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Effect of Cooling Time on the Microstructure and Properties of the Weld Heat-Affected Zone in TMCP890 Steel Postprint

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Abstract

The effects of cooling time from 800°C to 500°C (t8/5) on the microstructural transformation behavior and properties of the coarse-grained heat-affected zone (HAZ) in TMCP890 steel were investigated using a Gleeble-3800 thermal simulator. The results show that when t8/5 is 6-20 s, the coarse-grained zone microstructure consists of lath martensite with hardness values of 334-328HV10; when t8/5 is 20-60 s, the microstructure comprises lath martensite + lath bainite with hardness values of 328-305 HV10 and Bs temperature of 490-510°C; when t8/5 is 150-2000 s, the microstructure consists of lath bainite + granular bainite with Bs temperature of 530-570°C and hardness remaining at 270 HV10. The Inagaki empirical formula is applicable for calculating t8/5 during actual welding of TMCP890 steel. When heat input E varies between 10-20 kJ/cm and T0 varies between 50-150°C, the hardness of the coarse-grained zone is 318-335HV10, with small fluctuations in hardness values and stable properties.

Full Text

Effect of Cooling Time from 800 to 500°C on Microstructure and Properties of HAZ for TMCP890 Steel

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Abstract

The effect of cooling time from 800 to 500°C (t8/5) on the microstructure and properties of the heat-affected zone (HAZ) for TMCP890 steel has been investigated using a Gleeble-3800 thermal simulator. The results show that the coarse-grained zone of the HAZ exhibits a microstructure consisting of lath martensite with hardness of 334-328HV10 when t8/5 is 6-20 s. When t8/5 is 20-30 s, it shows a microstructure of mixed lath martensite and lath bainite with hardness of 328-305HV10 and Bs ranging from 490 to 510°C. When t8/5 is 150-2000 s, it shows a microstructure of lath bainite and granular bainite with hardness of about 270HV10 and Bs ranging from 530 to 570°C. The Michio Inagaki formula is suitable for t8/5 calculation; accordingly, with heat input E of 10-20 kJ/cm and T0 range of 50-150°C, the hardness of the coarse-grained zone can be expected to be in the range of 318-335HV10.

Keywords

metallic materials, Q890 steel, low-carbon bainitic steel, thermal simulation, microstructure, hardness

Introduction

Q890 steel produced by quenching and tempering (QT) process is tempered martensite steel [1], whose strength mainly originates from carbon solid solution strengthening. However, carbon impairs the weldability of low-alloy high-strength steels, leading to high hardening tendency in the heat-affected zone (HAZ), susceptibility to cold cracking, and resulting in embrittlement, softening, and grain coarsening in the HAZ [2,3]. Q890 low-carbon bainitic steel (TMCP890) produced by thermo-mechanical controlled processing involving high-temperature controlled rolling and rapid cooling after non-recrystallization region deformation [4] utilizes microalloying elements such as Ti, Nb, V, Mo, and Cu to form carbonitrides that hinder austenite grain growth, yielding fine-grained bainitic structures with high dislocation density [5]. When TMCP890 steel serves as the base metal for welding, the substrate near the fusion zone undergoes austenitization under welding heat input. The high peak temperature causes austenite grain coarsening, forming a coarse-grained zone. During cooling, the austenite transforms into martensite or bainite, possibly accompanied by ferrite or other phases [6]. Currently, research on HAZ microstructure in welded joints of low-alloy high-strength steels primarily focuses on tempered martensitic steels [7,8]. For low-carbon bainitic steels with yield strength reaching 890 MPa grade, welding tends to induce cracking and lower fatigue strength [9]. This study investigates the effect of cooling time from 800 to 500°C (t8/5) on the microstructure and properties of the HAZ in TMCP890 bainitic steel using a Gleeble-3800 thermal simulator.

