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A Novel Approach for Welding SS 304B4 using Standard Austenitic Consumables with Low Cracking Tendency

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Abstract

304B4 SS is an austenitic stainless steel used for neutron shielding applications that contains ~1.3 wt.% of boron in the form of Cr_2B borides distributed in the matrix. Though weldability of this steel is reported to be good because of backfilling of cracks by eutectic liquid formed during solidification, welding using standard E309 electrode during fabrication of components revealed high cracking tendency. This was attributed to base metal dilution in weld metal which alters the microchemistry of a portion of weld metal such that insufficient eutectic liquid is formed to heal the cracks. In order to overcome the cracking issue due to base metal dilution, an additional step of buttering was done using E309 on sides of 304B4 SS plates prior to welding. The concept of buttering was introduced because cracking tendency in the butter layer would be less in spite of significant base metal dilution due to less restraint present while buttering. Thickness of buttering layer is optimized such that at least 2-3 mm of undiluted E309 is deposited at the outermost edge to be joined. Welding is carried out on the buttered edges using E309 and subsequently specimens were suitably extracted for varestraint test from the weld joint. Spot varestraint test carried out at the "butter layer–weld" interface showed very low susceptibility for liquation cracking than direct joint tested at "base metal-weld" interface in earlier study. This is attributed to negligible dilution in the weld metal from the butter layer during actual joining when significant restraint is present.

Keywords: Borated stainless steel; Hot cracking; Varestraint test; Dilution.

1.0 Introduction

Borated stainless steels (BSS) are a class of austenitic stainless steels (SS) that contain 0.2 to 2 wt.% boron dispersed in the form of chromium borides (Cr_2B) in the austenite phase. According to ASTM specification A887, BSS are classified in to 8 types according to its boron content (AISI 304B to 304B7) [1]. These steels find applications in the nuclear industry for construction of nuclear fuel transportation casks, spent fuel storage racks, absorber rods for nuclear criticality control and neutron shields for structural components. This is because natural boron contains ~18 % of B^{10} isotope which is an effective neutron absorber [2]. For example, AISI 304B4 provides effective neutron shielding as compared to SS 304. In general, weldability of borated stainless steels is poor due to their high susceptibility to hot cracking. It is to be noted that in this steel boron is an alloying element. Also, it is well known that solubility of boron in austenite phase is negligible and hence gets partitioned to the liquid phase which leads to formation of low melting eutectic phases that accumulate at interdendritic spaces during last stages of solidification. The presence of interdendritic eutectic phases increases the susceptibility of the welds to hot cracking. However, it is reported in the literature that BSS with 0.5-2 wt.% boron is resistant to hot cracking under moderate restraint forces. This is attributed to effective backfilling of the hot cracks by the eutectic liquid formed in the fusion zone [3]. E309 welding electrode is recommended for joining SS 304B4 as it solidifies in ferritic mode. This mode of solidification is beneficial in reducing hot cracking [4, 5]. But the irony is that, though, 309 electrode was used during fabrication of thick section borated stainless steel, severe cracking of weld joints were observed [4, 5]. In the earlier study of these authors, it was found that the high cracking susceptibility was due to base metal dilution in the weld metal which introduced boron in the weld metal and induced liquation cracking in weld metal HAZ. This was attributed to presence of critically low boron content (0.2-0.4 wt.%) which forms insufficient eutectic liquid to back fill the cracks [6]. Hence, the aim of the present study is to develop a procedure to weld 304B4 SS using standard 309 electrode which has reduced tendency for hot cracking.

2.0 Experimental Procedure

2.1 Base Material

AISI 304B4 SS (0.02C-18.05Cr-12.29Ni-1.24B) plates of 12 mm thickness were used for fabrication of weld joints using E309 electrode and Shielded Metal Arc welding process.

2.2 Welding Procedure used for Joining SS 304B4 using E309 Electrode

The difference between the conventional welding procedures followed for welding SS 304B4 and the modified welding procedure is that an extra step of buttering is included in the latter. In this welding procedure, at first, the edges to be joined are buttered using E309 welding consumable. The welding parameters, current - 120 A and voltage - 25 V were used during the buttering process. The buttered layer should be of sufficient thickness such that after edge preparation on the buttered layer for subsequent welding, dilution from base metal must be zero. As actual joining is not performed during buttering, residual stresses generated during buttering is almost negligible. In this stage, risk of cracking would be considerably less despite susceptible weld metal microstructure. Weld joint was made in 1G position using 309 electrode (4 mm Φ) with 125 A current / 25 V. Welding speed was maintained at 1.6 mm/s during welding.

