Advances in Materials Technology for Fossil Power Plants
Proceedings from the Eighth International Conference
October 11–14, 2016, Albufeira, Algarve, Portugal
https://doi.org/10.31399/asm.cp.am-epri-2016p1207

J. Parker, J. Shingledecker, J. Siefert, editors

Influence of Fusion Ratio on Carbon Migration Phenomenon in the Narrow Gap Welding of Dissimilar Metals in 9% Chromium Steels

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ABSTRACT

Carbon migration in narrow-gap welding joints of dissimilar steels has been studied using bead-on-plate specimens to determine the factors that influence the formation of a soft ferrite structure in the carbon-depleted zone. Carbon migration was found to occur during tempering, with a ferrite structure formed at the intersection of multiple layers due to severe carbon migration. This was attributed to a steep gradient in Cr content caused by the low fusion penetration at the intersection. Experimental results and the relationship between fusion penetration and weld bead alignment confirmed that low fusion penetration is the main cause of ferrite-structured carbon-depleted zones.

INTRODUCTION

The increasing need to reduce pollution and improve heating efficiency in energy generation has led to dissimilar steel welding becoming an ideal way of manufacturing larger turbine components [1, 2]. This method overcomes conventional constraints on forging capacity and flexibility in structure design, while also reducing costs and fully utilizing the unique properties of different materials [3]. Unfortunately, differences in the structural, chemical and mechanical properties of different base metals make the microstructural and micro-chemical stability of dissimilar weld joints an area of major concern. Problems such as element diffusion, microstructure inhomogeneity and residual stress are already known to exist in dissimilar weld joints, and these can affect the weld strength and long term performance of a component [4]. These issues can, however, be avoided when creating rotors for steam turbines through much stricter process design, such as the use of proper filler metals and heat treatment parameters [5, 6].

Narrow-gap submerged arc welding is often used in the production of large components that operate at elevated temperatures, such as turbine steam rotors [7], but the intense concentration of heat during welding causes the heat affected zone (HAZ) to undergo severe thermal cycles. Consequently, this has long been recognized as the place in which failure is most likely to occur in service or in test specimens. Carbon migration is just one of the problems that can occur in the HAZ of dissimilar weld joints during post weld heat treatment (PWHT) or service at elevated temperatures [8], and can be detrimental to long term performance [9]. This migration occurs as a result of a difference in carbon activity between two base metals of different chemical composition, as carbide forming elements (e.g., Cr, Mo, V, Nb and Ti) reduce carbon activity, whereas elements such as Si, Al and Ni increase it. This ultimately results in the formation of a carbon-depleted zone on one side of the weld interface, with a carbon-enriched zone on the other [10].

In a past study of 9 % Cr steels, a coarse ferritic structure with low micro-hardness was found to form in the carbon-depleted zone [11]. As this zone is usually low in creep strength and weak in terms of stress rupture, it tends to be a potential failure location during service at elevated temperatures [12]. In contrast, the carbon-enriched zone has a high hardness and strength due to the precipitation of Cr-rich carbides. As these two zones lie adjacent to each other, they produce a sudden change in composition, microstructure and physical properties across the weld interface in a very narrow region, which can greatly degrade the thermal fatigue properties of the welded joint at elevated temperature [10, 13].

Studies aimed at preventing carbon migration have reported that Ni-based filler metals can reduce thermal stress, thereby minimising the extent of migration through a decrease in the carbon activity gradient and the inherently low diffusivity of carbon in Ni-based alloys [14]. In addition, the use of intermediate layers with progressively increasing amounts of carbide-forming elements has proven to be a reliable method of creating dissimilar welds between martensitic and pearlitic steels [3, 15, 16]. Sudha et al. have also found that although the width of the soft zone and carbon-enriched zone increases with heat treatment time, this eventually slows to a maximum value [13].

This article aims to figure out the fracture performance of a large dissimilar welding turbine rotor of 9 % Cr and 2.25 % Cr, and to find out the cause of the fracture path deflection. As carbon migration has been observed in this dissimilar welded rotor components, experiments has been designed to determine the factors that influence carbon migration using bead-on-plate specimens of special weld bead alignment. This information is then used for the future development of rotor design based on the same materials and technology with the aim of increasing the performance of carbon migration in the weld interface and the fracture strength at high temperature.

