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Estimation of Tensile Properties of RPV Steels in KSNPP using Small Punch Test

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1. Introduction

Materials in long-term operated nuclear power plants are suffered from aging problems. For instance, the tensile properties degrade and the ductile to brittle transition temperature (DBTT) increases. For the safety and life extension of aging nuclear power plants, integrity of materials in components should be assured. 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 [1-3]. Small punch (SP) test is one of the miniature test techniques. It has been developed for nuclear applications, but SP test for metallic materials is not yet standardized. The European Committee for Iron and Steel Standardization (ECISS) has tried to standardize SP test method [4]. Many organizations in Europe participates in standardization and international round-robin test are now in progress as ASTM work item WK47341 and interlaboratory study (ILS1408) [5]. Korea Atomic Energy Research Institute (KAERI) tried to derive material properties using SP test in early 2000s. Recently, KAERI participated in ILS1408 [6-7]. Previous SP test performed in KAERI was slightly different from SP test in ASTM WK47341 and ILS 1408. In this study, two SP test methods were compared using Finite Element Method (FEM) simulation. SP test results performed in KAERI were reviewed.

2. Experiments

The SP test materials were mainly SA508 Gr.3 Cl.1 steels used in Korea Standard Nuclear Power Plants (KSNPPs). For the standard tests, tensile test were performed at -196°C ~ RT. 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 [8]. The 0.2% offset stress method was used to determine the yield strength from the engineering stress-strain curves.

Previously performed SP tests in KAERI (K-SP) used rectangular shape specimen (10x10x0.5mm) and punch ball (diameter 2.4 mm and hardness 62~67 HRC). K-SP test rig had 4 mm receiving die bore and round edge (0.2 mm R). Test velocity was 1 mm/min. New SP test method (S-SP) according to the ILS1408 use disc shaped specimen (8ϕ x 0.5 mm) and Punch/ball (dia. 2.5 mm and hardness > 55 HRC). S-SP test rig have 4 mm receiving die bore and chamfer edge (0.2mm l, 45 degree). Detailed comparison of K-SP method and S-SP method are described in Table 1 and Figure 1. K-SP and S-SP method results are compared using FEM simulation.

Through the SP test, force-punch displacement or/and force-specimen deflection data can be obtained. This data contains information about the elastic-plastic deformation and material properties. Through the load-displacement/deflection curves, material characteristic such as F_m, F_e, u_m, u_f, and E^{sp} can be determined and those values are used to derive material properties. Determination of SP-data characteristics in K-SP and S-SP are explained in Figure 2.

Table 1. Comparison of two SP test conditions.

	K-SP (performed in KAERI in early 2000s)	S-SP (SP test according to ILS1408 test methods)
Specimen Shape	Rectangular (10 x 10 x 0.5 mm)	Disc (8ϕ x 0.5 mm)
Punch	Ball (dia. 2.4mm, Hardness 62~67HRC)	Ball (dia=2.5mm, hardness: 62~65HRC)
Test Rig Edge	Round (0.2mm R)	Chamfer Edge (0.2mm l, 45 degree)
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.	10 Nm
Data Measurement	Force-Punch displacement	Force-Punch displacement and/or force-deflection

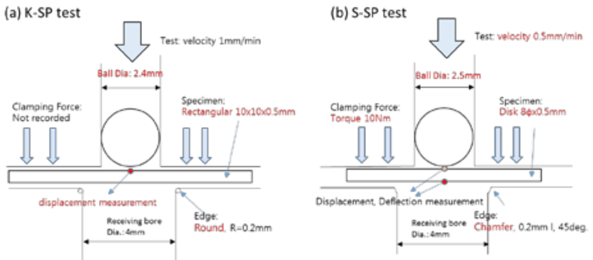

Figure 1. Schematic diagram of two SP test methods. (a) K-SP test: SP test performed in KAERI in early 2000s, (b) S-SP test: SP test according to ILS1408 for preparing standardization.

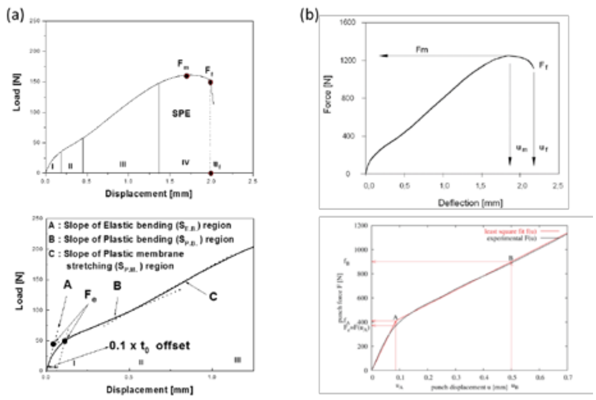

Figure 2. Determination of SP characteristic values such as F_e, F_m, u_m, F_f, and u_f from the load-displacement curve; (a) K-SP and (b) S-SP.

