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Microstructure, local mechanical properties and stress corrosion cracking susceptibility of an SA508-52M-316LN safe-end dissimilar metal weld joint by GTAW

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ABSTRACT

The microstructure, local mechanical properties and local stress corrosion cracking susceptibility of an SA508-52M-316LN domestic dissimilar metal welded safe-end joint used for AP1000 nuclear power plant prepared by automatic gas tungsten arc welding was studied in this work by optical microscopy, scanning electron microscopy (with electron back scattering diffraction and an energy dispersive X-ray spectroscopy system), micro-hardness testing, local mechanical tensile testing and local slow strain rate tests. The micro-hardness, local mechanical properties and stress corrosion cracking susceptibility across this dissimilar metal weld joint vary because of the complex microstructure across the fusion area and the dramatic chemical composition change across the fusion lines. Briefly, Type I boundaries and Type II boundaries exist in 52Mb near the SA508-52Mb interface, a microstructure transition was found in SA508 heat affected zone, the residual strain and grain boundary character distribution changes as a function of the distance from the fusion boundary in 316LN heat affected zone, micro-hardness distribution and local mechanical properties along the DMWJ are heterogeneous, and 52Mw-316LN interface has the highest SCC susceptibility in this DMWJ while 316LN base metal has the lowest one.

1. Introduction

Dissimilar metal weld joints (DMWJs) widely exist in the nuclear power system as many kinds of structural materials are chosen to make different components which should be welded together to make the whole system, e.g. low-alloy steels (LAS) for steam generators, pressure vessels and their nozzles, 316L (N) stainless steels for primary pipes and 690 nickel-based alloys for heat-exchange pipes in steam generators. Among these kinds of DMWJs, safe-end (a transition tube between the pipe-nozzle of pressure vessels and the primary pipe) DMWJ has attracted much attention of researchers and operating enterprises [1–4], as premature failures, mainly stress corrosion cracking failures, have occurred in these kinds of joints [5]. Since the nozzles of pressure vessels and safe-ends are usually fabricated using LAS and stainless steels respectively, the filler metal together with the LAS nozzle and the stainless steel safe-end forms the safe-end DMWJ. What's more, the study of DMWJ has become a new industry hot spot [6–11].

Though stainless steels, e.g. ER308L, ER309L, are usually used as the filler metals for safe-end DMWJ for the operating nuclear power plants now [12,13], using nickel-based welding consumables, such as, Alloy 82/182, Alloy 52/152, and Alloy 52M has become the trend due to their high corrosion resistance and proper coefficient of thermal expansion. However, SCC has been found in DMWJs with austenitic stainless steels, low-alloy steels, nickel-based alloys and Alloy 82/182 weld metals. Coolant leakage in the primary pressure boundary of pressurized water reactors caused by primate water SCC in Alloy 82/182 has been reported [14,15]. By detailed characterization of the transition region of Alloy182/SA508 interface and SCC behavior of this area in primary water environment, Peng et.al found that the SCC was usually confined in the weld metal Alloy 182 [16]. Though Alloy 52/152 has higher chromium content and accordingly has higher corrosion resistance than alloy 82/182, Alloy 52/152 is also susceptible to hot cracking, specifically, ductility-dip cracks, as their very long and straight grain boundaries are easily cracked during thermal-force loading or during the multi-pass welding process [17,18]. As a result, by

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increasing the content of molybdenum and niobium to form MC carbides at the grain boundaries to inhibit their migration which leads to the winding grain boundaries, 52M weld metal was developed. Though 52M are commonly used as filler metals now, most of the published researches or technical papers are about the microstructure, SCC behavior, and mechanical properties of safe-end DMWJ with Alloy 82/182 [1,19] and Alloy 52/152 [3] as filler metals. Detailed researches about the safe-end DMWJ with 52M should be performed as the knowledge of this kind of DMWJ is limited and no in-service experience is reported.