EXPERIMENTAL

A large size, dissimilar welded rotor of FB2 and 2.25CrNiMo1V steel (Fig. 1), with diameter of 890mm, was manufactured using narrow gap submerged arc welding (NG-SAW) technique and a multi-layer and multi-pass process. The compositions of the base metal and filler metal are given in Table 1 and the components was subjected to a PWHT of 680 °C for 20h.

Figure 1: Dissimilar welded rotor of FB2 and 2.25Cr2NiMo1V steel.

Table 1: Chemical composition of base and weld metals

Element (wt.%)	C	Cr	Mo	W	V	Nb
FB2	0.12–0.15	9.00–9.40	1.40–1.60	——	0.15–0.25	0.04–0.06
25Cr2NiMoV	0.21–0.30	2.00–2.50	0.95–1.25	0.64	0.21–0.29	——
Filler Metal	0.10–0.13	2.45–2.60	0.95–1.08	——	0.24–0.29	0.019–0.023
Element (wt.%)	Mn	Ni	Co	Si	N	B
FB2	0.30–0.50	0.10–0.20	0.90–1.30	0.10	0.015–0.03	0.008–0.011
25Cr2NiMoV	0.35–1.00	0.50–0.95	——	0.07	——	——
Filler Metal	0.49–0.53	0.11–0.14	——	0.10~0.14	0.0007	0.0005

Quasi-static fracture toughness testing was conducted on the HAZ of the FB2 side at 470 °C. Compact tension (CT) specimens with a pre- crack of 30mm were tested using a MTS 810- 50T testing machine, the test procedure strictly referred to the national standard GB/T 21143-2007. Load-displacement curve was recorded during the test. Among the specimens tested, 5 specimens revealed unstable crack propagation after peak load during fatigue testing. One of these unstable crack propagating specimens was selected for further analyse. The initiation of the unstable extending was located and was cut perpendicular to the crack path. After cleaning, grounding, polishing with 2.5 μm and 0.5 μm diamond powders then etching with Vilella reagent (95ml absolute ethyl alcohol+ 5ml hydrochloric acid+ 1g picric acid), the specimen was observed under an optical microscope (OM, Olympus MX51). Specimens of the weld joint on FB2 side in the rotor have also been observed under the OM.

Bead-on-plate specimen, 16 mm thick, was created by depositing 2.25%Cr filler metal onto a FB2 base plate so as to mimic the fabrication of an actual steam turbine rotor mentioned previously. The compositions of the base metal and filler metal are given in Table 1, with the material in a normalized and tempered condition. In order to analyse the effect of fusion penetration on carbon migration, the alignment of the weld beads matched that shown in Fig. 2. After preheating the samples to 170 °C, direct current electrode positive (DCEP) welding was conducted at an operating voltage of 29 V and a current of between 400 and 550 A. Three weld layers were deposited on the plate, with the weld bead of the root pass being aligned over a relatively large distance. This ensured that the second layer bead mixed with both the root pass and base metal, which led to a relatively low fusion penetration.

The welded specimen was cut perpendicular to the weld surface by spark erosion cutting, as indicated in Fig. 2. One piece was subjected to PWHT at 720 °C for 20 h, while the other was kept in an as-welded condition. The use of a PWHT temperature higher than the temper temperature of the real turbine rotor was designed to magnify the effects of carbon migration in the weld joint. The surfaces of both cut pieces were ground, polished and etched using Vilella reagent for metallographic observation.

Micro-hardness measurements (MH-5L) were carried out across the weld interface of the first weld layer and multilayer intersection using a load of 200 g for 5 s. Quantitative chemical analysis was performed using an electron probe micro-analyser (EPMA, JXA8230) to determine the distribution of elements across the weld interface and identify the formation of ferrite.

