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Applicability Of Modified Ritchie-Knott-Rice Failure Criterion To Predict The Onset Of Cleavage Fracture For The Test Specimen With Residual Stress Introduced To The Crack Tip

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Abstract

In this work, applicability of the modified Ritchie-Knott-Rice (RKR) failure criterion (which predicts the onset of cleavage fracture when the crack opening stress measured at four times the crack-tip opening displacement σ_{22d} exceeds a critical value σ_{22c}) is demonstrated for the test specimen with residual stress. This was done by comparing the results of the fracture toughness test and elastic-plastic finite element analysis results. 0.45 % carbon steel JIS S45C, whose tensile to yield stress ratio was equal to 1.5 was chosen as material for the test. SE(B) specimen of width 46 x thickness 23 mm, which complies the ASTM E1921 was used for the test. The residual stress was introduced to the crack-tip by mechanical pre-loading. The results showed that though scatter of the fracture toughness J_c was large, scatter of the critical value σ_{22c} was very small. Thus, the modified RKR failure criterion has been shown to be applicable to the S45C SE(B) specimens of thickness 23 mm with residual stress by mechanical pre-loading. In addition, the J corresponding to the load that σ_{22d} first reaches σ_{22c} seemed to predict the lower bound toughness for the material and the specified specimen configuration.

Keywords: Fracture toughness; Modified Ritchie-Knott-Rice failure criterion; Residual stress; SE(B) specimen

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Nomenclature

B	Specimen thickness
E	Young's modulus
J	J-integral
J_c	Fracture toughness
J_{cFEA}	J obtained at the fracture load P_c via FEA
K_c	Stress intensity factor corresponding to the fracture load P_c
K_{max}	Maximum stress intensity factor during precracking
K_{Jc}	$= [EJ_c/(1-\nu^2)]^{1/2}$: Cleavage fracture toughness
M	$= b_0\sigma_{YS}/J_c$
P	Load
P_c	Fracture load
P_{max}	Maximum force during precracking
P_{min}	Minimum force during precracking
V_g	Crack-mouth opening displacement (CMOD)
W	Specimen width
a	Crack length
b_0	$= (W - a)$: Initial ligament size
δ_t	Crack-tip opening displacement (CTOD)
ν	Poisson's ratio
ρ	Initial blunted notch
σ_B, σ_{B0}	True and nominal tensile strength
σ_{YS}, σ_{YS0}	True and nominal yield stress
σ_{22}	Crack-opening stress
σ_{22c}	Critical crack-opening stress
σ_{22d}	σ_{22} measured at a distance from the crack tip equal to four times the crack-tip opening displacement (CTOD) δ_t at the specimen mid-plane
σ_{22d0}	Converged value of σ_{22d}

1. Introduction

Test specimen size effects on the cleavage fracture toughness J_c of a material in the ductile-to-brittle transition temperature (DBTT) region has been known to exist (Wallin, 1985; Dodds, Anderson and Kirk, 1991; Nevalainen and Dodds, 1995; Rathbun et al., 2005). Large scatter in J_c has also been known. Chen et al. have reported scatter of the fracture toughness, as follows; "it is necessary to distinguish the concepts of the minimum toughness or the lower boundary of toughness values from that of the scatter band of toughness. The former is a definite parameter determined by the specimen geometry and yielding properties, and the latter is statistical behavior determined by the distribution of the weakest constituent (Chen et al., 1997)". Meshii et al. interpreted Chen et al.'s opinion as that at least for the specimen size effects of minimum J_c can be reproduced by running an elastic-plastic finite element analysis (EP-FEA) with some failure criterion (Lu and Meshii, 2014; Meshii, Lu and Fujiwara, 2015; Meshii and Yamaguchi, 2016). For this failure criterion, Meshii et al. considered the modified Ritchie-Knott-Rice (RKR) failure criterion, which predicts the onset of cleavage fracture when the crack-opening stress σ_{22}, measured at distance from the crack tip equal to four times the crack-tip opening displacement (CTOD) δ_t, hereinafter denoted as σ_{22d}, exceeds a critical value σ_{22c}. They showed that the modified RKR failure criterion is applicable to explain the test specimen thickness (TST) effect on J_c observed for 1) 0.55 % carbon steel and non-proportional SE(B) specimen, whose thickness to width ratio B/W was varied in the range of 0.25 to 1.5 (Meshii, Lu and Takamura, 2013), and 2) the reactor pressure vessel steel A533B and proportional SE(B) specimen whose B/W was kept constant, but thickness was changed in the range of 8 to 254 mm (Meshii and Yamaguchi, 2016). In the latter work, Meshii and Yamaguchi