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Estimation of Yield Strength of RPV steels by Empirical Correlation and Analytical Method using Small Punch Test

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1. Introduction

Integrity of materials was usually tested by bulk-size destructive test methods such as tensile, impact, and fracture toughness tests. In response to the structural integrity test for nuclear components, where the amount of material available for destructive testing is limited, much effort has been performed to estimate material properties using miniature testing techniques. Small punch (SP) test is one of the miniature test techniques. The European Committee for Iron and Steel Standardization (ECISS) has tried to standardize SP test method [1]. Many organizations in Europe participated in standardization and international round-robin test. As a result, the small punch test (SPT) has been standardized as ASTM E3205-20 [2], and it can be used for evaluation of the mechanical properties of metallic materials.

In ASTM E3205, two methods for derivation of tensile properties were described in Appendix as nonmandatory information: 1) empirical correlation between SP and tensile tests result, and 2) Analytical methods requiring modelling. In the case of empirical correlation method, empirical correlation equations for YS and TS were suggested, but detail material-dependent empirical constants were not mentioned. In the case of analytical methods, the constitutive stress-strain model using Ramberg-Osgood model were recommended and other additional analytical approach involving the use of neural networks and finite element simulation were proposed. However detail method were not described in ASTM.

In this study, estimation method for YS of RPV steels were developed using SPT by two methods: 1) empirical correlation and 2) analytical method using FEM and neural networks. By comparing the results of SP and tensile test of domestic RPV steels, YS estimation methods for RPV steels were developed. Furthermore, it was verified whether it could be used to predict the YS of irradiated PRV steels.

2. Experiments

The SP test materials were mainly SA508 Gr.3 Cl.1 steels used in Korea Standard Nuclear Power Plants (KSNPs). For the standard tests, tensile test were performed at -196°C ~ 286°C. Round bar-type tensile specimens (gauge length 16 mm, diameter 2.5 mm) were prepared in the transverse direction and were tested using a universal testing machine (model MTS 810, MTS, USA) with a 10-ton capacity under a strain rate of 5.2×10^{-4}, according to ASTM E8M. Plate type tensile specimens were used for irradiated RPV steels. The 0.2% offset stress method was used to determine the yield strength from the engineering stress-strain curves.

Two SP test methods were used in this study. One was standard SP test method(S-SP) in ASTM E3205, and the other was non-standard SP test (K-SP) performed in early 2000s in KAERI [3-4]. Detailed comparison of K-SP method and S-SP method are described in Table 1. Through the SP test, force-punch displacement can be obtained. This data contains information about the elastic-plastic deformation and material properties. Through the load-displacement/deflection curves, material characteristic parameters such as F_m, F_e, u_m, u_f, and E^{sp} were determined according to the ASTM E3205.

Table 1. Comparison of two SP test conditions.

	K-SP (performed in KAERI in early 2000s)	S-SP (ASTM E3205 methods)
Specimen Shape	Rectangular (10 x 10 x 0.5 mm)	Disc (8ϕ x 0.5mm)
Punch	Ball (dia. 2.4mm, Hardness 62~67HRC)	Ball (dia=2.5mm, hardness: 62~65HRC)
Test Rig Edge	Round (0.2mm R)	Round (0.2mm R)
Test Velocity (Punch v.)	1 mm/min	0.5 mm/min
Sample Preparation	EDM Cutting	EDM cutting (0.65mm) and grinding to final thickness(0.5mm) using abrasive paper (P320~P1200)
Clamping force	Not Recorded.	10Nm
Data Measurement	Force-Punch displacement	Force-Punch displacement and/or force-deflection

3. Results

3.1. Empirical correlation method for YS estimation

ASTM method use bilinear function to determine the elastic-plastic transition force, F_e. The following procedure describes how to determine F_e [2].

$$f(u) = \frac{f_A}{u_A} \qquad for\ \ 0 \le u < u_A$$

$$= \frac{f_B - f_A}{u_B - u_A}(u - u_A) + f_A \qquad for\ \ u_A \le u < u_B$$

Minimization of the error:

$$\text{err} = \int_0^{u_B} [F(u) - f(u)]^2\, du$$

Then, the yield displacement $u_e = u_A$, $F_e = F(u_A)$. u_B is free parameter but it is recommended to choose $u_b = h_0$

In ASTM E3205 appendices, derivations of tensile properties are described as follows [2]:

$$\text{YS} = \beta_{\text{YS}} \cdot F_e / h_0^2$$

Where β_{YS} is empirical constants.

YS_SP of KSNP RPV steels were derived by SP test and compared with YS estimated from the result of standard tensile test at RT. Those results are shown in Figure 1. The F_e showed linear relation with YS. The empirical constant β_{YS} for KSNP RPV steels was 0.39.

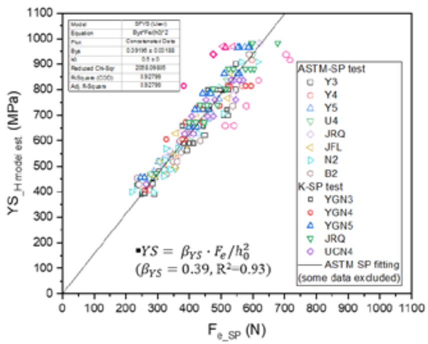

Fig. 1 The relationship between yield strength(σ_0) and yield load(F_e)

3.2. Analytical method for YS estimation

To estimate the YS from the results of SPT by anlaytical method, FEM simulation was conducted with same condition as SP test. Ramberg-Osgood model was used for the material constitutive stress-strain model in FEM simulation. Arbitrary parameter for Ramberg-Osgood model was set in FEM simuation and then the load-displacement curve from FEM simulation was compared with the test results of SPT by neural network. From the neural network, optimized parameter was set and optimum stress-strain curve of materials was derived. The YS was determined by 0.2 offset method in optimum stress-strain curve. The results of YS estimated by SPT method were shown in Figure 2. Both empirical and analytical methods well estimated the yield strength of RPV steels. Both methods could predict the yield strength of the irradiated RPV steels.

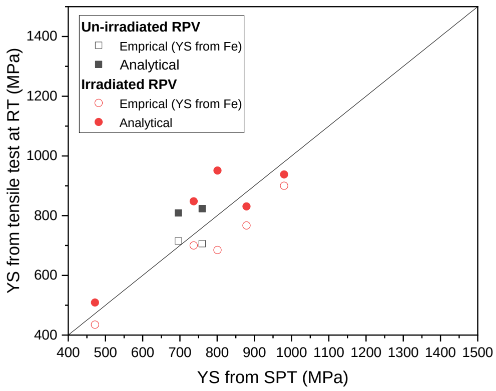

Figure 2. The relationship between yield strength and estimated yield strength of un-irradiated and irradiated RPV steels by two SPT methods

4. Conclusions

In this study, derivation of yield strength using SP test was conducted according to the ASTM E3205 method. F_e values showed linear correlation with YS. Both empirical and analytical methods could predict the YS of RPV steels regardless of irradiation.

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