2.3 Varestraint Test

Varestraint test specimens (**Fig. 1**) of dimensions 127 x 25 x 3 mm were prepared from the fabricated weld pad. The interface between the buttering layer and weld metal is placed at the center of the specimen. Spot Varestraint test was carried using Varestraint test set up by producing a stationary weld pool at the center of the specimen so that HAZ is created around the butter-weld interface. The parameters used for spot Varestraint test is given in **Table 3**. The spot Varestraint tests were conducted at different augmented strains as per procedure described in the literature [7]. The tested specimens were immediately pickled to remove the oxide layer on the surface. Crack length measurements were carried out using a stereo microscope. From the measured crack lengths, Maximum and Total Crack lengths were determined for specimens subjected to various augmented strain levels.

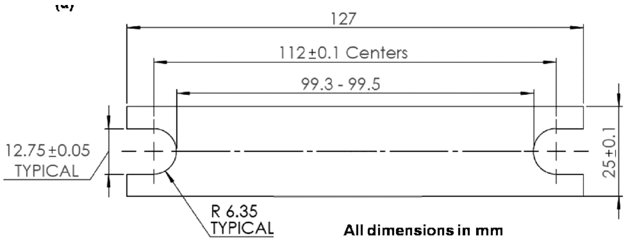

Fig.1 : Schematic of a varestraint test specimen

2.4 Metallography

Selected specimens after spot Varestraint tests were sectioned and prepared by grinding and polishing up to 1 micron surface finish. The specimens were electrolytically etched using 10% oxalic acid solution at 3 V DC for 10 seconds. The specimens were then observed using Zeiss make light optical microscope.

3.0 Results

3.1 Microstructure of the Weld Joint prepared after Buttering

Fig. 2 shows the macrostructure of SS 304B4 weld joint (prepared using modified welding procedure) and the microstructures of individual zones of the weld joint. From the **Fig. 2(a)** it is evident that there are two interfaces in the weld joint, (i) an interface between SS 304B4 base metal and 309 buttered layer and (ii) an interface between the 309 buttered layer and 309 weld metal. **Fig. 2(b)** shows the microstructure of PMZ formed on 304B4 base metal which consists of partially molten and solidified austenite (γ) grains and completely molten and solidified eutectic phases. **Fig. 2(c)** shows the microstructure of unmixed zone (UMZ) formed next to PMZ which consists of dendritic - γ and interdendritic eutectics. In **Fig. 2(d)**, the region of 309 butter layer close to the interface-1 in which substantial base metal dilution has occurred is shown. The microstructure consists of γ phase and a mixture of eutectic phase and δ ferrite in the interdendritic region as shown in the figure. The microstructure in **Fig. 2(e)** shows the butter region far away from the interface -1 which contains γ dendrites and δ ferrite. The microstructure in **Fig. 2(f)** shows the interface between the 309 butter layer and the weld metal. This microstructure consists of high fraction of δ ferrite. The microstructure of 309 weld metal deposited after buttering (**Fig. 2(g)**) shows only γ dendrites and δ ferrite.