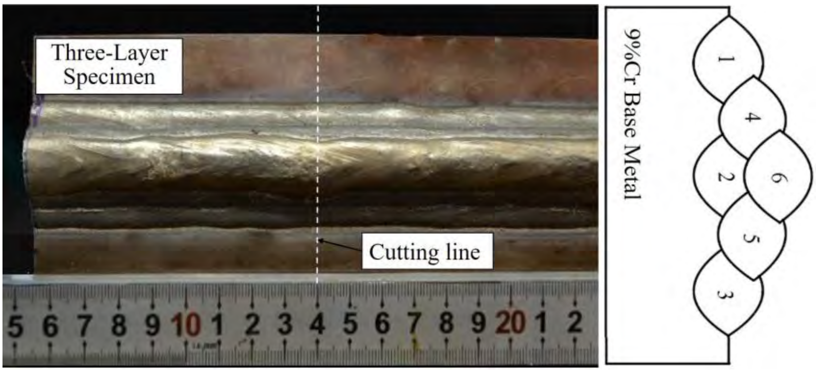

Figure 2: Bead-on-plate specimen and weld bead alignment. White dashed line shows the spark erosion cutting line during PWHT

Having determined that the appearance of ferrite in the carbon-depleted zone can be attributed to a relatively low fusion penetration, a new steam turbine rotor was produced by the cooperating organization using the same materials and narrow gap submerged arc welding technique, but with much closer attention to fusion penetration during welding. This was then subjected to high temperature fracture toughness tests.

RESULTS AND DISCUSSION

Carbon migration in the rotor component

The load- displacement curve of the unstable crack propagation specimen and a normal tested one was shown in Fig. 3. The unstable tested specimen has suffered a sudden unload once reaching the maximum axial load comparing to the normal one. In the OM image of the crack propagation path in the CT specimen (Fig. 4), the path can be divided into three parts, pre- crack, deflection path and crack growth path. Pre-crack appears to deflect toward the weld, with a stripe of dark zone appearing just below its propagation path. The dark zone has been proved to be carbon-enriched zone using micro-hardness test, while the crack deflection path corresponds to a carbon-depleted zone.

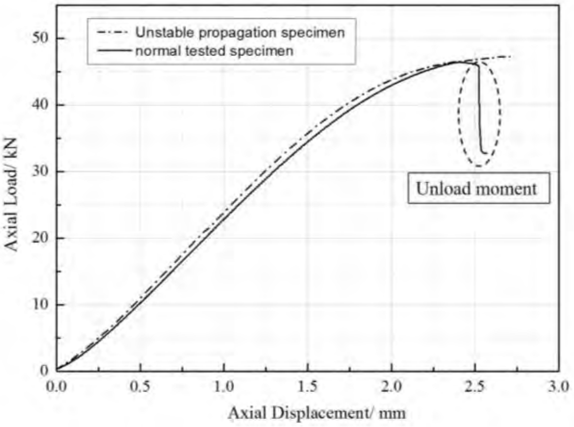

Figure 3: Load- displacement curve of unstable propagation and normal specimens

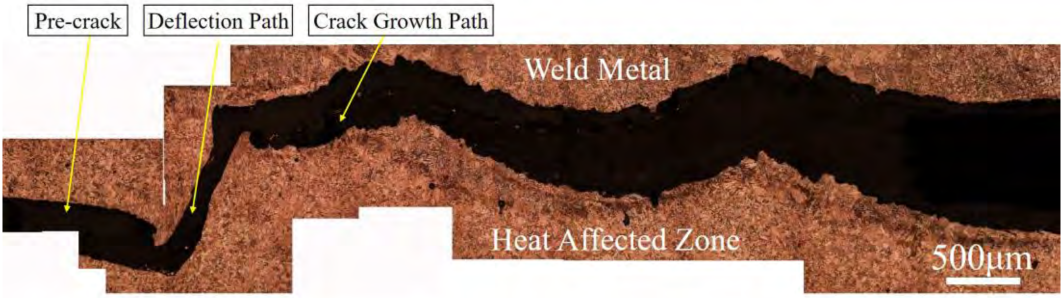

Figure 4: Deflection path during fracture toughness test

Further metallographic observation of the weld joint in the rotor identified a ferritic structure without precipitates adjacent to the weld interface (Fig. 5), which has a micro-hardness as low as 150HV compared to 325HV of the carbon- enriched zone, which could bring affects to the properties of the rotor component.

