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Development of a small specimen test machine to evaluate irradiation embrittlement of fusion reactor materials

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Abstract

Small specimen test techniques (SSTT) are essential to use an accelerator-driven deuterium–lithium stripping reaction neutron source for the study of fusion reactor materials because of the limitation of the available irradiation volume. A remote-controlled small punch (SP) test machine was developed at the hot laboratory of the Japan Materials Testing Reactor (JMTR) in the Japan Atomic Energy Research Institute (JAERI). This report describes the SP test method and machine for use in a hot cell, and test results on irradiated ferritic steels. The specimen was either a coupon $10 \times 10 \times 0.25$ mm^3 or a TEM disk 3 mm in diameter by 0.25 mm in thickness. Tests can be performed at temperatures ranging from 93 to 1123 K in a vacuum or in an inert gas environment. The ductile to brittle transition temperature of the irradiated ferritic steel as determined by the SP test is also evaluated. © 2000 Elsevier Science B.V. All rights reserved.

1. Introduction

For plant life extension of commercial light water reactors (LWR), small specimen test techniques (SSTT) have been applied to evaluate the performance of the on-site annealing of radiation-hardened reactor vessels [1–3]. Moreover, for the development of structural materials for fusion reactors, SSTT have been developed as one of the key technologies for an accelerator-driven D–Li neutron source, in which the irradiation volume will be quite limited [4,5]. Utilization of small specimens also makes it easier to control irradiation conditions and reduces radioactive waste.

In this paper, a small punch (SP) test machine developed for irradiated specimens and installed in the hot laboratory of the Japan Materials Testing Reactor (JMTR) in the Japan Atomic Energy Research Institute (JAERI) is described. Moreover, the ductile to brittle transition temperature (DBTT) of irradiated 2.25Cr–1Mo steel was examined from the results of SP tests.

2. Description of SP test

Based on the load–displacement curve obtained from SP tests, Baik et al. [6] described that the deformation stages of a specimen during testing are classified into elastic bending, plastic bending, plastic membrane stretching and plastic instability. The energy for the deformation and fracture of the specimen is defined as an SP energy, whose value is calculated from the area under the load–displacement curve. Okada et al. [7] and Suzuki et al. [8] examined load–displacement curves of irradiated and unirradiated ferritic steels. Okada et al.

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[7] pointed out that the maximum load of the punch test correlated well with tensile strength, and Suzuki et al. [8] reported that tensile yield stress exhibited a similar change with the transition load from the elastic to the plastic stage by irradiation. Suzuki et al. [8], McNaney et al. [9] and Misawa et al. [10] also showed that the relation between the DBTT from the SP tests and that from Charpy V-notch tests for several different steels could be expressed as a simple equation.

3. SP test machine

A schematic drawing of the remote-controlled SP test machine in a hot cell in the JMTR hot laboratory is shown in Fig. 1. Furthermore, a schematic of the remote operation turntable installed in the vacuum chamber and the mounting process of the specimen is shown in Fig. 2. The SP test machine consists of a load control unit, turntable, vacuum chamber and furnace. Twelve holders, each containing a specimen, are set into the holes in the turntable by a manipulator. The turntable was rotated clockwise to place one of the holders above a lower rod. The specimen holder was lifted up by the lower rod and was fixed between the upper and lower rods. The lower rod pushes the holder to the upper rod to apply force on the holder clamping the specimen between the upper and lower parts of a holder. The maximum force to clamp the specimen between upper and lower holders is 5 kN. An actuator goes down to deform the specimen, and after the test, the lower rod travels down to place the holder back in the hole of the turntable. Then, the turntable is rotated clockwise to place the next holder above the lower rod. This sequence can be automated with a computer.

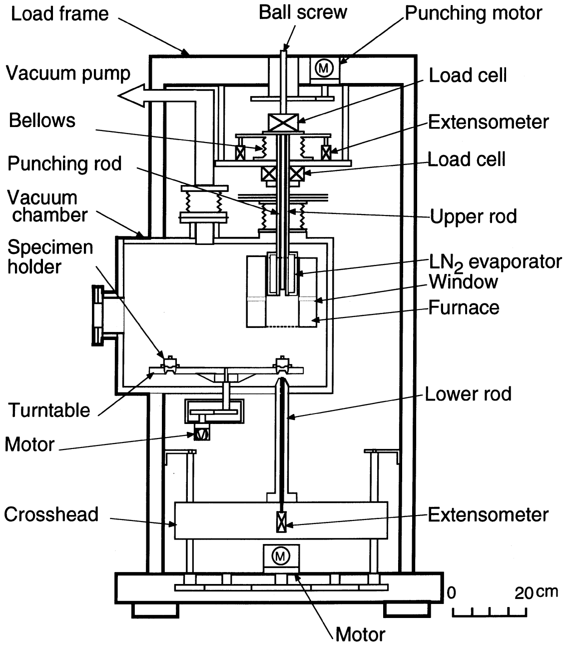


Fig. 1. Schematic drawing of remote-controlled small punch test machine.

