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Comparative study of microstructure and properties of low-alloy-steel/nickel-based-alloy interfaces in dissimilar metal weld joints prepared by different GTAW methods

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ABSTRACT

Low-alloy-steel/buttering (or welding) metal interfaces in safe-end dissimilar metal weld joints (DMWJs) at nuclear power plants are weak parts. To optimize the quality of the safe-end DMWJs used for the construction of domestic nuclear power plants and to improve the welding productivity, a series of DMWJs in full-size have been manufactured by using different gas tungsten arc welding (GTAW) methods. The microstructure, chemical composition distribution and local properties across the SA508/52(M) interfaces in these DMWJs are studied. The high heat input and long high temperature duration during hot-wire GTAW process promote the carbon diffusion and grain boundary migration and hence the DMWJ by hot-wire GTAW has the largest amount of type I and type II boundaries and the widest carbon depleted zones and carbon enriched zones, which resulting in the worst performance among the DMWJs in simulated primary water. Type I and type II boundaries are high angle random grain boundaries (RGBs) and Cr-depleted zones are found along type II boundaries resulting in their high susceptibility to SCC. In addition, these boundaries are prone to be cracked during mechanical bending process.

1. Introduction

During the construction of nuclear power plants (NPPs), dissimilar metal weld joints (DMWJs) are applied to connect the low-alloy-steel (LAS) nozzles of the pressure vessels to the stainless steel safe-end pipes [1–3]. And operating experience of the major NPPs show that DMWJ can jeopardize the plant availability and safe operation as premature failures, mainly stress corrosion cracking (SCC), occurred at this point, especially at the LAS/buttering (or welding) metal interface [4]. Some safe-end DMWJ failures have happened, and the most typical case was found in V.C. Summer NPP in 2000 [5]. The failure initiated from the welding defect in the cladding layer, then propagated to the LAS/buttering metal interface and then kept propagating along this interface.

Nickel based 52/52M alloys rather than 82/182 alloys have been widely used as the filler metals to fabricate this kind of DWMJs in newly designed NPPs because of their higher corrosion, hot cracking and SCC resistance than 82/182 alloys [6–9]. However, the selection of new materials for the safe-end DMWJ is based on the laboratory experiments and short-term service experience, no long-term service experience of these DMWJs is available. And some researchers have announced that the LAS/weld-metal (WM) interface is the weakest part of the safe-end DMWJs as the existence of type I boundaries, type II boundaries, martensite layer, carbon diffusion, dilution, and the dramatic change of mechanical properties across this interface, etc. [2,10–15]. The low resistance to SCC of this interface is closely related to these particular microstructures and composition distribution.

Some research concerning the microstructure and properties of the LAS/52 (or 52M) WM have been published [3,12,16]. The microstructures of several DMWJ mock-ups were studied by Hänninen et al. and very complicated microstructure and hardness distribution were found [17]. Local mechanical properties and microstructure of the LAS/52M interface were thoroughly investigated by Wang et al. as they were significant for the integrity assessment of the DMWJ [1]. Chung et al. found the presence of the type II boundaries could significantly reduce the resistance to SCC in a multi-pass Alloy 52/SA508 dissimilar weld [3]. The microstructure and SCC of the Alloy 152-A533B interface were studied by Hou et al. and found that the special microstructure at this interface could significantly decrease its SCC resistance [2].

Although the microstructure and related properties of the LAS/52 (or 52M) WM have been widely studied, some problems still exist: (i) The welding parameters used to fabricate the weld joint in most of the research are different from the ones used to make the DMWJ in real

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NPPs which could result in extremely different microstructure and related properties. (ii) More detailed microstructure characterization and related properties including micro-hardness, SCC resistance et al. should be performed to understand the DMWJs.

To optimize the quality of the safe-end DMWJs used for the construction of domestic nuclear power plants in China and to improve the welding productivity, Shanghai Electric Group (China) has manufactured a series of DMWJs in full-size (the same size and same shape as the ones used in the nuclear power plants) using automatic multi-pass gas tungsten arc welding (GTAW) with different welding parameters. This research includes three DMWJs: a DMWJ with a buttering layer fabricated by cold-wire GTAW (named as C-DMWJ), a DMWJ with a buttering layer fabricated by hot-wire GTAW (named as H-DMWJ) and a DMWJ without a buttering layer (named as W-DMWJ). Detailed microstructure characterization of these three DMWJs have been published [18–20]. The focus of this research is to reveal the effect of welding methods on the microstructure and properties of the low-alloy-steel/nickel-based alloy interfaces in these three DMWJs.