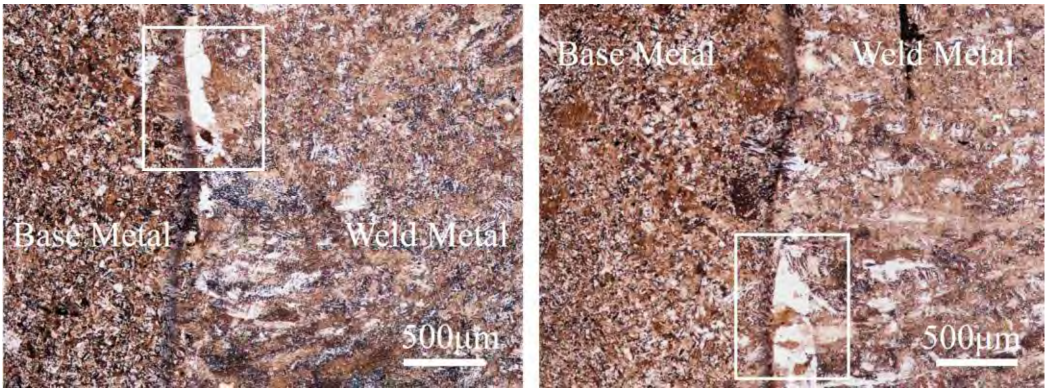

Figure 5: Ferrite structure in carbon-depleted zone in weld joint

Carbon migration after PWHT

In the OM images of the weld interface in the as-welded and PWHT specimens (Fig. 6), the fusion line of the different weld beads is indicated by a white dashed line. The region of intersection of multiple layers that is of particular focus is also marked. Note that the base metal exhibits a predominantly tempered martensitic microstructure, with clear martensitic lathes distributed in austenite grains. Columnar grains can be seen in the weld metal, whereas the HAZ consists of fine equiaxed grains. This metallographic analysis revealed that no apparent carbon migration occurred in the as-welded specimen, but the PWHT specimens clearly contain a dark carbon-enriched zone in the base metal and a bright carbon-depleted zone in the weld metal, which are adjacent to each other. This can be explained by the very different Cr contents of the two metals, which creates a distinct carbon activity differential that causes C atoms to move from the low-Cr (2.25 %) weld metal to the high-Cr (9 %) base metal. This is in good agreement with the theory that carbon migration occurs in the weld interface of dissimilar welds subjected to PWHT, but the ferrite structure formed in the weld bead intersection is likely to result in poor mechanical properties that could have disastrous results.

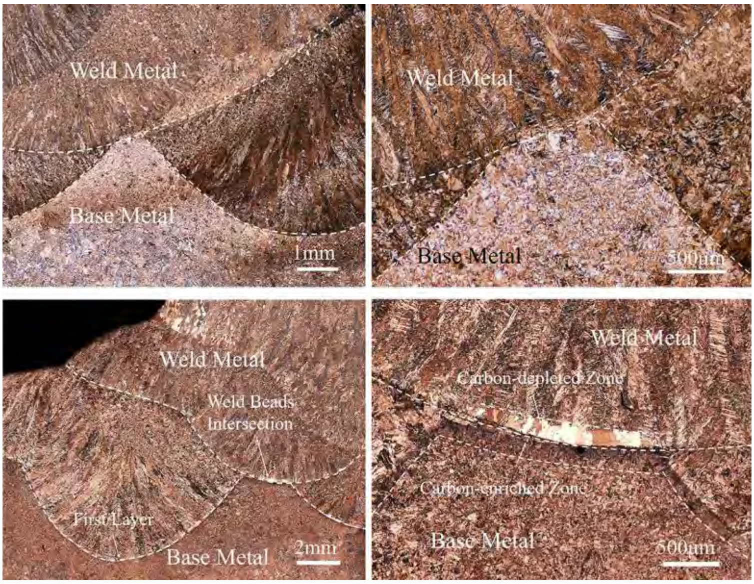

Figure 6: Optical micrographs of (a,b) as-welded specimen, (c) specimen after PWHT and (d) multilayer intersection in specimen after PWHT.

Prior to studying the formation of the ferrite structure in the weld joint, the distribution of Cr and C across the weld interface was analysed by EPMA. As shown in Fig. 7, the C concentration of the ferrite structure decreases across the interface, which provides clear evidence of carbon migration. The concentration of Cr also shows a slight decrease from the weld metal to the carbon-depleted zone, which is consistent with a decrease in carbides in the carbon-depleted zone [17].

