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Extracting ductile fracture toughness from small punch test data using numerical modeling

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ABSTRACT

This paper presents a numerical method to extract ductile fracture toughness from notched small punch test data using FE ductile damage analysis based on the stress-modified fracture strain model. To validate the proposed method, analysis results are compared with series of mechanical (notched tensile, fracture toughness and small punch) test data for three different materials; low alloy steel SA508 Gr.3, TP316L austenitic stainless steel and CF8M cast austenitic stainless steel. Comparison with experimental fracture toughness data shows that the proposed method can predict fracture initiation values relatively well and tearing resistance conservatively.

1. Introduction

Proper estimation of fracture toughness for aged materials is important in structural integrity assessment of operating plant components. To quantify the effect of aging on fracture toughness, destructive testing methods using fracture toughness testing specimens satisfying size requirements are highly desirable but often are not possible due to unavailability of materials in operating plants. In this respect, semi-destructive testing methods such as the small punch test [1–25] would be useful in practice. The small punch test has been applied to estimate tensile [1–9], fracture toughness [10–15] and creep properties [16–19]. Note that there have been many attempts to extract fracture toughness using the small punch test but most of works have been for brittle fracture with empirical correlations. Recently there have been some attempts to extract *J*–R data for ductile fracture using the small punch test combined with FE damage analysis [20–22]. A key point is how to determine parameters associated with a damage model used in FE damage analysis. As failure of thin small punch test specimens for ductile materials is close to ductile rupture rather than ductile fracture, notched small punch specimens were introduced [23–25]. Even with notched small punch specimens, determination of parameters in damage models can be problematic. For instance, parameters in Gurson–Tvergaard–Needleman (GTN) model [20,21,23] or Rousselier model [22] were determined using iteration processes to fit the simulation results to the small punch test data. Some of the parameters in the models were assumed to the reference values that were found in literature, and the other parameters were determined with the iteration processes. Such determination process would not be straightforward in general.

This paper presents a numerical method to extract ductile fracture toughness from small punch test data using FE ductile damage analysis. The present FE damage analysis is based on the stress-modified fracture strain model and thus an important key in the proposed method is whether this model can be reliably estimated from small punch test data. To show its possibility, the present work consists of three parts. The first part is to determine the stress-modified fracture strain model from notched bar tensile test data. The second part is to predict fracture toughness (*J*–R curve) using FE damage analysis based on the stress-modified fracture strain model. The third part is to estimate the stress-modified fracture strain model from the small punch test and check whether fracture toughness can be estimated. In each step, results are compared with experimental data to gain confidence. Experimental results of three different materials are given in Section 2. Section 3 describes how to determine the stress-modified fracture strain model and to predict fracture toughness using FE

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Nomenclature

a, b	initial crack and ligament length, respectively
B, W	specimen thickness and width, respectively
J	J-integral
L_e	element size
P, P_L	load and limit load, respectively
R_n	notch radius
ε_f	fracture strain
σ_e, σ_m	von Mises equivalent and hydrostatic stress, respectively
σ_y	yield strength
ω, $\Delta\omega$	damage and its increment value
α, β, γ	material constants in the stress-modified fracture strain, see Eq. (2)
Δa	average crack growth amount
$\Delta\varepsilon_p$	plastic strain increment
C(T)	compact tension
NSP	notched small punch
LLD	load line displacement
SP	small punch

damage analysis. In Section 4, FE damage analysis is applied to simulate small punch tests. A method to extract the stress-modified fracture strain model from small punch test data and to predict fracture toughness is suggested in Section 5. The presented work is concluded in Section 6.

2. Experiments

2.1. Materials

Three materials, SA508 Gr.3, TP316L and CF8M, were considered in experiments, commonly used as structural materials in pressurised water reactor nuclear power plants. SA508 Gr.3 is a low alloy steel mainly used for reactor pressure vessels and TP316L austenitic stainless steel used in branch piping of reactor coolant systems. Finally CF8M is a cast austenitic stainless steel used for main coolant piping, pump casing and valve body. The chemical compositions of these materials are listed in Table 1, which are taken from the certified material test report provided by material suppliers.

