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Effect of buffer-layered buttering on microstructure and mechanical properties of dissimilar metal weld joints for nuclear plant application

Dinesh W. Rathod [a,*,1], P.K. Singh [b], Sunil Pandey [a], S. Aravindan [a]

[a] Department of Mechanical Enggineering, Indian Institute of Technology Delhi, Hauz-khas, New Delhi 110016, India
[b] Bhabha Atomic Research Centre, Mumbai 400085, India

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ABSTRACT

In this study, we present the metallurgical and mechanical investigation of four dissimilar welds between SA508Gr.3Cl.1 and SS304LN. The welding processes for buttering deposition and fill-pass welding were varied with ERNiCr-3/ENiCrFe-3 consumables. The Ni-Fe alloy buffer layer was introduced as intermediate layer in buttering and then the joints (with and without buffer layer in buttering) were fabricated. The effect of Ni-Fe buffer layered buttering and welding processes on the resulting weld joints properties has been addressed. Metallurgical and mechanical properties, fracture toughness were measured and various examinations were carried out for integrity assessment on all the weld joints. Addition of a Ni-Fe buttering layer leads to the development of more favourable properties than observed in welded joints made using the current practice without a buffer layer. Control of carbon migration and its subsequent effect on metallurgical, mechanical properties due to buffer layer has been justified in the study. Conventional procedure of DMW fabrication has been proven to be the least favourable against the new technique suggested. Modification in current integrity assessment procedure would be possible by considering the properties at interfacial regions, introduction of yield strength ratio mismatch and the plastic instability strength in the integrity assessment.

1. Introduction

In nuclear power plants, the light water reactor pressure vessel is made of ferritic steel, typically SA508Gr.3Cl.1, which must be joined to stainless steel pipelines, usually made of SA312 Type 304LN, using arc welding processes. Such dissimilar metal welds (DMW) are typically made with Ni-base consumables as the filler metal in an attempt to mitigate the strong variation in physical, chemical and mechanical properties across the weld [1,2]. It is also common practice deposit a Ni-base (ERNiCr-3) buttering layer onto the ferritic steel before making the joining weld to reduce carbon migration [1–4]. The Ni-base consumables (ERNiCr-3/ENiCrFe-3) are extensively used for DMW joint fabrication because of certain advantages of carbon migration. Despite the necessity of DMW, and the improvement in properties conferred by the use of Ni-base consumables, the desired design life has not been achieved [3–5] and many failures [3,6–9] have occurred. The types of failures and locations [3,6–9] in DMW joints are still remain the big challenge to assess the causes of failures. The performance of DMW joints is greatly affected by other often-associated problems [1–4,10] like degradation of ferritic steel due to oxide notch (low oxidation resistance), metallurgical deterioration at the interfaces, and residual stresses during buttering and welding. During any welding procedure, thermal stresses develop which can be detrimental for structural integrity and performance [11]. In case of DMWs the mismatch in coefficient of thermal expansion (CTE) of austenitic and ferritic steel can cause different stress profile across the weld joint [1,12–18]. The chemical and microstructural variations across the joint can also be severe; the formation of a carbon depleted soft zone and carbon enriched hard zone which forms due to carbon migration [1,2,7,9,12,13,15,17,19–22] has been implicated in failure. Controlling the carbon migration is therefore crucial to minimising the likelihood of failure of the weld. DMW joints have varying metallurgical, mechanical and fracture toughness properties across the weld joint, which also affect the integrity of joints.

Although it has been shown in earlier study of Rathod et al. [7] that carbon migration can be controlled through the use of Ni-Fe alloy buffer layer in buttering made with Gas Metal Arc Welding (GMAW) process and ERNiCr-3. The implications of a Ni-Fe alloy buffer layer in buttering using GMAW process on the mechanical properties of the joint have yet to be documented. Variations in welding processes also have the potential to influence

* Corresponding author.
E-mail address: dineshvrathod@gmail.com (D.W. Rathod).
[1] Present address: MTRL, School of MACE, University of Manchester, United Kingdom, M13 9PL.

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metallurgical and mechanical properties across the joint. Standard practice is to deposit buttering layer of Inconel 82 (ERNiCr-3) using Gas Tungsten Arc Welding (GTAW) process and a completion weld (fill-pass welding) with filler metal Inconel 182 (ENiCrFe-3) using Shielded Metal Arc Welding (SMAW). This study compares the microstructural and mechanical properties of joints produced using standard practice and those made with an intermediate Ni-Fe alloy buffer layer in the buttering deposited with GMAW [7,23] technique. GMAW process is not commonly used for preparing DMWs due to mixing of O_2 or CO_2 in argon gas shielding to maintain the arc stability. In present study, we demonstrate the use of GMAW with pure argon shielding for buttering and completion of welds. A comprehensive assessment of the integrity of the welds was carried out by means of 100% radiographic inspection of weld joints, all-weld tensile test of weldment zones, composite tensile test, Charpy V-notch test of weldment zones, fracture toughness of weld, angular distortion, chemical analysis, microstructure evolution and the micro-hardness measurement across the weld joints.

