

Carbon Diffusion in Cr5Mo/A302 Dissimilar Metal Welds and Its Effect on High-Temperature Creep Life (Postprint)

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Abstract

Based on aging treatment experiments, microhardness measurements, and Fick's second law, the carbon diffusion behavior in Cr5Mo/A302 dissimilar welded joints was investigated. Subsequently, creep rupture tests were conducted on dissimilar welded joints with a pre-existing 200 μm decarburized layer and on as-welded joints without a decarburized layer to study the influence of the decarburized layer on joint life under different stress levels. The results indicate that with increasing aging time, the carburization and decarburization phenomena intensify, and the width variations of both carburized and decarburized layers follow a parabolic law, with experimental measurements being essentially consistent with fitting results based on Fick's second law. The pre-formed decarburized layer can reduce the high-temperature creep rupture life of the joint by several times under high stress conditions, causing premature fracture. However, as the stress level continuously decreases, the fracture time progressively increases, and the influence degree of pre-formed carbon diffusion on the creep rupture life of the joint continuously declines; when the stress is reduced below 36% of the joint's tensile strength, its influence can be neglected. The relationship between the carbon diffusion influence factor S and stress was established, and the critical stress value at which the pre-existing decarburized layer has no influence on high-temperature life was determined.

Full Text

Carbon Migration and Its Effect on High Temperature Creep Life of Cr5Mo/A302 Dissimilar Welded Joint

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Abstract

Based on considerations of economy and ease of on-site construction, Cr5Mo/A302 dissimilar welded joints are widely used in elevated temperature applications such as coal-fired power stations, nuclear plants, and petrochemical industries. Due to differences in carbide-forming elements across the fusion line, carbon migration occurs during service and can lead to premature failure. While calculation methods for carbon migration and its detrimental effects on creep life have been investigated for decades, previous studies paid little attention to the effect of carbon migration on creep life at different stress levels, and few have focused on relationships among carbon migration degree, stress level, and creep life.

This work first investigated the carbon migration behavior of Cr5Mo/A302 dissimilar welded joints through aging treatment tests, micro-hardness measurements, and Fick's second law. Subsequently, creep tests were performed on joints with a pre-existing 200 μ m decarburized zone and on as-welded joints without decarburization to study the effect of decarburization on joint life under different stress levels. The results showed that carbon migration intensified with increasing aging time, with the widths of both carbon-rich and decarburized zones following a parabolic relationship. Experimental measurements were basically consistent with Fick's second law predictions.

The pre-formed decarburized zone could reduce the high-temperature creep life by several times under high stress conditions, causing premature fracture. However, as the stress level decreased and rupture time increased, the influence of pre-existing carbon diffusion on joint life diminished progressively. When stress fell below 36% of the yield strength, this effect became negligible. The relationship between the carbon diffusion impact factor S and stress was established, and the critical stress value below which the pre-existing decarburized zone does not affect high-temperature life was determined.

Keywords: Cr5Mo/A302 dissimilar welded joint, carbon diffusion, carbon diffusion impact factor S

Introduction

Cr-Mo heat-resistant steel is widely used for high-temperature equipment in thermal power, nuclear, and petrochemical industries due to its good creep strength, oxidation resistance, and economic viability. For economic and construction convenience, Cr-Mo steel welding often employs austenitic stainless steel electrodes such as A302. This welding process requires no preheating or post-weld heat treatment, reducing energy consumption and costs while facil-

itating on-site installation of large equipment. However, during actual high-temperature service, carbon diffuses from the side with lower alloy content (typically the base metal) to the side with higher alloy content (typically the weld), affecting joint performance.

Studies have shown that carbon diffusion reduces high-temperature creep rupture life and causes premature failure, with creep cracking primarily located in the decarburized zone. Carbon diffusion in dissimilar welded joints is a multi-component system diffusion driven by the carbon chemical potential gradient across the fusion interface. Under this gradient, carbon diffuses from the region of higher activity to lower activity. The effective carbon activity is influenced by the combined effects of alloying elements including C, Cr, Ni, Mn, Mo, and Ti. In dissimilar welded joints, since carbon diffusivity in α -Fe is much greater than in γ -Fe (39 times greater at 910 °C, 126 times at 755 °C, and 835 times at 500 °C), carbon cannot easily diffuse over long distances into the austenitic weld. Therefore, carbon is mainly distributed in the martensite (M) or martensite-like (M-L) zone near the fusion line in the weld metal, following a parabolic law.