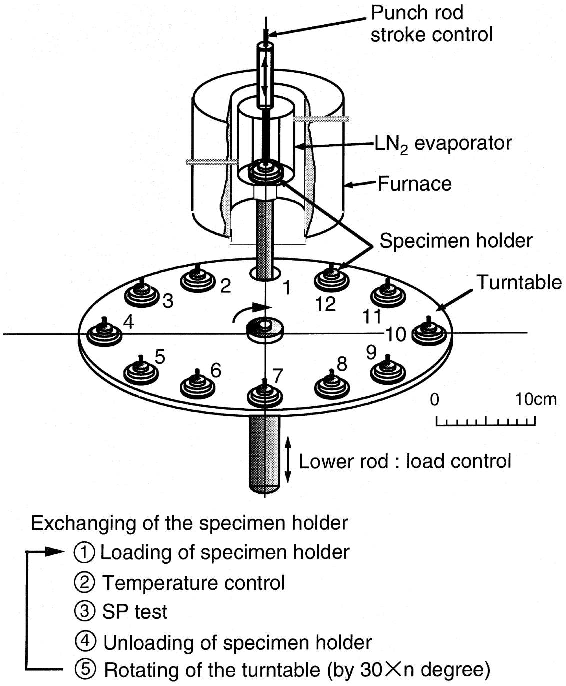
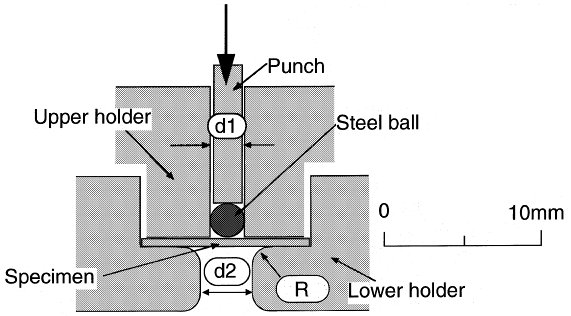


Fig. 2. Schematic of remote operation turntable system installed in the vacuum chamber and exchange method of specimen holder.

Displacement of the specimen needs to be measured accurately. The actuator rod of the machine is relatively long and may compress elastically during testing. A displacement measurement rod equipped with a linear variable differential transformer (LVDT) is attached to the bottom surface of the specimen to minimize the error by elastic deformation. The LVDT can measure the displacement range of 0.01–20 mm.

A cross-sectional view of a specimen holder for the SP test is shown in Fig. 3. The specimen holder consists of the upper and lower holders, punch and steel ball. Three kinds of specimens can be used: (1) 10 × 10 × 0.5 mm^3, (2) 10 × 10 × 0.25 mm^3, and (3) 3 mm in diameter by 0.25 mm in thickness (TEM disk). Steel balls of 2.4 and 1 mm diameter are used, with hardness ranging from HRC 62 to 67. The SP test specimen and steel ball were installed in the holder by a manipulator and air tweezers. The steel ball and punch were pushed by the punch rod. The maximum load and stroke of the punch rod is 5 kN and 8 mm, respectively. The punch speed ranges from 0.003 to 3 mm/min.



	Coupon type	TEM disk type
d1	ϕ 2.4	ϕ 1.0
d2	ϕ 4.0	ϕ 1.5
R	0.2	0.2
Steel Ball	ϕ 2.4	ϕ 1.0

Unit:mm

Fig. 3. Cross-section of the specimen holder for the SP test.

A schematic of a test temperature control system for the SP test in the hot cell is shown in Fig. 4. SP tests were carried out at temperatures ranging from 93 to 1123 K with an accuracy of ±2 K. At temperatures from 93 K to room temperature (RT), the temperature of the specimen holder was controlled by the electric heater and by liquid nitrogen in a vessel attached to the upper rod.

A flow diagram of the SP test sequence in the hot cell is summarized in Fig. 5. Miniaturized tension tests can also be performed by this machine.