As well known, a traditional DMWJ consists of four distinct microstructural zones (fusion zone, unmixed zone, heat affected zone and base metal) and two distinct interfaces (e.g. low alloy steel-Alloy 52M interface and Alloy 52M-stainless steel interface for safe-end DMWJ). Every zone has its own microstructure and correspondingly has its own mechanical and SCC resistance properties. In the HAZ, solid-state transitions make the microstructure much more complex. What's more, due to the very different compositions and crystallographic structures across the interfaces, the microstructures and properties near the fusion lines differ greatly from those of the base metals and filler metals [2,20]. In addition, phenomena which are detrimental to the performance of the DMWJ occur during the welding process, e.g. the formation of carbon depleted zone near the fusion boundary in the HAZ of LAS due to C migration [12,21,22], the formation of Type I boundaries and Type II boundaries which have been proved susceptible to SCC in fusion zone near fusion boundary [1,23,24], the generation of residual stress/strain near the fusion boundary because of the differential thermal expansion between the base metal and the filler metal [12,22], the changes of the grain boundary type in the HAZ of austenitic stainless steels [25], the formation of martensite layer at the LAS-weld metal interface [21], and so on.

The microstructure, mechanical properties and SCC behavior of the safe-end DMWJ with 52M as filler metal in the nuclear plant should be studied in detail to improve the structural integrity of the weld joint and the safe operation of the future plants as no in-service experience of this kind of DMWJ is available. As a result, the microstructure, local mechanical property and local SCC behavior of a domestic safe-end DMWJ with SA508 LAS and 316LN as base metals and 52M as filler metal was studied in this research.

2. Materials and experimental procedures

2.1. Materials and welding process

SA508Gr.3 Cl.1 low alloy steel (SA508) and SA182 F316LN stainless steel (316LN) were the bases metals, while Alloy 52M was chosen as the filler metal of this domestic DMWJ. At first, a buttering layer with the thickness of 20 mm was deposited on the single-V groove of SA508 which had been preheated to more than 121 °C through an Alloy 52M welding wire (Φ 1.2 mm, cold wire) by automatic multi-pass gas tungsten arc welding (GTAW). Then post weld heat treatment (at 610 °C for about 40 h) was performed on the buttering to release the weld-residual stress. Then, multilayer welding was carried out between the buttering layer and the 316LN stainless steel safe-end pipe by GTAW and Alloy 52M welding wire (Φ 0.9 mm), without any post weld heat treatment. To be convenient, the buttering layer was named as 52Mb and the lateral welding area was named as 52Mw. The chemical composition of the base metals and the filler metal are given in Table 1. The welding parameters are given in Table 2. The photograph of the DMWJ is shown in Fig. 1. The inner part of pipe nozzle was protected by stainless steel cladding (309L and 308L).

Table 1
Chemical composition of materials in DMWJ (wt%).

Materials	C	Si	Mn	Cr	Ni	S	P	Fe	N	Mo	Co	Cu	Sn	Al	Ti	Nb	Cb (Nb)+Ta	V	As	B	Zr	Others
316LN	0.023	0.52	1.65	16.73	11.32	0.004	0.019	Bal.	0.109	2.34	0.028	–	0.003	–	–	–	–	–	0.006	–	–	–
SA508	0.22	0.18	1.25	0.008	0.86	0.002	0.005	Bal.	–	0.47	0.007	0.07	–	0.007	0.006	0.003	–	0.001	–	0.002	–	–
52Mb	0.024	0.10	0.75	30.21	59.12	0.0005	0.003	8.56	0.009	0.01	0.006	0.02	–	0.11	0.23	–	0.83	0.01	–	0.001	< 0.01	< 0.494
52Mw	0.023	0.11	0.90	29.76	58.80	< 0.0005	0.003	8.74	0.006	0.10	0.006	0.02	–	0.11	0.19	–	0.89	–	–	0.0005	0.003	< 0.494