Researchers have used error function solutions to Fick's law to calculate carbon diffusion behavior, achieving reasonable agreement with experimental results. Others have employed nonlinear regression and finite difference methods, also obtaining consistent trends. However, comparisons between the life of joints with pre-existing carbon diffusion and that of new joints, as well as the relationship between life differences and stress levels, have not been reported.

This work investigates carbon diffusion behavior on both sides of the fusion line in Cr5Mo/A302 dissimilar welded joints based on aging experiments combined with Fick's second law, and examines the effect of stress level on the high-temperature life of joints with a pre-existing decarburized zone of approximately 200 μ m.

Experimental Procedures

Materials and Welding

The base material was Cr5Mo steel pipe with a diameter of 198 mm, wall thickness of 12 mm, and length of 600 mm. A 60° V-groove was used, with SH S820 welding wire for TIG root pass and A302 austenitic electrode for TIG cover passes, completed in four passes. Interpass temperature was controlled below 150 °C, with no preheating or post-weld heat treatment. The chemical composition (mass fraction, %) of Cr5Mo base metal was: C 0.14, Si 0.27, Mn 0.38, S 0.005, P 0.018, Cr 5.9, Mo 0.5. The A302 electrode composition was: C 0.08, Si 0.47, Mn 1.62, S 0.015, P 0.032, Cr 22, Ni 12.9, Mo 0.15.

Aging Treatment and Characterization

Aging experiments were conducted in an SX-2.5-1 box-type resistance furnace controlled by an AI-708 industrial regulator at 650 °C for durations of 100, 257,

460, and 1160 h. An HXD-1000TM hardness tester measured hardness distribution near the fusion zone, while an EPMA-1610 electron probe microanalyzer (EPMA) analyzed carbon content near the fusion line.

Mechanical Testing

High-temperature tensile and creep specimens with welds located at the center were machined from both as-welded Cr5Mo/A302 joints and joints aged at 650 °C for 257 h (which developed a decarburized zone of about 200 μm). High-temperature tensile tests at 550 °C were performed on an EHF-EG250-40L materials testing machine, while creep rupture tests at 550 °C under constant loads of 80–180 MPa were conducted on an RD2-3 creep testing machine. An XJZ-6 optical microscope (OM) observed carbon diffusion characteristics and fracture features after creep rupture tests.

Results and Discussion

2.1 Aging Experiments

Figure 1

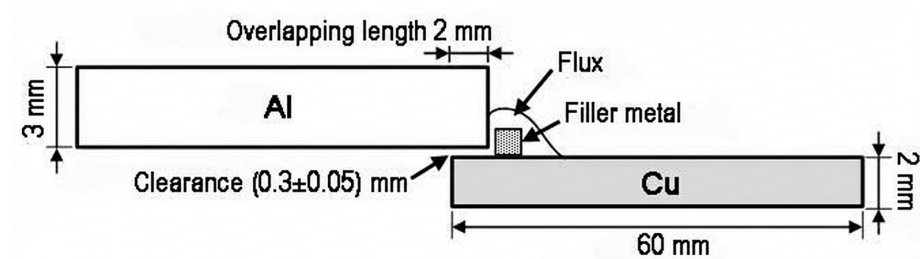


Figure 1: Figure 1

shows OM images near the fusion line of Cr5Mo/A302 dissimilar joints in the as-welded condition and after aging at 650 °C. In the as-welded condition, no obvious carbon diffusion was observed. During aging at 650 °C, the carbon-rich zone widened with increasing time, exhibiting a serrated diffusion front.

2.2 Hardness Distribution

The hardness distribution near the fusion line of the as-welded Cr5Mo/A302 joint is shown in Figure 2 [FIGURE:2]. After welding, the overall hardness of the Cr5Mo base metal heat-affected zone (HAZ) increased, forming a hardened layer approximately 3000 μm wide. Metallographic observation revealed this region encompassed the entire HAZ of the base metal, including coarse-grain, fine-grain, and partial transformation zones, with hardness exceeding 380 HV, indicating strong quenching tendency in Cr5Mo. However, this hardened layer disappeared after aging.

