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An experimental investigation of local fracture resistance and crack growth paths in a dissimilar metal welded joint

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ABSTRACT

An experimental investigation on the local fracture resistance and crack growth behavior in a Alloy52M dissimilar metal welded joint (DMWJ) between A508 ferritic steel and 316L stainless steel has been carried out by using the single-edge notched bend (SENB) specimens. The local J-resistance curves and crack growth paths of 13 cracks located at various positions in the DMWJ were determined, and the effects of the local strength mismatch on local fracture resistance, crack growth paths and integrity assessment for the DMWJ were analyzed. The results show that the cracks always deviate to the materials with lower strength, and the crack path deviations are mainly controlled by the strength mismatch, rather than toughness mismatch. The J-resistance curve with larger crack path deviation only reflect the apparent fracture resistance along the crack growth region, rather than the intrinsic fracture resistance of the material at the initial crack-tip region. Without considering the local fracture resistance properties of heat affected zone (HAZ), interface and near interface zone, the use of the J-resistance curves of base metals or weld metals following present codes will unavoidably produce non-conservative (unsafe) or excessive conservative assessment results. In most cases, the assessment results will be potentially unsafe. Therefore, it is recommended to obtain and use local mechanical and fracture resistance properties of all regions of the DMWJ if the complex local mismatch situation is a concern. And new integrity assessment methods based on local damage and fracture models also need to be developed for the DMWJs.

1. Introduction

Dissimilar metal welded joints (DMWJs) are widely used in primary water systems of pressurized water reactors (PWRs) in nuclear power plants (NPPs). They are mainly used to join the ferritic steel pipe-nozzles of the pressure vessels (such as reactor pressure vessels, steam generators and pressurizers) to the austenitic stainless steel safe-ends, as typically shown in Fig. 1. Nevertheless, the welds were indicated to be vulnerable components from the international surveys, owing to their proneness to different types of flaws. Axial and circumferential defects within DMWJs caused by stress corrosion or fatigue have been found in the NPPs in many countries [1,2]. In addition, serious leakage events on such DMWJs have also been reported [3,4]. Thus, maintaining integrity of such joints in case of defect presence and structure overloading is critical to ensure their safe service. To do this, an accurate structural integrity assessment for such DMWJ structure is very important.

Determining complete fracture information on the critical regions of welded joints is essential for conducting an accurate integrity assessment and understanding the joint performance in service. However, due to highly inhomogeneous nature across the DMWJ in terms of microstructure, mechanical, thermal and fracture properties, it is difficult to conduct analytical or experimental fracture investigations on the DMWJs. In the literature [5–13], some studies on the fracture behavior for the DMWJ can be found. A series of fracture and tensile tests have been performed to evaluate the tensile properties and fracture resistance of DMWJ between SA508 ferritic steel and 304L stainless steel (SS) using E308L SS as a filler metal in the BiMET and ADIMEW programs within the European Commission [5–7]. More recently, the tensile properties and local fracture resistance of weld joints between SA508 ferritic steel and F316 SS using Alloy82/182 as a filler metal have been evaluated at room temperature (RT), and the spatial variation of these properties along the width and thickness of the weld joints have been examined [8–10]. Laukkanen et al. [11] conducted an investigation using Charpy-size three point bend (3 PB) specimens on the fracture behavior for various regions of SA508/AISI304 DMWJ. Samal et al. investigated the failure behavior of a DMWJ by experiments and numerical simulations [12,13]. Most studies above have shown that the local fracture resistance behavior and crack growth paths are different when initial cracks were located at different positions of the welded joints. However, the studies above were mainly limited as-welded plates, which may not reflect the local mechanical and fracture properties of a real

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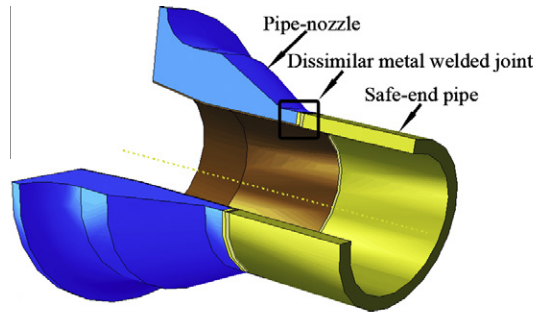

Fig. 1. The DMWJ structure for connecting the pipe-nozzle of the AP1000 reactor pressure vessel to safe-end pipe.

DMWJ made for NPPs. Besides, Inconel Alloy82 and 182 were found to be susceptible to stress corrosion cracking (SCC) in the primary water environment [14,15]. Inconel Alloy52 and 152 with high resistance to SCC have been used to replace the Alloy82 and 182 in new PWRs. High chromium nickel-base weld filler metal Alloy52 (ERNiCrFe-7) and Alloy52M (ERNiCrFe-7A) have been widely used as filler metals for repair applications and fabrications for new nuclear power plants. Thus, clarifying the fracture behavior of the DMWJs made from these new materials is critical for integrity assessment and design of the DMWJ structures. An in situ observation for local fracture behavior in an Alloy52M DMWJ has been performed by authors, and different crack initiation and growth behaviors were found when the initial cracks were located at various positions of the DMWJ [16].