Experimental Methods

The experimental steel plate was Q890 bainitic steel produced by TMCP, with a thickness of 25 mm. The chemical composition is listed in Table 1 . The calculated Pcm value was 0.253, which exceeds 0.2, indicating a certain cold cracking tendency according to the International Institute of Welding standards. Figure 1 [Figure 1: see original paper] shows the microstructure of the experimental TMCP890 steel, revealing a predominantly lath bainitic structure. Since the SHCCT diagram can reflect the microstructure and hardness of the HAZ under different cooling conditions, the SHCCT diagram of TMCP890 steel was determined according to the YB/T 5128-93 (formerly GB5057) standard "Determination Methods for Continuous Cooling Transformation Diagrams of Steel" . The critical points of the steel were measured using a Formast thermal simulator with cylindrical specimens of 3 mm diameter and 10 mm length. The transformation behavior of the HAZ coarse-grained zone under different welding thermal cycles was investigated using a Gleeble-3800 thermal simulator. Specimens were taken from the 1/4 thickness position of the 25 mm thick TMCP890 steel plate as cylindrical samples of 10 mm diameter and 80 mm length. The test parameters are listed in Table 2 .

2.1 Microstructure of CGHAZ in TMCP890 Steel

The microstructure and phase fractions of the TMCP890 steel HAZ coarse-grained zone (CGHAZ) under different t8/5 conditions are shown in Figures 2 [Figure 2: see original paper] and 3 [Figure 3: see original paper]. After high-temperature thermal cycling, the TMCP890 steel base metal became fully austenitized, and the original rolled microstructure disappeared, transforming into blocky structures. Due to the high peak temperature, the undercooled austenite grains coarsened and gradually increased with increasing t8/5. As seen in Figure 2 [Figure 2: see original paper], when t8/5 was less than 20 s, the CGHAZ primarily consisted of lath martensite; at t8/5 of 30-60 s, the microstructure was mainly lath martensite + lath bainite; at t8/5 of 150 s, it became lath bainite + granular bainite, with lath bainite gradually decreasing and granular bainite increasing as t8/5 further increased. With increasing t8/5, the lath morphology in the CGHAZ became increasingly blurred and less directional, indicating that the substructure of the lath structure changed with extended cooling time. According to the phase fraction calculations from Figure 3 [Figure 3: see original paper], for TMCP890 steel welding, the CGHAZ exhibited lath martensite when t8/5 was 6-18 s; at t8/5 of 18-122 s, the microstructure was primarily a mixture of martensite + lath bainite, with the martensite fraction gradually decreasing and lath bainite increasing as t8/5 increased; when t8/5 $>$ 122 s, the CGHAZ mainly consisted of lath bainite + granular bainite, with lath bainite gradually decreasing and granular bainite increasing as t8/5 increased.

2.2 Hardness of HAZ in TMCP890 Steel

The Vickers hardness measurement results of the HAZ coarse-grained zone under different t8/5 conditions are shown in Figure 4 [Figure 4: see original paper]. The hardness of the HAZ gradually decreased with increasing t8/5. Due to the low carbon content of the base metal, even the low-carbon martensite formed during rapid cooling could not achieve high hardening. The hardness remained nearly unchanged from t8/5 = 6 s to 20 s because the corresponding microstructure was lath martensite. After t8/5 exceeded 30 s, the hardness gradually decreased with increasing bainite content. When t8/5 increased to 150 s, the slower cooling rate reduced the dislocation density in bainite and ferrite, weakened lath directionality, and caused lath coarsening and merging. Simultaneously, second phases in the coarse-grained structure underwent ripening and growth, diminishing precipitation strengthening and reducing the pinning force on grain boundaries, which led to further grain growth and a more significant hardness reduction. Nonlinear fitting of t8/5 versus hardness yielded the relationship: 10 = 70.2 × + 269.8.

2.3 SHCCT Diagram of TMCP890 Steel

The critical phase transformation points measured using the Formast thermal simulator are listed in Table 4 . Table 5 gives the Bs points of the coarse-grained zone under different t8/5 conditions. The SHCCT diagram of TMCP890 steel was constructed based on the microstructure and hardness analysis of the coarse-grained zone, as shown in Figure 5 [Figure 5: see original paper]. The Ms point of TMCP890 steel is relatively high, and the self-tempering process that occurs during cooling of the welding HAZ helps improve toughness. The Bs point slowly increased with increasing t8/5. When t8/5 $\leq$ 60 s, the transformation temperature was 480-510°C, which falls within the medium temperature range of bainite transformation, ensuring stable low-carbon bainitic structures over a wide cooling time range. As t8/5 continued to increase, the transformation temperature rose, favoring the formation of granular bainite.