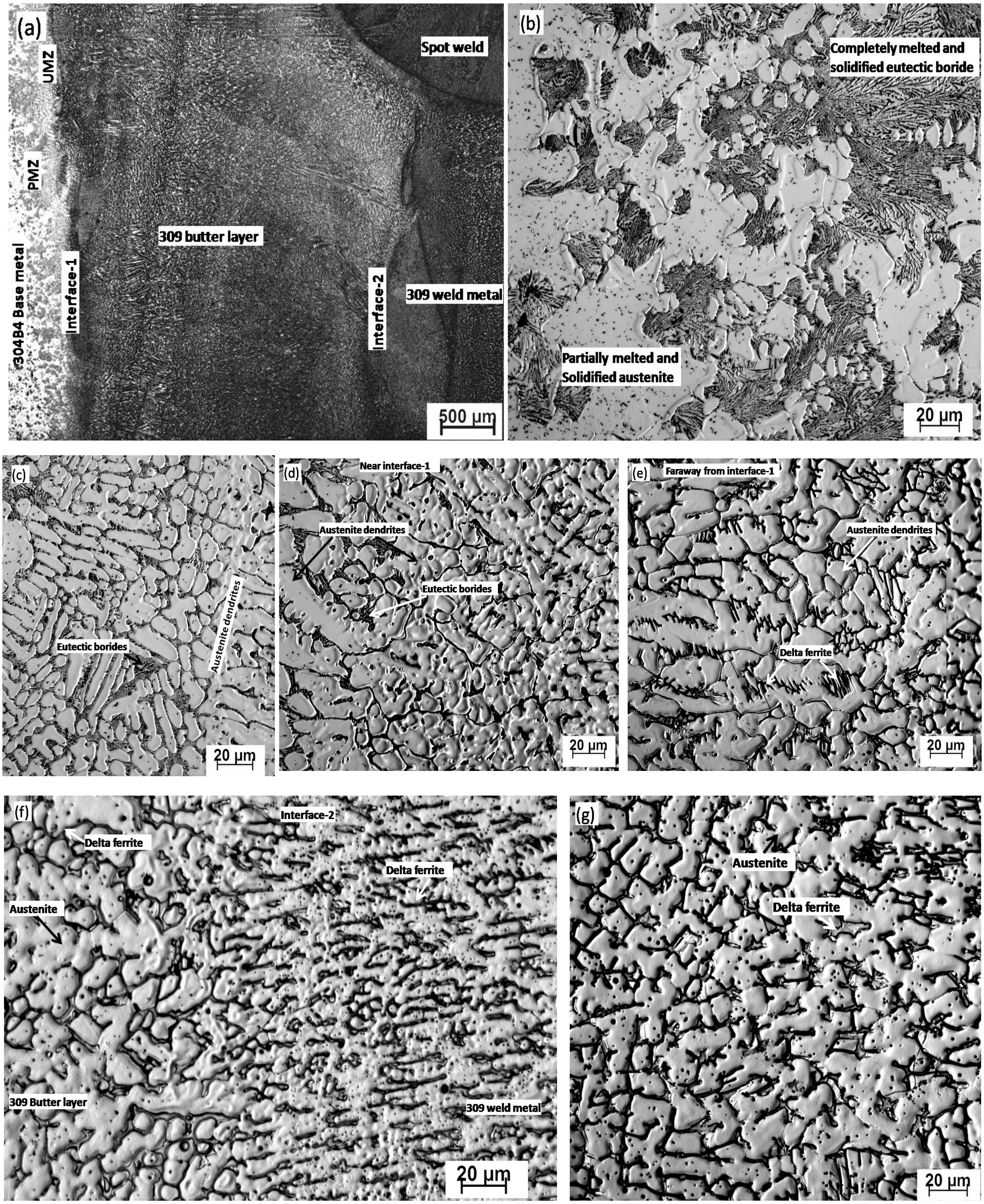

Fig. 2 : (a) Macrostructure of 304B4 SS weld joint prepared using modified welding procedure (b) Microstructure of PMZ formed on 304B4 SS base metal (c) Microstructure of UMZ formed next to PMZ Microstructures of 309 butter layer (d) near (e) far away from 304B4 SS base metal-309 butter layer interface (interface -1) (f) Microstructure of interface between 309 butter layer and 309 weld metal (interface-2) (g) Microstructure of 309 weld metal.

3.2 Hot Cracking Susceptibility

In **Fig. 3**, plots of Maximum Crack Length (MCL) vs % augmented strain obtained from weld joints prepared using 309 electrode with and without buttering (taken from earlier studies [6]) is shown. The MCL at threshold strain (ε_2)(1%) is 0.5 mm for the joint prepared using buttering layer whereas the same (ε_1) is ~ 2.5 mm for the joint prepared using without buttering as shown in the figure. The crack length measurements taken on the specimens **(Fig. 3)** reveal that the weld joint prepared after buttering the edges has lower susceptibility to cracking than that of the direct joint.

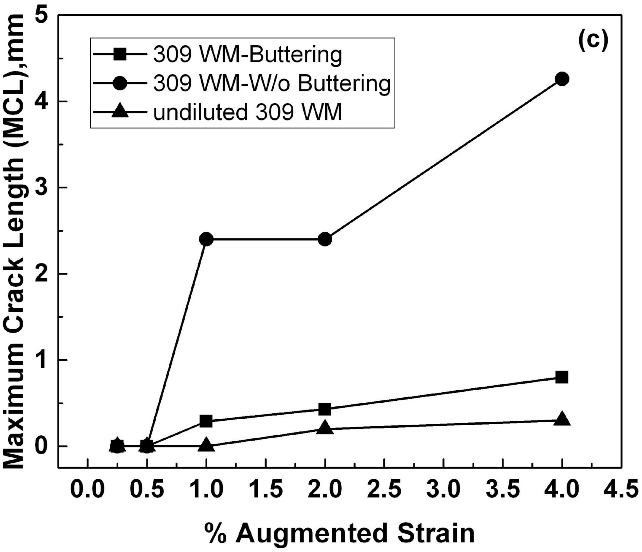

Fig.3 : Comparison of cracking susceptibilities of SS 304B4 weld joints prepared using E309 with and without buttering and undiluted 309 weld metal.