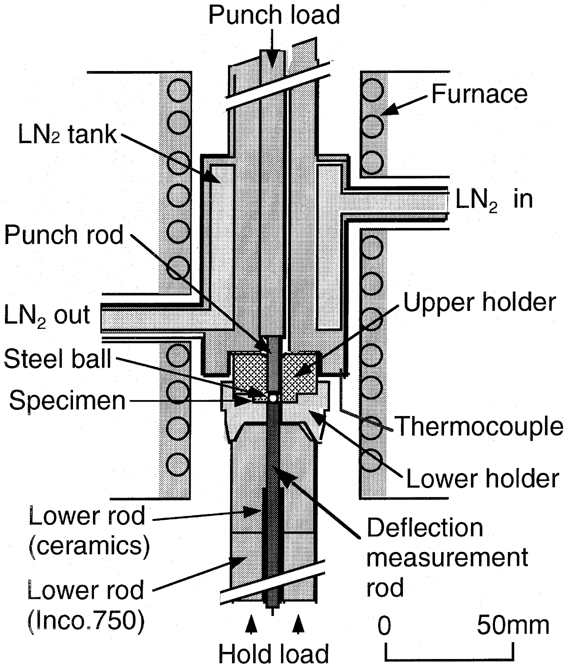


Fig. 4. Schematic of the test temperature control system for SP test in a hot cell.

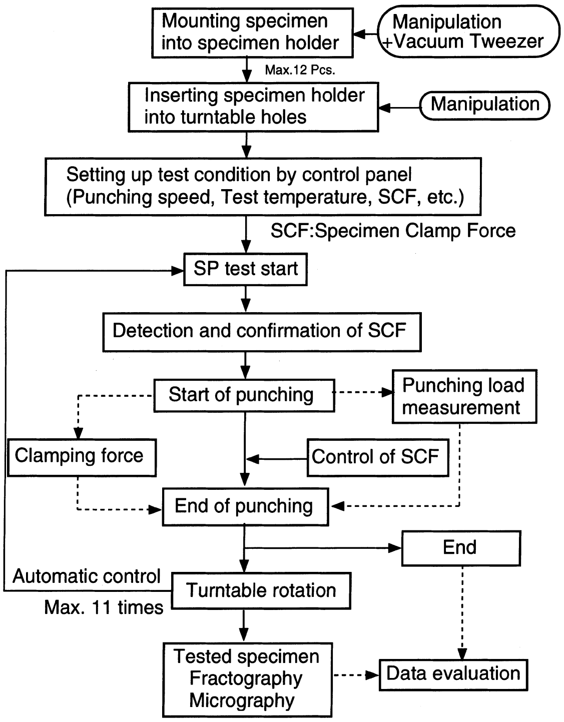


Fig. 5. Flow diagram of the SP test sequence in a hot cell.

4. Test results of irradiated 2.25Cr–1Mo steel

SP tests of 40 irradiated specimens for normalized and tempered (NT) and annealed (AN) 2.25Cr–1Mo steel were performed by this machine. These specimens were irradiated in the JMTR at temperatures ranging from 600 to 620 K up to a fluence of 2.6×10^{23} n/m^2 ($E > 1$ MeV).

The load–displacement curves obtained by SP tests for the irradiated and unirradiated specimens of 2.25Cr–1Mo steel are shown in Fig. 6. The maximum load for the irradiated specimens is higher than that for the unirradiated specimens. Displacement to fracture was decreased by irradiation.

The SP energies for the irradiated and unirradiated specimens of 2.25Cr–1Mo steel are plotted as a function of the test temperature in Fig. 7. Charpy impact tests on NT 2.25Cr–1Mo steel irradiated at 573 K up to a fluence of 2×10^{23} n/m^2 ($E > 1$ MeV) were performed [8]. The DBTT shift by Charpy test was 17 K. On the other hand, DBTT shift by SP test after irradiation was evaluated to be 14 K [11]. The DBTT shift from the SP test was similar to that from the Charpy V-notch tests for the irradiated specimens, although the DBTT determined by the SP test was lower than that by the Charpy test.

The scanning electron microscope (SEM) images of the fracture surfaces on the irradiated SP test specimens

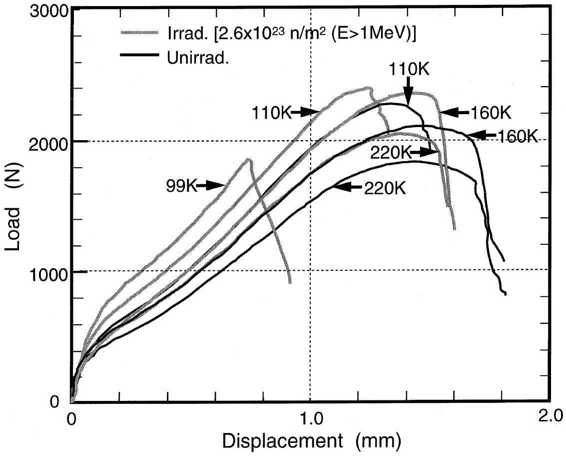


Fig. 6. Load–displacement curves obtained by SP tests for irradiated and unirradiated specimens of 2.25Cr–1Mo steel.

