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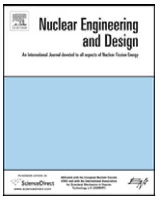

Plastic η factor considering strength mismatch and crack location in narrow gap weldments

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ABSTRACT

The fracture toughness for LBB analysis of piping is generally determined in terms of the *J*-integral according to ASTM E1820. The *J*-integral consists in the elastic component J_{el} and the plastic part J_{pl}. Experimental evaluation of J_{pl} requires the plastic η factor. The *J*-integral evaluation by ASTM method was developed, however, essentially for homogeneous material. The fracture toughness of a strength mismatch weld evaluated as per ASTM method can, thus, differ from its actual value. In this study, the plastic η factors of similar as well as dissimilar metal narrow gap weld are suggested considering the influence of weld strength mismatch, weld width, and crack location. The proposed plastic η factors are compared with detailed finite element results. Few fracture tests were performed to quantify the influence of weld strength mismatch on fracture toughness of low alloy steels using C(T) specimens.

1. Introduction

Since the weld width by the method of narrow gap welding is smaller than that by general welding techniques and the narrow gap welding method reduces the amount of shrinkage and deformation of a welding metal and decreases the residual stresses due to the reduction of welding time, narrow gap welding of the piping of large-scaled structures such as a nuclear power plant has recently become more common (Yang et al., 2011; Engelhard et al., 2000; Henderson and Steffens, 1976; Jang et al., 2010). Most researches on narrow gap welding have focused weld integrity evaluation. In particular, some have focused on the application of leak-before-break (LBB) analysis, which is essential for the design and the management of nuclear power plant piping (Henderson and Steffens, 1976; Zanaboni et al., 2005; Lee et al., 2010).

The fracture toughness for LBB analysis of piping is generally determined according to ASTM E1820(ASTM, 2001) and in the case of plane strain, the *J*-integral is determined by superposing the elastic component J_{el} and the plastic component J_{pl} as follows:

$$J = J_{el} + J_{pl} \tag{1}$$

where

$$J_{pl} = \frac{\eta A_{pl}}{B_N b} \tag{2}$$

In the case of a CT specimen:

$$\eta = 2 + 0.522\frac{b}{W} \tag{3}$$

where η, called the plastic η factor, is a dimensionless constant; A_{pl} is the area of the load-plastic displacement curve; B_N is the net specimen thickness; and b is the residual ligament length. Eq. (3) was found by Clarke and Landes (1979) based on the curve fitting result from a limit load analysis of homogeneous structures.

Generally, in the case of welded piping, cracks can arise at any location of a welded joint, such as a weld metal or the fusion line. Crack analysis for a homogeneous pipe was established by many related studies, but that for a welding pipe has yet to present definite results because of the complex effects of a weld (Saxena et al., 2010;Wang et al., 2011;Kim et al., 2003). Xuan et al. (2005) reported that because Eq. (3) is developed for cracks located in homogeneous materials, it is not suitable for cracks located in welded joints. And in the case of a welded specimen, the equation needs to be modified because of the material mismatch. Also, they insisted that although Tu and Yoon (1999) introduced the material mismatch coefficient to reflect the effect of material mismatch based on FE analysis, it is also necessary to have the simplified estimation for engineering calculations. Also, Wang et al. (1997) reported that the existing equations developed by assuming homogeneous and perfectly plastic material properties may obtained inaccurate results

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Abbreviations: ASTM, American Society for Testing and Materials; CT, compact tension; FEA, finite element analysis; HAZ, heat affected zone; LBB, leak-before-break; R–O, Ramberg–Osgood; 3-D, 3-dimensional.

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Table 1
Chemical composition of materials.

Material	C	Si	Mn	P	S	Ni	Cr	Mo	Al
SA508 Cl.1a	0.2	0.22	1.15	0.01	0.002	0.22	0.096	0.056	0.032
SA508 Cl.3a	0.19	0.08	1.35	0.006	0.002	0.82	0.17	0.51	0.009

Table 2
Welding conditions.

Welding method	Filler metal	
	AWS class	Size (mm)
GTAW (Machine Welding)	ER70S-6	Ø0.9

when the equations are applied to non-homogeneous specimens and materials with strain hardening and proposed the CTOD equations expressed in terms of weld width, strain hardening rate, and mismatch levels.

In welding, the yield strength difference between the base metal and the weld metal affects the whole mechanical property of the welded structure. The ratio of the yield strengths of the base metal and the weld metal is referred to the strength mismatch ratio. The strength mismatch ratio of the base metal and the weld metal M_W, called the mismatch factor, is as follows (Kim et al., 2003; Lee et al., 2010; Kim and Schwalbe, 2001):

$$M_W = \frac{\sigma_{YW}}{\sigma_{YB}} \tag{4}$$

where σ_{YB} and σ_{YW} are the yield strengths of the base metal and the weld metal, respectively. $M_W = 1$ occurs when the whole material is the base metal. $M_W > 1$ occurs when the yield strength of the base metal is lower than that of the weld metal, which is commonly called an overmatch. $M_W < 1$ occurs when the yield strength of the base metal is higher than that of the weld metal, which is called an undermatch.