Metallographic examination of the fusion zone (Fig. 1a) indicated no significant carbon diffusion occurred during welding. Figure 3 [FIGURE:3] shows the hardness distribution near the fusion zone after aging at 650 °C for 100-1160 h. A decarburized zone appeared on the Cr5Mo base metal side, with hardness gradually decreasing to about 230 HV and width increasing to approximately 500 μm . Correspondingly, a carbon-rich zone formed on the weld side. Although narrow (maximum width $\sim 10 \mu\text{m}$), its hardness increased to 350 HV.

2.3 High-Temperature Tensile and Creep Properties

During high-temperature tensile testing of Cr5Mo/A302 joints, fracture occurred in the base metal. The as-welded joint exhibited tensile strength $\sigma_b = 383 \text{ MPa}$, yield strength $\sigma_{0.2} = 211 \text{ MPa}$, and elongation $\delta = 22.5\%$. After aging at 650 °C for 257 h, the joint showed $\sigma_b = 358 \text{ MPa}$, $\sigma_{0.2} = 200 \text{ MPa}$, and $\delta = 25.4\%$. These results indicate that aging slightly decreased strength while slightly improving ductility.

Figure 4 [FIGURE:4] compares the creep rupture lives of as-welded and aged (650 °C, 257 h) Cr5Mo/A302 joints at 550 °C under various stress levels. At stresses of 180, 150, and 130 MPa, the rupture lives of aged joints were significantly shorter than those of as-welded joints. For example, at 180 MPa, the as-welded joint life was 5.14 times that of the aged joint. As stress decreased, the life difference diminished; at 80 MPa, the difference was only 12.4%. Except for specimens tested at 180 MPa that fractured in the base metal, all others failed in the HAZ adjacent to the fusion line.

Figure 5 [FIGURE:5] shows OM images of fracture locations after creep testing at 550 °C and 100 MPa. All fractures occurred in the decarburized zone, but fracture morphology differed. The as-welded joint exhibited a straight main crack, while the aged joint showed a tortuous main crack with numerous creep cracks intersecting it. Figure 5 also reveals that during creep testing, the as-welded joint without prior carbon migration experienced carbon diffusion, with the carbon-rich zone width increasing by about 3.3 μm . In contrast, the pre-aged joint with existing carbon diffusion showed slower growth of only about 2.3 μm .

3.1 Theoretical Analysis of Carbon Diffusion

To further investigate carbon diffusion and compare with experimental results, Fick's second law was applied for numerical analysis. Carbon diffusion in dissimilar welded joints is a one-dimensional non-steady-state problem. The expression of Fick's second law can be written as [9]:

The error function solution of Eq.(1) is:

where B_1, B_2, B_3, B_4 are constants; D_b is carbon diffusivity in base metal (m^2/s); D_w is diffusivity in weld metal (m^2/s). According to references [12,22,23], $D_w = 3.0935 \times 10^{-17} \text{ m}^2/\text{s}$ and $D_b = 3.0766 \times 10^{-18} \text{ m}^2/\text{s}$.

Since the weld metal has finite width and the fusion zone width is negligible compared to the weld width, the diffusion problem can be simplified as a diffusion couple: 1. At initial time ($t = 0$), carbon concentrations on both sides of the fusion line are the base metal carbon content (bc) and weld metal carbon content (wc), respectively. 2. At $x = \infty$ (far from the fusion line), carbon concentrations remain at the original values of base and weld metals. 3. At $x = 0$ (fusion line), carbon concentrations are the minimum in the decarburized zone and maximum in the carbon-rich zone.

Additionally, based on equal carbon diffusion flux and chemical potential at the fusion line ($x = 0$):

where J is diffusion flux ($\text{kg}/(\text{m}^2 \cdot \text{s})$); J_w and J_b are fluxes in weld and base metal, respectively; μ is chemical potential (J/mol); μ_w and μ_b are chemical potentials in weld and base metal; k is Boltzmann constant (J/K); T is thermodynamic temperature (K); μ_0 is standard chemical potential (J/mol); C_0 is carbon mass fraction at fusion line; c_f is activity coefficient.

