooling temperature produces more bainite and less untransformed austenite. Meanwhile, the low initial partitioning temperature limits carbon diffusion from bainite to austenite, resulting in low austenite stability. Consequently, low-temperature coiling yields minimal retained austenite, mostly in thin film form between bainite laths [Figure 13: see original paper]. As coiling temperature increases, higher initial partitioning temperature and longer partitioning time enhance carbon diffusion, allowing more carbon from bainite to diffuse into untransformed austenite and increasing its stability. This increases retained austenite content and widens austenite films between laths [Figure 14: see original paper]. At sufficiently high coiling temperatures, high final cooling and initial partitioning temperatures produce less bainite, while carbide precipitation in the bainite matrix reduces available carbon for diffusion to austenite, decreasing retained austenite content [Figure 15: see original paper].

Quantitative XRD analysis of retained austenite is shown in [Figure 16: see original paper]. Typical diffraction peaks and the content variation curve demonstrate that retained austenite content first increases then decreases with coiling temperature, showing a peak distribution consistent with TEM observations.

In (B+M/A) pipeline steel, retained austenite significantly affects plasticity. As a face-centered cubic structure with 12 easy slip systems, austenite can activate multiple slip systems to deform with the matrix during deformation, coordinating grain deformation and improving plasticity. Retained austenite distributed between bainite laths separates bainite domains, refining effective grain size and hindering crack propagation. Additionally, transformation-induced plasticity occurs as retained austenite transforms to martensite under increasing stress, further improving ductility. This strengthening effect enhances with increasing retained austenite content. The variation of retained austenite content with coiling temperature—first increasing then decreasing—correlates well with the plasticity trend shown in [Figure 3: see original paper].

3. Conclusions

1. Through coiling continuous HOP treatment, the experimental X80 steel obtained a (B+M/A) duplex microstructure.
2. With increasing coiling temperature, tensile strength and yield strength gradually decreased, while total elongation and uniform elongation increased. At higher coiling temperatures, tensile strength increased and

total elongation decreased.

3. As coiling temperature increased, decreased bainite content and dislocation density and increased retained austenite content led to reduced strength and increased plasticity.
4. At high coiling temperatures, carbide precipitation and reduced retained austenite content caused strength increase and plasticity reduction.
5. At various coiling temperatures, the experimental steel exhibited low yield ratio, high uniform elongation, and high strain hardening index, meeting the technical requirements for high deformability pipeline steel.

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