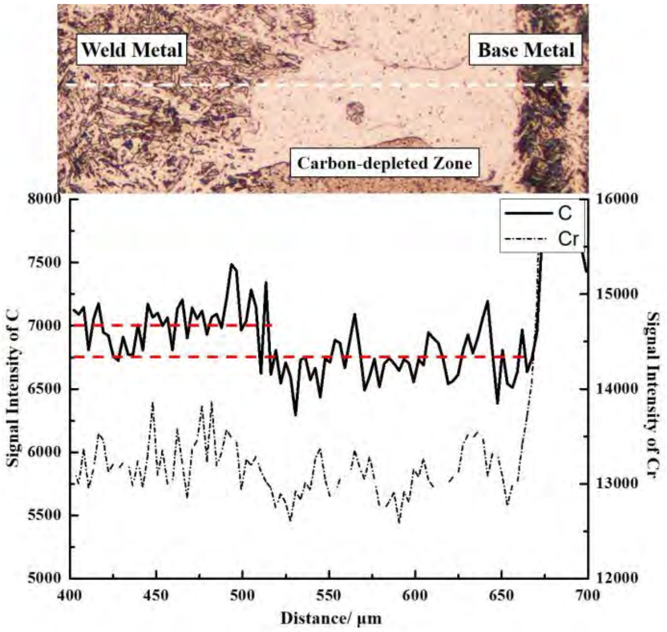

Figure 7: Distribution of Cr and C across the weld interface after PWHT at 720 °C for 20 h

Extent of carbon migration

In the OM images showing the root pass of the PWHT specimen in Fig. 8 carbon migration can be observed, albeit with relatively narrow carbon-enriched and carbon-depleted zones and no ferrite structure in the weld interface. Considering the alignment of the specimen and the different rates of dilution of the first and second weld layer, it is proposed that the different extents of carbon migration in different layers of the same specimen can be attributed to a difference in fusion penetration caused by the alignment of the weld bead.

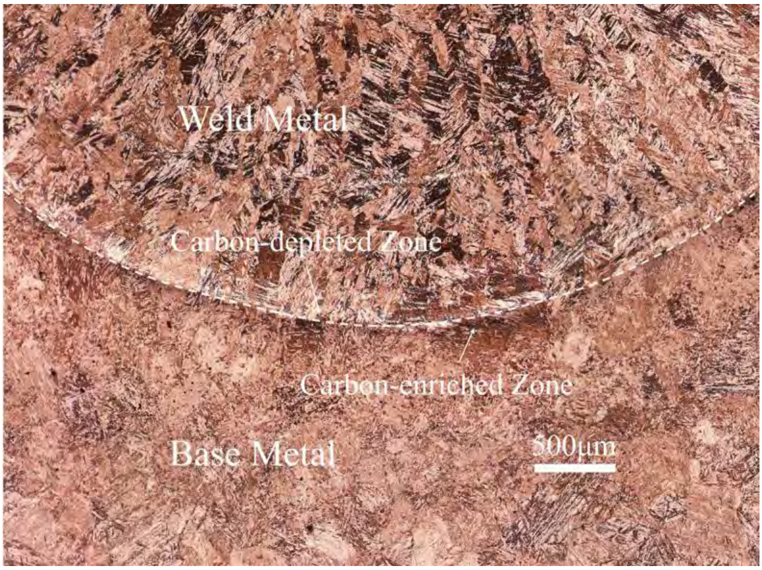

Figure 8: Optical micrographs of root pass after PWHT

Micro-hardness testing was performed to confirm that different physical properties exist in regions adjacent to the fusion line due to carbon migration. Both the first layer and weld bead intersection were measured for comparison, with the microstructure of weld bead intersection and respective micro-hardness profiles shown in Fig. 9. We can see from this that the micro-hardness in the weld metal adjacent to the weld interface decreases in both testing positions, but more rapidly so in the weld bead intersection region (to about 116 HV), due to decarburization caused by carbon migration. The micro-hardness rapidly improves to about 280 HV once across the weld interface and into the carbon-enriched zone, and then gradually decreases to around 240 HV in the martensitic structure of the base metal. A comparison of the two micro-hardness profiles reveals that the gap between the carbon-enriched and carbon-depleted zones is larger in the weld bead intersection. The low micro-hardness of the ferrite structure (116 HV) could leads to the poor mechanical properties of the weld joint, and suggests that the carbon-depleted zone is the most critical factor. It would also appear that the weld bead intersection suffers from more severe carbon migration than the first layer after PWHT, as evidence by the greater difference in micro-hardness between the carbon-enriched and carbon-depleted zones.