2.2. Smooth and notched tensile tests

Tensile properties were obtained from smooth bar tensile tests. Furthermore to investigate the effect of tri-axial stress states on tensile deformation and fracture characteristics, tensile tests were also carried out using notched round bars with three different notch radii, R_n = 2.0, 4.0 and 16.0 mm. For all specimens, the diameter of the minimum section was 4.0 mm, as shown in Fig. 1 with other relevant dimensions. Tensile tests were conducted at

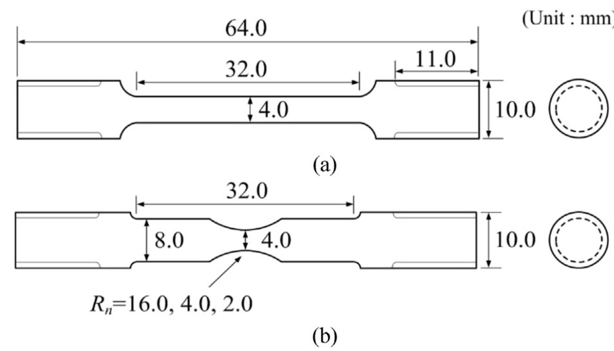

Fig. 1. Dimensions of smooth and notched tensile bars: (a) smooth bar and (b) notched bar.

room temperature, according to ASTM standards [26]. Three specimens were tested for each material and specimen geometry. In tests, the specimens were deformed with the displacement rate of 0.5 mm/min, and the axial displacement of specimen was measured using extensometer with the gage length of 25 mm.

The measured tensile properties are summarised in Table 2. Experimental engineering stress–strain curves from all tensile tests are summarised in Fig. 2a–c. For all materials, as the notch radius decreases, the yield and tensile strengths increase but ductility decreases. Scattering in engineering stress–strain data is relatively significant for CF8M compared to other materials, which is induced by micro-structural inhomogeneity. Average true stress–strain curves for three materials, obtained from smooth round bar tests using the Bridgman correction [27], are shown in Fig. 2d.

2.3. Fracture toughness tests

Fracture toughness test was conducted using C(T) specimens. Standard 1-T C(T) specimens were used for the tests of TP316 and CF8M. For SA508 Gr. 3, however, smaller-size C(T) specimens with the thickness of 7.5 mm and width of 15 mm were used, see Fig. 3, due to the thickness of available material blocks. All specimens were side-grooved and pre-cracked by fatigue according to ASTM standards [28]. After fatigue pre-cracking, initial crack length, a_0, was ~59% of the width, W.

All tests were conducted at room temperature. Tensile load with a speed of 0.5 mm/min was applied to the specimens and the load-line displacement was measured using a gage with the length of 6 mm. Three specimens were tested for each material. During tests, the crack extension was monitored by elastic unloading compliance method for CF8M specimens, but measured using direct current potential drop (DCPD) method for TP316L and SA508 Gr.3 specimens.

Fig. 4 summarises the normalised load–load line displacement (LLD) and J–resistance curves of three materials. The load, P, is normalised with respect to the limit load, P_L, given by Ref. [29].

Table 1
Chemical compositions of three materials used in the present study.

Materials	Element (wt%)												
	C	Si	Mn	P	S	Ni	Cr	Mo	Co	V	Cu	Al	Fe
SA508 Gr.3	0.20	0.26	1.21	0.012	0.001	0.82	0.16	0.47	–	–	0.03	0.04	Bal.
TP316L	0.03	0.69	0.77	0.027	0.003	12.25	18.00	2.25	–	–	–	–	Bal.
CF8M	0.06	1.48	0.72	0.018	0.004	9.15	19.49	2.56	0.12	–	–	–	Bal.