On the other hand, in the integrity assessment methods for weld joints in existing codes, such as R6 [17], SINTAP and FITNET FFS [18], the weld joints are often simplified as a sandwich composite composed of base metal and weld metal, and the effects of the interface fusion regions between different materials and heat affected zones (HAZs) are usually ignored. In fact, defects in welded structures can occur anywhere, such as in the fusion zone, HAZ, weld, near weld, interface region, and base metal. The use of adequate and precise material input parameters (based on the experimental observation of the local damage and fracture process in the joint area) is particularly essential to describe and predict the critical condition in welded structures [18]. Therefore, the local fracture resistance and crack growth behavior of all regions should be investigated and understood.

In this study, the local fracture resistance and growth paths in a real Alloy52M dissimilar metal welded joint (DMWJ) between A508 ferritic steel and 316L stainless steel in NPP were investigated by using the single-edge notched bend (SENB) specimens. The effects of the local strength mismatches at various crack positions on local fracture resistance properties, crack growth paths and integrity assessment were analyzed.

2. Experimental procedures

2.1. Materials and fabrication of the DMWJ

A full scale mock up of the DMWJ was fabricated by Shanghai Company of Nuclear Power Equipment in China, as shown in Fig. 2a, and it was prepared for connecting the safe end to pipe-nozzle of the Westinghouse design AP1000 reactor pressure vessel. The pipe-nozzle material is ferritic low-alloy steel (A508), and the safe end pipe material is austenitic stainless steel (316L). The weld was manufactured by applying a buttering technique and the buttering material as well as weld material is the same nickel-base alloy (Alloy52M), but their manufacture procedures were different. The detailed geometry and size of the DMWJ are shown in Fig. 2b (the detail of the "A-A" in Fig. 2a). The buttering layer was deposited through an Alloy52M welding wire (the diameter of wire is 1.2 mm) by automatic gas-tungsten arc welding (GTAW) on the ferritic nozzle face. The welding current, voltage and speed

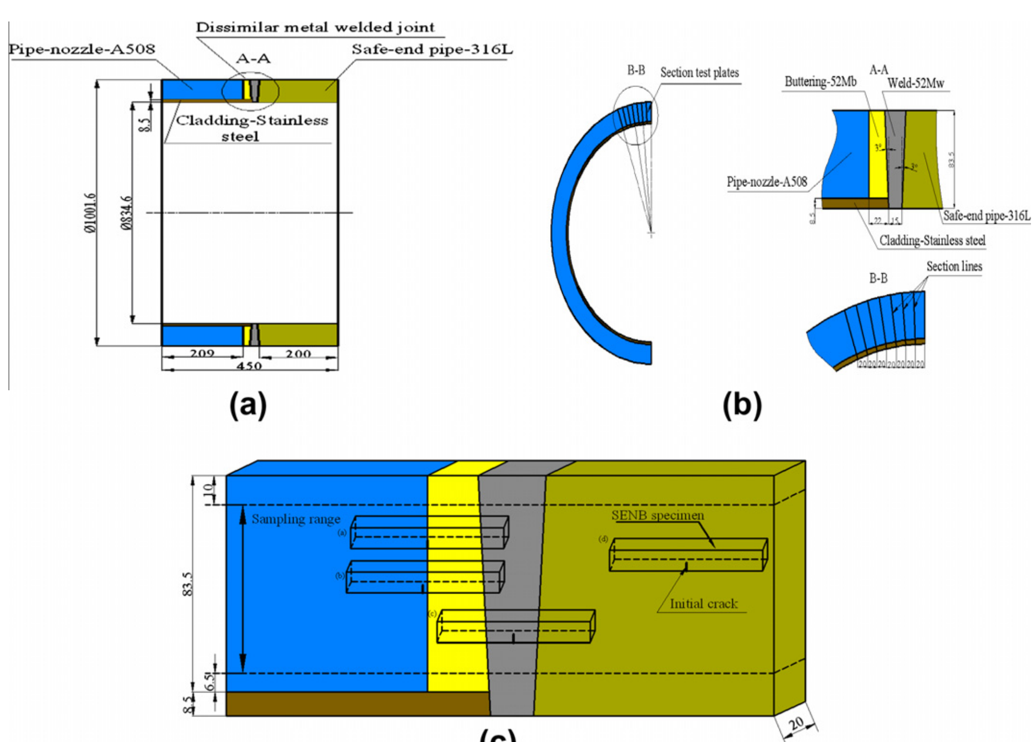

Fig. 2. Geometry of a full scale mock up of the DMWJ (a), the DMWJ sizes and method of cutting testing plates from the mock up (b), and the location of sampling SENB specimens from the testing plates (c); the detail of the "A-A" in (a) being shown in (b).