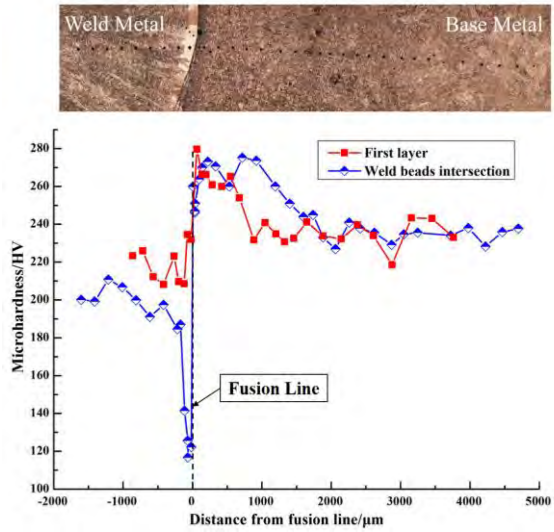

Figure 9: Micro-hardness distribution of the first layer and weld bead intersection after PWHT

In order to determine the reason for the difference between the first layer and weld bead intersection in the same specimen, another line of EPMA was performed to determine the redistribution of C and Cr across the second and first layer to the base metal. As can be seen in Fig. 10, the distribution of Cr can be perfectly divided into three parts representing the three areas being tested. The increase in Cr concentration across the interface between the second and first layer, as well as between the first layer and base metal, is easy to understand in light of the alignment of the weld bead. That is, the second layer is fused with both the first layer and base metal, leading to a relatively low fusion penetration in this area. A large distance between weld beads and/or insufficient fusion penetration can also lead to relatively poor mechanical properties and cause serious problems in dissimilar welded components that operate at elevated temperature if a ferrite structured carbon-depleted zone is created during PWHT.

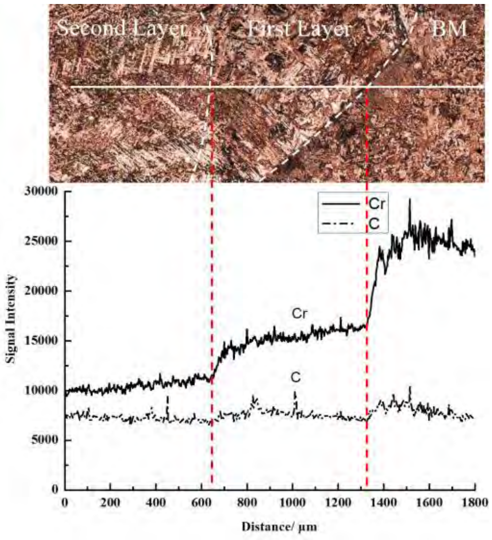

Figure 10: Distribution of Cr and C from the second layer to the base metal after PWHT

CONCLUSIONS

The overlaying of FB2 steel with 2.25%Cr filler metal was used to study carbon migration in a FB2/ CrMoV dissimilar weld. From observations of a ferrite structured carbon-depleted zone in the weld intersection of specimens exposed to PWHT and analysis of the micro-hardness, the following conclusions have been reached:

(1)Carbon migration occurs gradually during PWHT and creates a carbon-depleted zone that causes deflection of the crack path during fracture toughness test.

(2)A ferrite-structured carbon-depleted zone created by carbon migration in the weld bead intersection has a low micro-hardness and causes a much greater difference between the mechanical properties of this zone and the carbon-enriched zone.

(3) Two stages of Cr composition suggest that the extent of carbon migration in the first layer and weld bead intersection vary in the same specimen because of different extents of fusion penetration. Weld beads with a fusion penetration that is too low tend to experience more serious carbon migration, which is detrimental to their mechanical properties.

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