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Development of a Small Punch Test Technique for an Evaluation of the Mechanical Properties of Irradiated Materials in a Hot Cell

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1. Introduction

Miniaturized specimens have been widely used to evaluate the mechanical properties of steels and plastics. Especially for a study on the irradiation effects in nuclear materials, the small specimen test techniques have attracted considerable attention. Therefore, it is essential that the test techniques be developed and verified to extract the mechanical properties information from small specimens.

Among the test techniques using small specimens, the small punch (SP) test technique using small disc-sized specimen has been successfully used to estimate the tensile properties (yield strength and ultimate tensile strength), DBTT (ductile-brittle transition temperature), fracture toughness and creep properties of metals irradiated in a reactor or a proton accelerator [1~3].

In this paper, the existing SP test techniques are reviewed and summarized. In addition, the information on the development of the SP test procedure is obtained to evaluate the radiation effects on the mechanical properties of nuclear materials in a hot cell.

2. SP test technique

The SP test has been successfully applied to examine the degradation of mechanical properties of various metals and plastics. From the test results of previous researchers, it is found that there are clear correlations between the mechanical properties obtained from the SP and the conventional standard test method including the tensile properties, fracture toughness and DBTT etc.

2.1 Experimental apparatus

The experimental apparatus for the SP test consists of a specimen holder (upper and lower die, clamping screw), a punch and a ball, as shown in Figure 1. The SP specimen is clamped to the specimen holder, the punch is forced into it, causing the specimen to bulge and ultimately fail.

By using this specimen holder, the specimens are prevented from an upward cupping during a punching, and therefore a plastic deformation is concentrated in the region below the punch. The load is applied to the center of the SP specimen through the steel or alumina ball with a hardness of more than HRC 60. The punch is fabricated from steel or alumina with hardness of more than HRC 50 to prevent a plastic deformation of the punch. The recommended dimensions of the specimen and the specimen holder are shown in Table 1 [1].

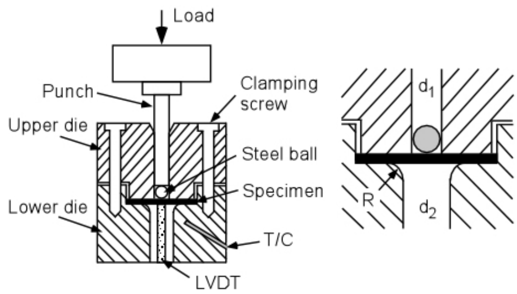

Figure 1. Schematic drawing of SP test.

Table 1. Dimensions of specimen holder (unit: mm).

	Coupon (10x10)	TEM (φ3)
t_o	0.50, 0.25	0.25
d_1	2.4	1.0
d_2	4.0	1.5
R	0.2	0.2
Steel ball	φ 2.4	φ 1

$$d_2 \geq d_1 + 2t_o$$

* t_o : the initial thickness of specimen

Alignment of the punch and die as well as a load-line centering is critical in the SP test in order to eliminate or minimize the anisotropy effects, which are caused by eccentricity. Ju et al. [4] used another steel ball (4 mm diameter) at the loading point on the upper surface of the punch for a system alignment and load-line centering.

2.2 Specimen

In general, two types of disc-shaped specimens are used. One is a coupon type disc specimen having dimensions of 10 mm by 10 mm by 0.25 or 0.5 mm in thickness. The other is a TEM disc type specimen having dimensions of 3 mm in diameter and 0.25 mm in thickness. Most of the SP specimens are made from fresh material, and then irradiated in reactors. Some of them are cut from the undamaged portion of a broken Charpy V-notch specimen. Both sides of the SP specimen are mechanically or electrochemically polished. For the mechanical polish, 1200 grit emery paper is used, and, in most cases, a buff is also used for a polishing. No additional polishing is made after the irradiation.

2.3 Heating and cooling device

The heating and cooling devices have the capacity of a temperature control within 2^{o}C for the target temperature during the SP test. It is required that the SP specimen contact with an inert gaseous environment during both a low and high temperature testing. During the tests, the temperature is monitored by a K-type thermocouple placed close to the specimen through a small hole in the lower die and it is controlled to within 2^{o}C.

3. Test results

Many researchers have performed the SP tests in various materials and test conditions, and validated the suitability of this test technique for an evaluation of mechanical properties through experimental and numerical analyses.

The SP-related parameters, $P_y/(t_o)^2$ and $P_{max}/(t_o)^2$, correlate well with 0.2% offset yield strength (σ_y) and ultimate tensile strength (σ_{uts}) obtained by the conventional method, respectively. The empirical correlation between them can be expressed by Eqs. (1) and (2).

$$\sigma_y = A\,(P_y / t_o^2) \quad (1)$$

$$\sigma_{uts} = B\,(P_{\max} / t_o^2) - C \quad (2)$$

where t_o is the initial thickness of the SP specimen, A, B and C are the correlation coefficients.

Elastic-plastic fracture toughness (J_{IC}) can be evaluated using a equivalent fracture strain (ε_{qf}) and the previously established relationship between these values on various materials. Most researchers have reported a linear relationship between J_{IC} measured by the conventional standard method and ε_{qf} as follows.

$$J_{IC} = k\varepsilon_{qf} - J_o \quad (3)$$

where k and J_o are the correlation coefficients.

DBTT measured by a Charpy V-notch test can be predicted from the results of the temperature dependency of the SP energy determined from the area under the load-deflection curve. The transition temperature (*SPDBTT*) is approximately linearly correlated with DBTT measured by a Charpy test (*CVN-DBTT*).

$$SPDBTT = \alpha \times CVN - DBTT \quad (4)$$

where α is the correlation coefficient ranging from 0.35 to 0.45 on various materials.

For evaluating the creep properties and a material deterioration due to thermal aging, the small punch creep (SP-C) test technique has been developed [3]. Material deterioration leading to a degradation of the creep rupture strength is remarkably well-reflected in the SP-C properties. However, it is required to establish a quantitative correlation between the small punch creep and uniaxial creep test data.

4. Conclusion

The existing SP test techniques have been reviewed to obtain the essential information for the development of the SP test procedure in a hot cell. And, the reasonable relationships between the mechanical properties obtained from the SP and the conventional tests are summarized.

1. The SP apparatus consists of a specimen holder, flat punch and steel ball. For a smooth handling of the SP specimen in a hot cell, holes are machined at the corner or the edge in the lower die for a specimen removal after a testing. Both a 10x10 mm^2 coupon type and 3 mm diameter TEM disc type specimens worked well in a remotely controlled system in a hot cell. During a deformation, the deflection at the center of the specimen is measured with the LVDT inserted from the hole below the specimen. For an observation of the deformation behavior, a borescope will be installed in the specimen holder.
2. Using a correlation of the mechanical parameters between the SP and the conventional tensile, Charpy, fracture toughness and creep tests, the irradiation induced changes, such as 0.2% offset strength, ultimate tensile strength, *DBTT*, J_{IC} and creep properties can be estimated properly from the SP test results. To improve the accuracy of the predictions, a sufficient database of both the SP tests and conventional pre-irradiation tests is needed.
3. The fracture appearance changed clearly after the irradiation, and the load-deflection curve changed accordingly. For the radiation-embrittled specimens, therefore, an evaluation of the radiation embrittlement based on a fractography-oriented analysis should be done together with a load-deflection curve analysis.

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