2. Materials and experiments

2.1. Materials and welding

The quenched and tempered SA508Gr.3Cl.1 and austenitic SS304LN steel supplied in solution annealed condition of pipe form were machined into plate form (150 × 50 × 18 mm) samples with single 'V' groove geometry with compound bevel joint design. Four DMW joints were fabricated with two different buttering procedures and two different completion weld procedures. For two samples, four layers of buttering, with total of sixteen passes of 2 mm diameter ERNiCr-3 TIG rod were deposited using GTAW process onto the machined surface of two SA508Gr.3Cl.1 plates. For remaining two samples, an initial intermediate buffer layer of Ni-Fe alloy (ERNiFe-CI) was deposited with GTAW process, the subsequent three buttering layers were deposited by GMAW process using 1.1 mm ERNiCr-3 MIG wires as described in earlier study [7] to give a total of thirteen passes for the four layers. The thermal expansion and the tensile properties of consumables and base metals are same as the properties reported in earlier study [8]. Chemical composition of base metals (BM) and filler metals (FM) used in study is given in Table 1.

The schematics of buttering layers employed on ferritic steel plates after re-machining for groove geometry are shown in Fig. 1 (A) and (B) for the groove geometry of buttering deposits without and with buffer layer respectively. GTAW buttering employed by 3 mm diameter tungsten electrode with straight polarity using ERNiCr-3 and ERNiFe-CI filler metals. Pure argon gas at 7 L/min was provided during GTAW while, 14 L/min was employed during GMAW process. The contact tube to work distance (CTWD) was

Table 1
Chemical composition of base metals (BM) and filler metals (FM).

Materials and Consumables	Weight Percentage (wt%)						
	C	Ni	Cr	Fe	Mn	Nb	Ti
SA508Gr.3Cl.1(BM)	0.197	0.53	0.12	96.95	1.30	–	–
SS304LN(BM)	0.025	8.22	18.09	70.83	0.83	0.01	–
ERNiFe-CI (FM) (TIG - 2.4 mm)	0.025	53.01	0.15	43.24	0.74	0.003	–
ERNiCr-3(FM) (TIG - 2 mm)	0.017	72.71	19.86	1.40	2.94	2.75	0.41
ERNiCr-3(FM) (MIG - 1.1 mm)	0.016	72.47	20.01	1.28	2.74	2.88	0.36
ENiCrFe- 3 (FM) (4 mm)	0.042	67.17	14.09	6.83	7.51	1.99	0.45

maintained ~15–18 mm while the wire feed rate adopted was 4.57 m/min for GMAW process. The interpass temperature during buttering and welding was maintained between 150 and 180 °C. The process parameters employed for the buttering are given in Table 2.

To attain lesser angular distortion, the compound bevel angle provided in the joint geometry followed by preliminary investigation. The compound bevel geometry as shown in Fig. 2 (A) and (B) has been employed for the joints fabricated with SMAW and GMAW processes respectively.

The buttering deposits were examined for defects using Dye Penetrant test as per the criteria of ASME Sec-V, Article 6. After finding them to be defect free, the completion welds were carried out. GTAW was used to produce two root passes using ERNiCr-3 TIG rods and back purging. The subsequent completion welds were made with either SMAW or GMAW. The process parameters during completion weld are given Table 3. The weld joints were classified as A-1, A-2, B-1 and B-2 according to the buttering and welding processes used and can be seen in Table 3.

All welding activities (GTAW and SMAW, GMAW) were carried out in manual mode as per requirement of ASME Sec-IX. Uniform dilution was attained by adopting the weaving bead deposition and the run-in and run-out defects were to minimised by using dummy blocks. The four as-welded joints after removal of dummy blocks are shown in Fig. 3.

All four weld joints were subjected to 100% radiographic inspection as per the requirement of ASME Sec-V, Article 2 and the joints were qualified according to the acceptance criteria of ASME Sec-III.

2.2. Testing methods and procedure

2.2.1. Specimen fabrication

The typical length of each weld joint was 150 mm out of which specimens were extracted for mechanical and metallurgical test. All specimens were extracted and machined using wire cut electric discharge machine (EDM). The location of specimens on the weld joints is shown in Fig. 4. Three specimens for composite tensile test (CTT), five sub-size specimens for Charpy V-notch test from each region of weldment, one specimen for fracture toughness of weld metal by single edge bend specimen (SEBN), two specimens for metallurgical investigation and remaining length was used to extract the four specimens from each weldment region for all-weld tensile test.

The extracted specimens and their respective positions on weld joints are shown in Fig. 5 for all-weld tensile test. The position of extraction of Charpy V-notch test specimens for each weldment region shown in Fig. 6. The specimen from HAZ ferritic steel, buttering, and weld metal regions are shown in Fig. 6A, B and C respectively.

The extraction position of composite tensile test specimens and fracture toughness (SENB) specimens are shown in Fig. 7(A) and (B) respectively.

2.2.2. Mechanical testing

ASTM E8M standard was used for machining and testing the sub-size tensile (standard sheet type) specimens at the ambient temperature (24 °C) for composite tensile test and the all-weld tensile test. The INSTRON 5582 machine was used with 2.5 mm/min strain rate for all tensile specimens under this test. The standard sub-size specimens for Charpy V-notch impact test were machined according to the dimensions specified in ASTM E23 standard by considering the notch position in desired weldment region. The V-notch dimensions were confirmed with shadowgraph profiler. The testing was conducted on conventional calibrated machine at the ambient temperature (24 °C). The specimen