SHCCT diagrams are primarily used to guide actual welding production and predict the properties of the coarse-grained zone. The cooling time t8/5 is closely related to welding heat input E and preheating temperature T0, and can be predicted using the Michio Inagaki empirical formula and the D • Vwer empirical formula. The Michio Inagaki empirical formula established by Inagaki et al. is [10]:

Critical plate thickness [10] is Cr = 0.043 - 4.3 × 10 0.67 - 5.0 × 10

where   is the heat efficiency (taken as 0.7 in calculations), E is the heat input (kJ/cm), and T0 is the initial temperature (°C). Considering the effect of heat input on weld wire strength, for TMCP890 steel under actual welding conditions, heat input E is 20 kJ/cm and preheating temperature is 150°C. Therefore, when calculating critical plate thickness with E taken as the maximum value of 20 kJ/cm and T0 as 150°C, the calculated δcr value is maximum at 11.34 mm. With plate thickness $\delta > \delta$cr, the condition conforms to three-dimensional heat transfer.

The D • Vwer empirical formula for three-dimensional heat transfer [10] is:

8/5 = (0.67 - 5 × 10

where F3 is the joint coefficient (taken as 1 in calculations). The calculation results are shown in Figure 6 [Figure 6: see original paper]. As seen in Figure 6, t8/5 gradually increases with increasing heat input and preheating temperature, with heat input having a greater influence on t8/5 than preheating temperature. The actual welding joint cooling time t8/5 of TMCP890 steel was measured at heat inputs of 12, 15, and 18 kJ/cm with a preheating temperature of 60°C, and the results are listed in Table 6 . Comparison with calculated values shows that for calculating the welding cooling time t8/5 of 25 mm thick TMCP890 steel, the Michio Inagaki empirical formula yields results closer to measured values than the D・Vwer theoretical empirical formula.

Combining equations (1) and (2) allows calculation of t8/5 under different heat inputs and preheating temperatures:

8/5 = [1 + 2

where K is the welding energy coefficient (taken as 0.345), E is the welding heat input (kJ/cm), n is the welding energy index (taken as 1.7), β is the joint coefficient (taken as 1), T0 is the initial temperature of the workpiece (°C), δ is the plate thickness (mm), $ $0 is the plate thickness compensation term (taken as 13), and α is the plate thickness correction coefficient (taken as 3.5).

When using the D・Vwer empirical formula to calculate t8/5 for the 25 mm thick test steel HAZ, it is necessary to determine whether heat conduction is three-dimensional or two-dimensional. For this purpose, the critical plate thickness is first calculated. According to welding heat transfer theory, the "critical plate thickness" [10] is:

Cr = 0.043 - 4.3 × 10

The hardness values of the TMCP890 steel CGHAZ under different heat inputs and preheating temperatures were calculated, and the results are shown in Figure 7 [Figure 7: see original paper]. The hardness of the CGHAZ continuously decreased with increasing heat input and preheating temperature. When heat input was 10-20 kJ/cm and preheating temperature was 50-150°C, the CGHAZ hardness varied between 318-335HV10.

Conclusions

Based on the SHCCT diagram of TMCP890 steel, when cooling time t8/5 varies from 6-20 s, the CGHAZ consists of lath martensite with hardness of 334-328HV10; when t8/5 is 20-60 s, the CGHAZ exhibits lath martensite + lath bainite with hardness of 328-305HV10 and Bs points of 490-510°C; when t8/5 is 150-2000 s, the CGHAZ shows lath bainite + granular bainite with Bs points of 530-570°C and hardness remaining around 270HV10.

The Michio Inagaki empirical formula is suitable for calculating t8/5 in actual welding of TMCP890 steel. When heat input E is 10-20 kJ/cm and T0 varies between 50-150°C, the hardness of the TMCP890 steel CGHAZ ranges from 318-335HV10, with small fluctuations, indicating stable performance.

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