3.3 Microstructural Characterization of Specimens

Fig. 4(a) reveals low magnification microstructure of spot Varestraint tested specimen where a few liquation cracks are present in the weld metal PMZ. **Fig. 4(b)** shows the microstructure of spot Varestraint tested specimen at 4% augmented strain. From the microstructure it appears that the liquation cracks have occurred along the Migrated Grain Boundaries (MGBs) in 309 butter layer. The microstructure in **Fig. 4(c)** (magnified image of area demarcated in **Fig. 4(a)**) shows presence of eutectic constituents along the MGBs below the crack tip. The microstructure taken in polarized light clearly differentiates the MGBs and cracks present in 309 weld metal as well as reveal the morphology of the eutectic constituents present along the MGBs. The microstructure in **Fig. 4(d)** shows polarized light image of 309 weld metal PMZ where no liquation cracks are present (right side of the interface-2). The microstructure clearly shows that at this location only γ dendrites and interdendritic and lacy δ ferrite are present with no indications of eutectic constituents.

4.0 Discussion

From earlier studies reported so far by these authors, the reason behind liquation cracking occurring while using boron free welding consumable is clearly understood. The presence of films of eutectic boride phases due to base metal dilution in weld metal is the primary cause for liquation cracking in the weld joints [6]. Also, it is reported that the problem of hot cracking remains unsolved even after using boron containing consumable since the weld joints are susceptible for cracking at high restraints [8]. Further, impact toughness of the weld joint made by boron added welding consumable is considerably inferior to those produced from E309 electrode [8]. Based on this understanding obtained from the previous studies, a modified welding procedure is proposed. The idea behind this welding procedure is that the risk of hot cracking can be considerably reduced if a susceptible microstructure can be avoided during actual welding, when residual stresses generated can facilitate cracking. Results indeed confirm this hypothesis. The microstructure of the zone that is likely to be crack prone (butter layer and the weld metal interfacial area) in the buttered weld joint is almost free of borides in the microstructure and its cracking susceptibility is considerably lower than that obtained in base meal - weld metal interface of the direct joint between 304B4 plates using E309 consumable from reference [6]. This is shown in **Fig. 3**, a comparison of MCL data obtained for the spot Varestraint test conducted for the two zones as mentioned above in the weld joints prepared with and without buttering along with that of the undiluted weld metal liquation cracking susceptibility of weld joint prepared after buttering the edges is far lower than the other.

Ideally the liquation cracking susceptibility (MCL value) in the weld joint prepared using the modified welding procedure should have been similar to that of virgin 309 weld metal but it is found to be slightly higher than that of the latter. This is because; boron is present in the 309 weld metal as result of dilution from the butter layer which can have some boron because of dilution from the base metal. This is clearly evident from the signatures of eutectic constituents present along the MGBs in the microstructure shown in **Fig. 4** in the weld metal near the buttered layer - weld metal interface. In addition to this, weld puddle produced during spot Varestraint test could not be accurately restricted within the butter layer - weld metal interface (interface-2, **Fig. 2(a)**). It can be observed that the spot weld has slightly moved towards the butter layer as shown in **Fig. 2(a)**. This could be the possible reason behind the observed cracking susceptibility of weld joint prepared using buttering which is slightly higher than the virgin 309 weld metal. On the other hand, it should be noted that the cracking

