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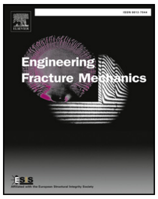

A comparison between fracture toughness at different locations of SMAW and GTAW welded joints of primary coolant piping

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ABSTRACT

Two primary coolant pipes were narrow-gap multipass circumferentially butt welded by gas tungsten arc welding (GTAW) and shielded metal arc welding (SMAW) methods separately and then subjected to micro-hardness tests to distinguish the base metal (BM), heat affected zones (HAZs), fusion zones (FZs) and weld metal (WM). Subsequently, uniaxial tensile tests were performed with a 3D DIC system to investigate the strain evolution of each area in GTAW and SMAW welded joints and to compare respective tensile properties. The fracture toughness has been investigated at the above four different locations of the SMAW and GTAW welded joints. Then the 0.2 mm offset line method and the stretch zone width method have been both employed to determine the critical initial fracture toughness J_i. The results indicate that the fusion zones (FZs) have the worst fracture toughness compared with other locations over both two types of weld joints. In addition, the GTAW welded joints have a better comprehensive performance than the SMAW welded joints.

1. Introduction

The cast austenitic stainless steels (Z3CN20.09M) are widely fabricated into primary coolant pipes utilized in nuclear power plants (NPPs) with pressurized water reactors (PWR) due to their adequate strength and superior corrosion resistance [1–3]. For primary coolant piping materials Z3CN20.09M, the main failure mode is fracture induced by cracks and manufacturing defects in the pipes [4]. Therefore, the fracture toughness values are the required parameters for characterizing material resistance to fracture. In view of the inherent characteristics of the welding process, the fracture toughness of heat affected zones (HAZs), fusion zones (FZs) and weld metal (WM) are harder to control than that of the base metal (BM) and these regions have therefore become a weak link in pipelines [5,6]. For this reason, it is necessary to investigate the fracture toughness difference between different regions of welded joints [7,8]. The most commonly used forms of welded pipeline are either with shielded metal arc welding (SMAW) joints or gas tungsten arc welding (GTAW) joints [9,10].

In general, the SMAW process is commonly employed in industry because it uses low cost fillers and can be more easily performed than other welding techniques [11,12]. However, the welding filler is a determining factor for the microstructure and mechanical properties of the welds. In processes with high thermal input alloying elements, such as Cr and Mo, the presence of dendritic or hard phases could result in reduced ductility and brittleness – even if the material is hard and strong [13]. Therefore, SMAW has a lower welding quality, efficiency and stability. In addition, the GTAW welding method has been widely applied to primary coolant piping in

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Nomenclature

A	elongation [%]
a	crack length [mm]
Δa	crack extension [mm]
B_N	net thickness due to side grooving [mm]
BM	base metal
C	fitting parameter in J-R curves
$C_{C(i)}$	specimen crack opening compliance on an unloading/reloading sequence, corrected for rotation
CMOD	crack mouth opening displacement [mm]
E	elasticity modulus [GPa]
f	polynomial function
FZs	fusion zones
HAZs	heat affected zones
J_Q	critical initial fracture toughness [N*mm/mm^2]
J_{IC}	critical initial fracture toughness (0.2 mm offset line method) [N*mm/mm^2]
J_{SZW}	critical initial fracture toughness (stretch zone width method) [N*mm/mm^2]
K_i	the stress intensity factor
n	strain hardening exponent in J-R curves
P_i	instantaneous load [N]
R_m	tensile strength [MPa]
$R_{p0.2}$	yield strength [MPa]
W	specimen width [mm]
WM	weld metal
γ	crack length dependent factors
η	geometry factor
ν	Poisson's ratio
σ_o	flow stress [MPa]

AP100 nuclear power plants because it can reduce not only the cross-sectional areas of welding grooves but also the filling amount of welded metals substantially [14]. More importantly, the GTAW can achieve the high efficiency welding under the low heat input of the welding process [15].

SMAW and GTAW welded joints of primary coolant piping are of fundamentally important in the nuclear power industry, but only few reports publicly available on the comparison between SMAW and GTAW welded joints, especially the comparison between fracture toughness at different locations of SMAW and GTAW welded joints. In this study, two primary coolant pipes were narrow-gap multipass circumferentially butt welded by GTAW welding and SMAW methods separately and then subjected to micro-hardness tests to distinguish the base metal (BM), heat affected zones (HAZs), fusion zones (FZs) and weld metal (WM). Subsequently, uniaxial tensile tests were performed with a 3D DIC system to investigate the strain evolution of each area in GTAW and SMAW welded joints and to compare respective tensile properties. The fracture toughness has been investigated at the above four different locations of SMAW and GTAW welded joints.

2. Material and experimental details

The two primary coolant pipes with an outer diameter of 935 mm, a thickness of 76 mm and a length of 250 mm were narrow-gap multipass circumferentially butt welded, using GTAW welding and SMAW method separately. The preheating temperature was 200 °C and the inter-pass temperature was kept below 100 °C. Welding specifications for each pass are given in Table 1. After welding, the heat treatment process (600 °C × 20 h) was applied to reduce residual stresses.

The material used in the pipe is Z3CN20.09M and the chemical compositions of the welded joints are presented in Table 2. The typical microstructure of the SMAW and GTAW welding joints is shown in Fig. 1.

After welding, the micro-hardness tests along the centerline and in the transverse direction of welded joint, accompanied with metallographic observation in the optical microscope, were carried out to distinguish the BM, HAZs, FZs and WM both in the GTAW welding and SMAW joints. Subsequently, as shown in Figs. 2 and 3, the uniaxial tensile specimens were cut from welding joints where base metal (BM) located in center and then subjected on MTS Model 810 test machine with a 3D DIC system (4 M, from GOM mhH Ltd., Germany) to investigate the strain evolution of each area in GTAW and SMAW welded joints. As shown in Fig. 4, the tensile and fracture toughness specimens were separately cut in BM, HAZs, FZs and WM of the GTAW and SMAW welded joints. The tensile specimens from each area both in the GTAW and SMAW welded joints were subjected on MTS Model 810 test machine to compare tensile properties.

Single-edge bend (SEB) specimens were shown in Fig. 5 and then employed for carrying out monotonic single specimen J-R tests on a servo hydraulic universal testing machine (MTS Model 810) at room temperature. According to ASTM E1820 (2015) specifications [16], fracture toughness specimens were fatigue pre-cracked under decreasing ΔK, and then each specimen was side-grooved to 10% of its gross thickness on each side. After fracture toughness tests, microstructural observations using a Tescan VEGA TS 5136XM scanning electronic microscopy (SEM) were employed to study the SZW spanning the culmination of pre-fatigue cracks and

Table 1
Welding specifications of the shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW) methods.

Welding methods	Base materials		Welding materials	
	Grades	Dimensions	Grades	Dimensions
Shielded Metal Arc Welding (SMAW)	Z3CN20.09M	Φ935 × 95 mm	OK Tigrod 316L + OK 63.25N	Φ1.6 + Φ3.2/Φ4.0
Gas Tungsten Arc Welding (GTAW)			ER316L/ER316LSi	Φ0.8/Φ1.0