2. Materials and Experimental Procedures

2.1. Materials and Welding Process

The photographs of the three DMWJs and their corresponding schematic cross-sections are shown in Fig. 1. The base metals and the filler metals are summarized in Table 1. Welding processes have been described in detail before [18–20]. Here, we just introduce these joints briefly. For C-DMWJ and H-DMWJ: the base metals were SA508 low alloy steels and 316LN stainless steels and 52M was used as filler metal; 52M was firstly buttered on the SA508 grooves by GTAW (C-DMWJ used cold-wire GTAW while hot-wire GTAW was applied for H-DMWJ); then the buttering layers were post weld heat treated (PWHT); after that, cold-wire GTAW was used to connect the buttering layers and the stainless steel safe-ends and no PWHT was applied after the final welding process. For W-DMWJ: base metals were SA508 and 316L respectively; no buttering technique was applied; the low alloy steel nozzle and the safe-end was directly connected by cold-wire GTAW with 52 filler metal; the weld joints was not post weld heat treated neither. To be convenient, the buttering layer was named as 52 Mb and the lateral welding area was named as 52 Mw. Detailed chemical compositions of the base metals and filler metals, and welding parameters are listed in Tables 2–7, respectively.

Table 1
Summary of the base metals, filler metals, welding methods and post weld heat treatment (PWHT) of DMWLs.

Weld joint	Base metals		Buttering layer		Weld zone		PWHT
C-DMWJ	SA508	316LN	52M	GTAW, cold-wire	52M	GTAW	Buttering, yes Weld, no
H-DMWJ	SA508	316LN	52M	GTAW, hot-wire	52 M	GTAW	Buttering, yes Weld, no
W-DMWJ	SA508	316L	Without		52	GTAW	No

2.2. Microstructure Characterization

Samples across the SA508/52(M) interfaces in the three DMWJs were cut by electro-discharge machining for microstructure characterization and micro-hardness test. For metallographic examination, the samples were gradually ground with successive silicon papers up to

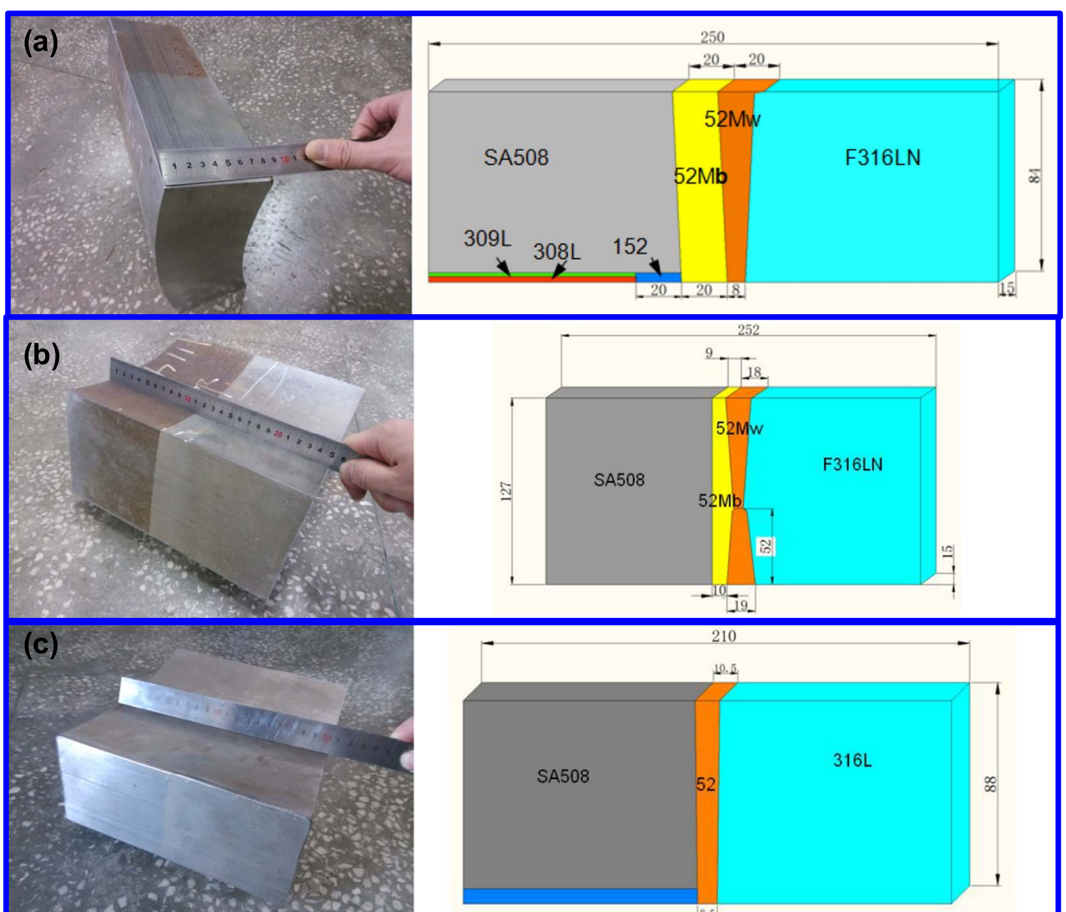

Fig. 1. Photograph of the three safe-end DMWJs and their schematic cross-sections: (a) C-DMWJ, (b) H-DMWJ and (c) W-DMWJ.

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