Combining Eqs.(2-9) yields constants B_1, B_2, B_3, B_4 , giving the carbon distribution across the fusion line as shown in Figure 6 [FIGURE:6]. Both decarburized and carbon-rich zone widths increase with aging time. The decarburized zone is wider (maximum $\sim 600 \text{ m}$) with gradual carbon content variation, with minimum carbon content (0.10%) not significantly different from the base metal (0.14%). The carbon-rich zone is narrower (maximum $\sim 10 \text{ m}$) but shows carbon content up to 2.22%, nearly 30 times higher than the normal weld carbon content (0.08%).

Figure 7 [FIGURE:7] compares calculated and measured widths of decarburized and carbon-rich zones. The experimental width distribution agrees well with numerical analysis.

3.2 Effects of Carbon Diffusion on Creep Rupture Life

High-temperature creep damage mechanisms are closely related to stress levels. At high stresses ($>0.4-0.5\sigma_{0.2}$), damage follows a plasticity-controlled mechanism. Carbides as high-temperature strengthening phases impede dislocation motion, improving creep strength. When a decarburized zone forms, carbide decomposition reduces this impediment, making the zone more susceptible to plastic deformation and eventual fracture.

At low stresses ($0.2\sigma_{0.2}-0.4\sigma_{0.2}$), creep damage is controlled by nucleation of creep cavities at grain boundaries. These cavities nucleate, grow, coalesce into microcracks, and gradually develop into macrocracks, leading to final fracture. In this mechanism, cavity nucleation and growth dominate the fracture process, so the reduction in creep strength due to decarburization is less significant than under plasticity-controlled conditions. Consequently, as stress decreases, the life difference between as-welded and aged joints diminishes.

Figure 8 [FIGURE:8] shows creep cracks in the decarburized zone after testing at

550 °C and 80 MPa. Numerous creep cavities appear at grain boundaries, with cracks propagating along them, indicating that cavity nucleation and growth dominate damage at low stress levels.

Additionally, carbon diffusion occurs during creep testing due to high temperature, with lower stresses leading to longer test times and greater carbon diffusion. Since carbon diffusion follows a parabolic law, with sufficient time, the degree of carbon diffusion in both joint types becomes increasingly similar, and the resulting damage gradually converges, leading to similar creep lives.

To quantitatively characterize the effect of pre-existing carbon diffusion on Cr5Mo/A302 joint life and establish its relationship with stress level, the carbon diffusion impact factor S is defined:

$$S = \frac{T_0 - T}{T_0} \times 100\%$$

where T_0 is the creep rupture life of the as-welded joint at a given stress level (h), and T is the life of the aged joint at the same stress level (h). A smaller S indicates less influence of pre-existing carbon diffusion on life; $S = 0$ indicates no effect.

The relationship between S and stress σ is shown in Figure 9 [FIGURE:9]. As σ decreases, S rapidly decreases following a quadratic relationship:

$$S = 0.0002\sigma^2 - 0.0292\sigma + 1.0678$$

From this equation, when $S = 0$, $\sigma = 72.99$ MPa, which corresponds to 36% of the yield strength. At this stress level, both joints have identical life, meaning pre-existing carbon diffusion from aging treatment has no effect on creep life.

Conclusions

1. At high temperatures, carbon diffuses from the Cr5Mo base metal to the A302 weld in dissimilar welded joints, forming a carbon-rich zone near the fusion line on the weld side and a decarburized zone on the base metal side. This diffusion behavior can be calculated using the error function solution of Fick's second law, showing good agreement with experimental results.
2. Due to reduced carbon content in the decarburized zone, its resistance to plasticity-controlled creep fracture decreases. Carbon diffusion significantly affects the high-stress creep life of Cr5Mo/A302 joints, reducing rupture life by several times.
3. As stress level decreases, the fracture mechanism changes, and the damage contribution from pre-existing carbon diffusion diminishes. The life

difference between as-welded and aged joints gradually decreases until becoming essentially identical.

4. The carbon diffusion impact factor S characterizes the sensitivity of Cr5Mo/A302 joints to pre-existing carbon diffusion at different stress levels. Joint sensitivity decreases with decreasing stress, following a quadratic relationship between S and σ . When stress falls below 36% of yield strength, pre-existing carbon diffusion has no effect on joint life.

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