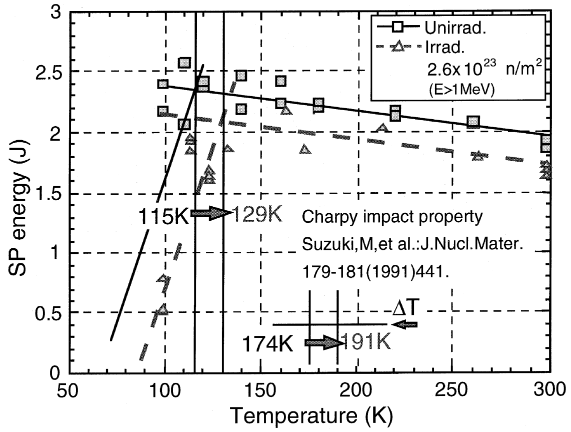


Fig. 7. SP energy for irradiated and unirradiated specimens of 2.25Cr–1Mo steel as function of SP test temperatures.

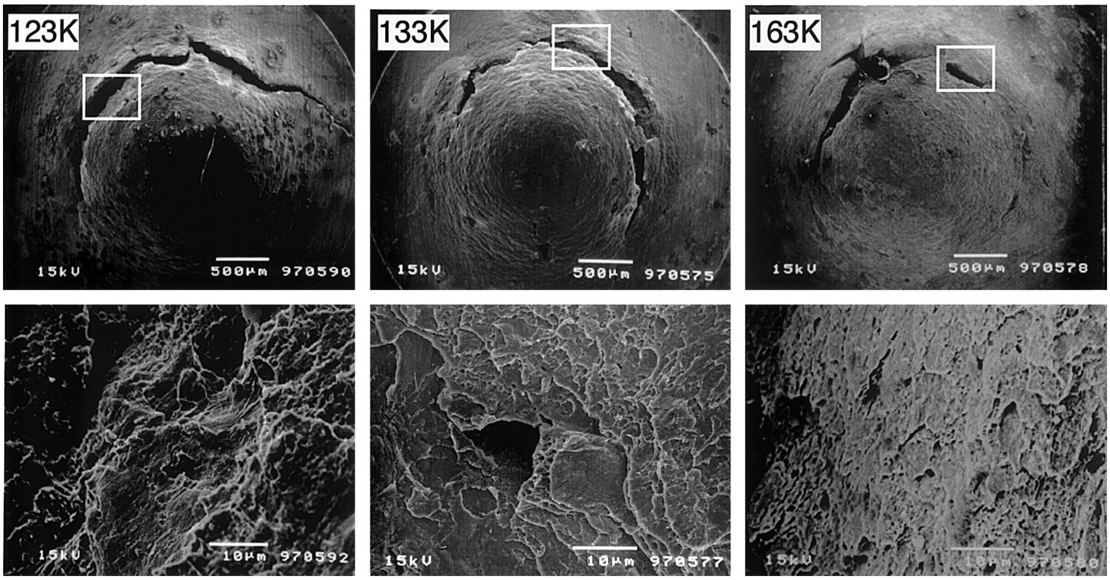


Fig. 8. SEM images of fracture surfaces on irradiated SP test specimens.

are shown in Fig. 8. A number of fragmented cleavage fracture surfaces are observed on the crack surface of the SP specimen tested at 123 K. Some evidence of brittle fracture was observed on the fracture surface of the SP specimen tested at 133 K. No evidence of brittle fracture was observed on the fracture surface for the SP specimen tested at 163 K.

5. Conclusions

An SP test machine for post-irradiation examination in the hot cell was developed in the hot laboratory of JMTR in JAERI. Irradiated specimens were examined by the machine.

1. A turntable with 12 holes for setting specimen holders is installed in the vacuum chamber to perform examination without breaking vacuum.
2. Test temperature ranges from 93 to 1123 K using liquid nitrogen in the vessel attached to the upper rod and using a furnace with an electric heater.
3. A displacement measurement rod equipped with a LVDT is attached to the bottom surface of the specimen during the test to avoid compliance problems from the deformation of the actuator rod.
4. The DBTT shift after irradiation was evaluated from the results of SP tests by this machine. The DBTT

shift from the SP test corresponded to that from the standard Charpy impact test for the irradiated specimens.

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