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Characterization of Material Fracture Behavior of 316L and 321 Stainless Steels

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1. Introduction

Local approach is an effective method to get geometry or loading type independent actual fracture resistance characteristics of various specimens and components(1,2). The application of it starts from calibrating material specific micro-mechanical parameters and, for the calibration, notched bar or cracked standard specimens have been used in general.

The purpose of this paper is to investigate the applicability of the local approach for two types of representative nuclear materials, 316L steel and 321 steel, based on small punch (SP) technique(3). A set of micro-mechanical parameters consisting Rousselier model are calibrated through comparison of the experimentally obtained load-displacement data and corresponding numerical analysis results. Then, employing the micro-mechanical parameters into the damage model, failure behaviors are analysed. Finally, material *J-R* curves are estimated for different sized CT (Compact Tension) specimens to resolve transferability issue.

2. Specifics of Rousselier Model

The Rousselier model(2) defines the yield surface as a function of hydrostatic stresses:

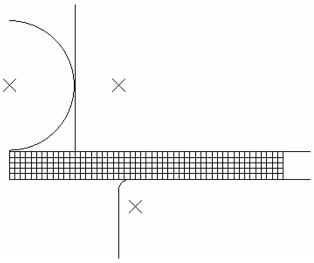
$$\Phi = \frac{\sigma_{eq}}{\rho} + D \cdot \sigma_1 \cdot f \cdot \exp\left(\frac{\sigma_m}{\rho\sigma_1}\right) - R(\varepsilon_{eq}^p) = 0 \qquad (1)$$

where, σ_1 and D are fitting constants, σ_{eq} is equivalent von Mises stress, σ_h is hydrostatic stress, ρ is material density, f is void volume fraction and $R(\varepsilon^p_{eq})$ represents a work-hardening law. In order to apply Rousselier model to a specific material, σ_1, D and initial void volume fraction (f_0) have to be determined. Rousselier recommended relevant ranges of σ_1 and D, however, it is desirable to get the material specific values through its own data.

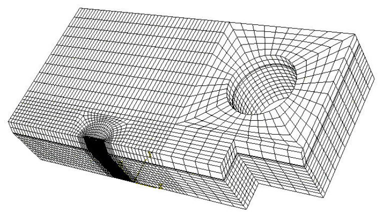
3. FE Analyses Incorporating Damage Model

3.1 Calibration and FE analysis

Determination of micro-mechanical parameters is a predominant procedure that requires a hybrid



(a) Two-dimensional SP specimen



(b) Three-dimensional 1T-CT specimen
Fig. 1 FE meshes adopted in this work

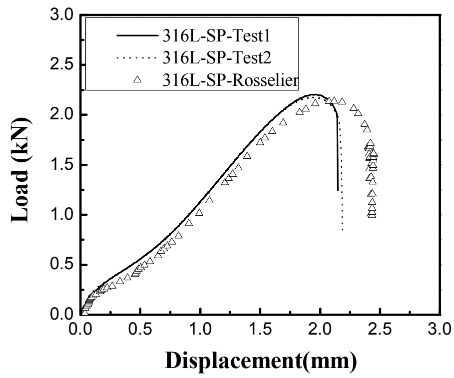


Fig. 2 Estimated results of SP specimen (316L steel)

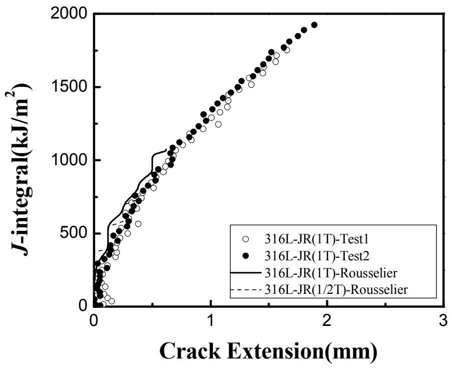


Fig. 3 Estimated *J-R* curves of 1T-CT and ½T-CT specimen (316L steel)

methodology combining test and numerical simulation data[4]. To calibrate the parameters, FE models of SP and 1T-CT specimens were generated. The mesh of SP specimen consisted of refined square elements ($125\mu m \times 125\mu m$) along the crack front. Also, the FE mesh of 1T-CT specimen was used refined square elements including cell size just like that of SP specimen. Fig. 1 shows the typical meshes of SP and 1T-CT specimens. The numerical simulation of SP and 1T-CT specimens was performed by using ABAQUS 6.5-1 and user subroutine (UMAT). Two-dimensional FE models for SP specimen were used for analyses. The reason was that two and three dimensional FE meshes gave same load-displacement curves. Thereby, the micro-mechanical parameters of the damage models for two materials were calibrated and summarized in Table 1.