3. Results

In previous SP test, the elastic-plastic transition force, F_e, was determined by offset method and tangent line intersection method. Suppose yield strengths are 500MPa and 700MPa and work hardening behavior follows the equation, load-displacement curve are calculated using FEM simulation with different strength constants (H) and hardening coefficients (N) values.

$$\frac{\sigma}{\sigma_0} = \mathrm{H}\left(\frac{\varepsilon}{\varepsilon_0}\right)^{\mathrm{N}}$$

F_e values determined by offset method change according to H and N values. However F_e values determined by intersection method do not change. It means that F_e values determined by intersection method is only dependent on yield strength. In figure 3, relationship between yield strength and F_e in K-SP test was shown. Both method showed that the elastic-plastic transition force, F_e, and yield strength show linear correlation. It is well matched with other researcher's result [1-2, 9]. Offset method have large deviation but intersection method have small deviation. Derivation of yield strength using K-SP test can be explained as following equations

$$\sigma_0 = \alpha \times P_y + \beta$$

Where α: 1.22 and β:77.98

Correlation between tensile strength and F_m in K-SP test is shown in figure 4. If failure occurred after instability, F_m values have linear correlation with tensile strength. Derivation of tensile strength using K-SP test can be explained as following equations

$$\sigma_{\mathrm{UTS}} = \alpha' \times P_{max} + \beta'$$

Where α: 0.27 and β:143.6

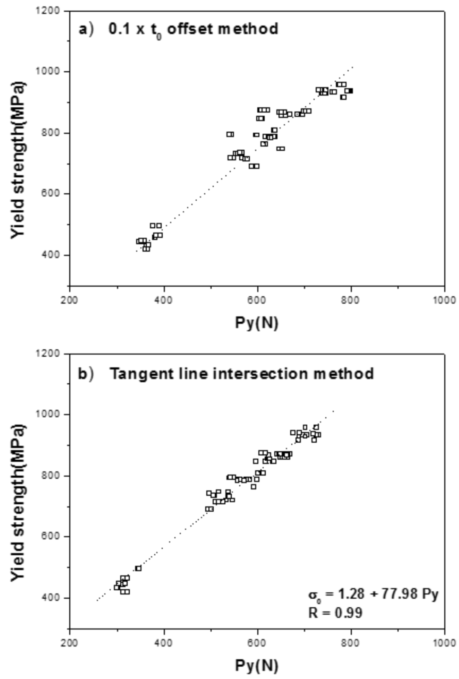

Figure 3. The relationship between yield strength(σ_0) and yield load(F_e) defined by a) offset method & b) intersection point method.

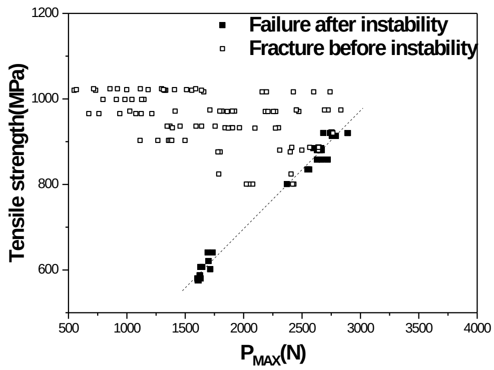

Figure 4. The relationship between tensile strength(σ_{UTS}) and maximum load(F_m) in K-SP tests.

4. Conclusions

In this study, derivation of tensile properties using SP test was conducted. Previously performed KAERI SP test (K-SP) were slightly differed from new SP test methods preparing standardization (S-SP). Using FEM simulation, K-SP and S-SP Load-displacement behaviors were analyzed. Initial load-displacement behavior of two SP methods was similar, but after the large displacement deformation over 1 mm the load of S-SP was higher because of larger ball size. F_e and F_m determined by K-SP test have linear correlation with yield strength and tensile strength. Yield strength and tensile strength can be derived by following equations:

$$\sigma_0 = 1.22 \times P_y + 77.98$$
$$\sigma_{\mathrm{UTS}} = 0.27 \times P_{max} + 143.6$$

However those equation formats are different with empirical correlation methods recommend by ASTM WK47341. For the further works, recalculation of K-SP data, new SP test, and derivation of mechanical properties such as tensile properties, DBTT, and fracture toughness is in progress according to ASTM WK 47341.

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