Also, during welding, the heat affected zone (HAZ) appears. Since the HAZ width is typically very small and the contribution of the HAZ properties to the mismatch yield load is minimal, the HAZ properties are negligible compared to the properties of surrounding constituents such as the weld and the base (Kim and Schwalbe, 2001). Therefore, in this paper, while the yield strength of HAZ was considered in FE analysis, however, the proposed plastic η factors ignored such effects.

In this paper, the plastic η factors in the narrow gap weldments of similar and dissimilar materials, respectively, are suggested with consideration of the effect of strength mismatch, weld width, and crack location. The reliability of the suggested plastic η factors is evaluated by finite element analysis (FEA) and fracture toughness tests, which use the single specimen method according to ASTM E1820.

2. Materials and Ramberg–Osgood constant

2.1. Materials and mechanical properties

The materials used in this study were SA508 Cl.1a and SA508 Cl.3a carbon steel, commonly used for the first stage of piping in nuclear power plants. The pipes have a diameter of 1000 mm and a wall thickness of 100 mm, and were manufactured by narrow-gap welding. Table 1 shows the chemical composition of the materials, and Table 2 shows the welding conditions.

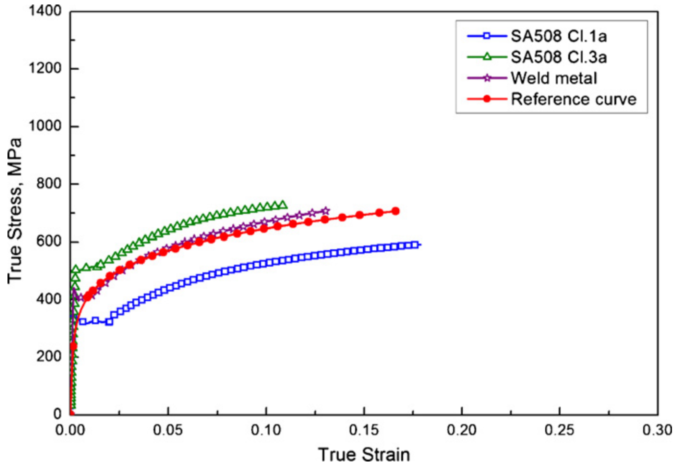

Fig. 1. True stress–true strain curves of base metals and weld metal and reference curve.

Tensile test specimens were collected from the weld metal and the base metal of a real pipe. A tensile test was performed according to ASTM E8 (ASTM, 2002) at room temperature. Table 3 shows the results of the tensile test: strengths of test specimens and the Ramberg–Osgood constant (Ramberg and Osgood, 1943). The mechanical properties of the heat affected zone (HAZ) were obtained using the micro-Vickers hardness tester. Since the hardness value of the HAZ was 5–10% higher than that of the base metal, the yield strength of the HAZ (σ_{YH}) was determined to be 10% higher than the yield strength of the base metal.

2.2. Determination of the R–O constant by reference curve

Fig. 1 shows the true stress–true strain curves for SA508 Cl.1a, SA508 Cl.3a and the weld metal. The R–O equation for the stress–strain relationship of elastic–plastic materials is (Ramberg and Osgood, 1943):

$$\frac{\varepsilon}{\varepsilon_0} = \frac{\sigma}{\sigma_{YS}} + \alpha\left(\frac{\sigma}{\sigma_{YS}}\right)^n \tag{5}$$

where σ_{YS}, ε_0 and n are the yield strength, strain, and the strain hardening exponent, respectively. The values of α and n for each part were obtained from the tensile data, as shown in Table 3. A reference curve similar to the true stress–true strain curve of the weld metal is sought, as shown in Fig. 1. Fig. 2 is obtained by shifting the reference curve according to the variation of yield strength. By using Eq. (5), α and n for the shifted reference curve are obtained as follows:

$$n = 0.01\sigma_{YS} + 1.8 \tag{6}$$

$$\alpha = 196.7\sigma_{YS}^{-0.7} \tag{7}$$

Table 3
Tensile test results.

Material	Yield strength (MPa)	Ultimate strength (MPa)	Ramberg–Osgood constant	
			α	n
Weld	397.7	645.0	3.386	5.188
SA508 Cl.1a	330.4	517.9	5.280	4.845
SA508 Cl.3a	499.3	645.6	2.622	7.727