A series of three-dimensional finite element analyses employing the calibrated micro-mechanical parameters were carried out. The values of *J*-integral can be determined by either the path integral or by the area under the load versus load-line displacement curve. Since it is known that the *J*-integral derived from the path integral is preferable, in this paper, the former was adopted. Also, the crack extension was identified as the size of the damage zone where void volume fraction has limited to fracture void volume fraction due to the void growth.

Table 1 The material parameters of Rousselier model

Materials		316L steel	321 steel
Parameters	f_0	0.0011	0.0004
	f_c	0.15	0.15
	D	2.8	4.3
	σ_l	1250	1500

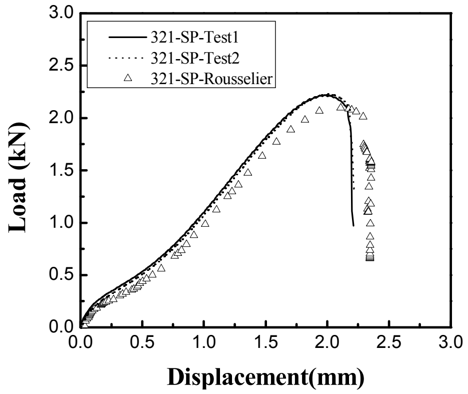


Fig. 4 Estimated results of SP specimen (321 steel)

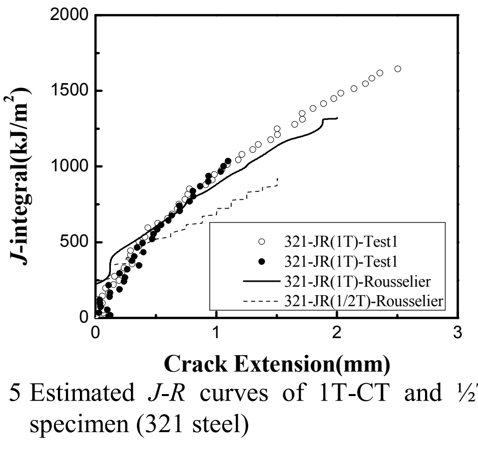


Fig. 5 Estimated *J-R* curves of 1T-CT and ½T-CT specimen (321 steel)

3.2 FE Analysis Results

P-δ curves and *J-R* curves of SP and CT specimens were predicted by using the damage model and depicted in Figs. 2~5 along with the corresponding experimental ones. The simulated deformation up to the fracture and relevant SP energy defined as the area under load-displacement curve agreed well with the test results, which could not be obtained by general elastic-plastic FE analysis. It is believed that the damage models are able to predict a local necking and furthermore a crack in SP specimens.

On the other hand, as expected, the estimated results of 1T-CT specimens agreed well with the corresponding test results. However, the two materials gave somewhat different trends for different sizes of CT specimens. In case of 316L steel, the predicted *J-R* curve of 1T-CT specimen by using Rousselier model was similar with that of ½T-CT specimen. In case of 321 steel, the predicted *J-R* curve of 1T-CT specimen was higher than that of ½T-CT specimen. In addition, on the whole, Rousselier model gave higher *J-R* curve than test results before 0.5*mm* of crack extension and smaller *J-R* curve than test result after 0.5*mm* of crack extension.

4. Conclusions

Parameters consisting Rousselier model were calibrated by using efficient SP specimens and standard 1T-CT specimens made of 316L and 321 steels. A series of FE analyses imploying the micro-mechanical parameters were performed, mainly, to predict *J-R* curves of ½T-CT specimens. It was proven that the method adopting the SP specimen is useful for prediction of fracture resistance characteristics of the 316L and 321 steels.

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