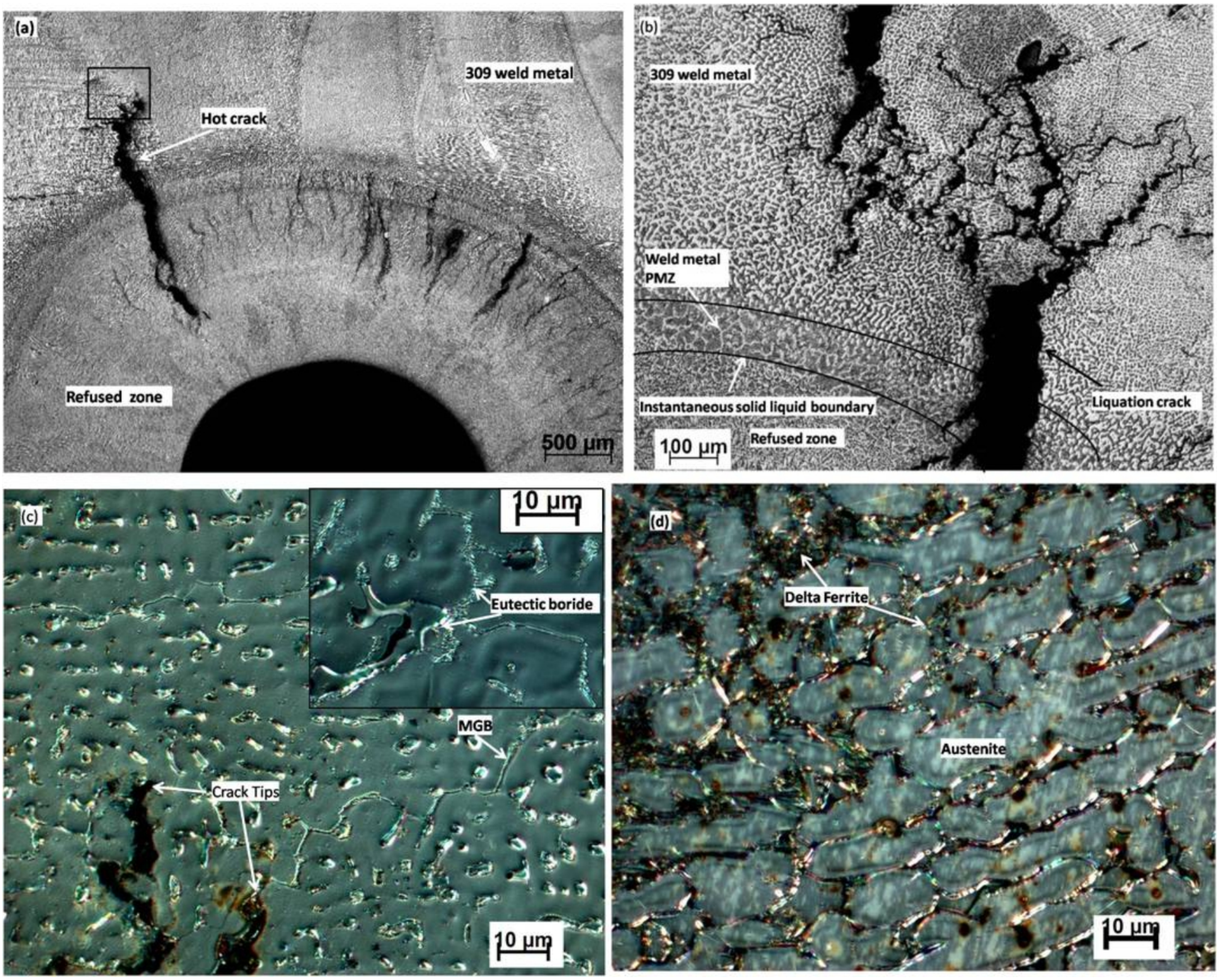

Fig.4: (a) Macrostructure of spot Varestraint tested specimens showing a liquation crack taken at low magnification (b) Microstructure of the liquation crack present in 309 weld metal taken at high magnification (c) Polarized light contrast microstructure of 309 weld metal showing MGBs taken at the crack tips and the inset to the figure shows features pertaining to eutectic films along the MGB at high magnification (d) Polarized light contrast microstructure of 309 weld metal showing austenite and delta ferrite at the location where liquation cracks are not present.

susceptibility of the weld joint has substantially reduced as compared to the direct joint prepared without buttering. Further, it is also possible that the TCL and MCL values of the weld joint produced using the modified procedure can be further reduced if proper care is taken during machining of buttered layer and subsequent testing. It may be possible that hot cracking resistance of the SS 304B4 weld joint can be made comparable to that of undiluted 309 weld metal using the modified welding procedure by carefully controlling the steps involved during weld joint fabrication process.

5.0 Summary

1. The modified welding procedure involving buttering, developed for SS 304B4 using standard E309 significantly reduced cracking susceptibility of the weld joint.
2. The idea behind the design of modified welding procedure is that even though base metal dilution takes place in the butter layer resulting in formation of eutectic borides, tensile stresses responsible for cracking, generated during buttering would not be as high as that formed during

welding. Subsequently, final welding is carried out between dilution free 309 buttered surfaces using 309 electrode where, weld metal microstructure produced is resistant to hot cracking.

3. Hence, buttering of the joint surface with E309 for sufficient thickness is recommended as an alternate procedure to join borated stainless steel to reduce the risk of hot cracking. Sufficient amount of butter layer should be ensured so that after edge preparation for subsequent welding, the surfaces to be welded together should be free of dilution from base metal (typically more than 5 mm).

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