Mechanical Tests Based on Ring Tensile Tests of High Burn-up Nuclear Fuel Cladding in Hot Cell

SEGFSM Topical Meeting on LOCA Issues
Argonne National Laboratory
May 25-26, 2004

S. Kim and C. Lee
Korea Atomic Energy Research Institute (KAERI)

Introduction

- The mechanical properties of fuel cladding materials are degraded during steady-state operation due to a combination of irradiation embrittlement, waterside oxidation, and hydrogen pickup & hydriding.
- Currently, to increase the operating efficiency of power reactors, the average burnup of the fuel assemblies and the coolant outlet temperature have been increasing. Both of these changes in reactor operation result in additional cladding degradation.
- This increased degradation may increase the likelihood of cladding failure during design basis accidents(DBA), including the loss of coolant accident(LOCA) and the reactivity induced accident(RIA).

It is essential to determine the mechanical behavior of high-burnup fuel cladding under LOCA and RIA conditions.

Objective

Development of the techniques and procedures for determining both the mechanical properties and the failure behavior of cladding after irradiation to high fuel burnup

- To accomplish this, we uses miniature specimen geometries subjected to the loading and thermal conditions associated with LOCA and RIA transients.
- Because of the plastic anisotropy of cladding tubes, it is necessary to determine the mechanical behavior in both the transverse (hoop) and longitudinal (axial) directions.

High-burnup fuel cladding material

1. Fuel assembly

: Westinghouse 17x17 type (Vantage-5H)

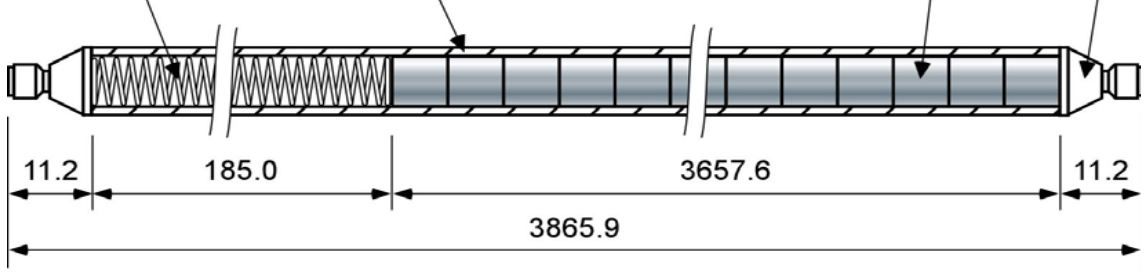
: Irradiated for 3 cycles in the Ulchin Unit 2 pressurized water reactor

2. Fuel rod

: Stress relieved seamless low-tin Zircaloy-4 tube

: OD & wall thickness of cladding tube = 9.5mm & 0.57mm

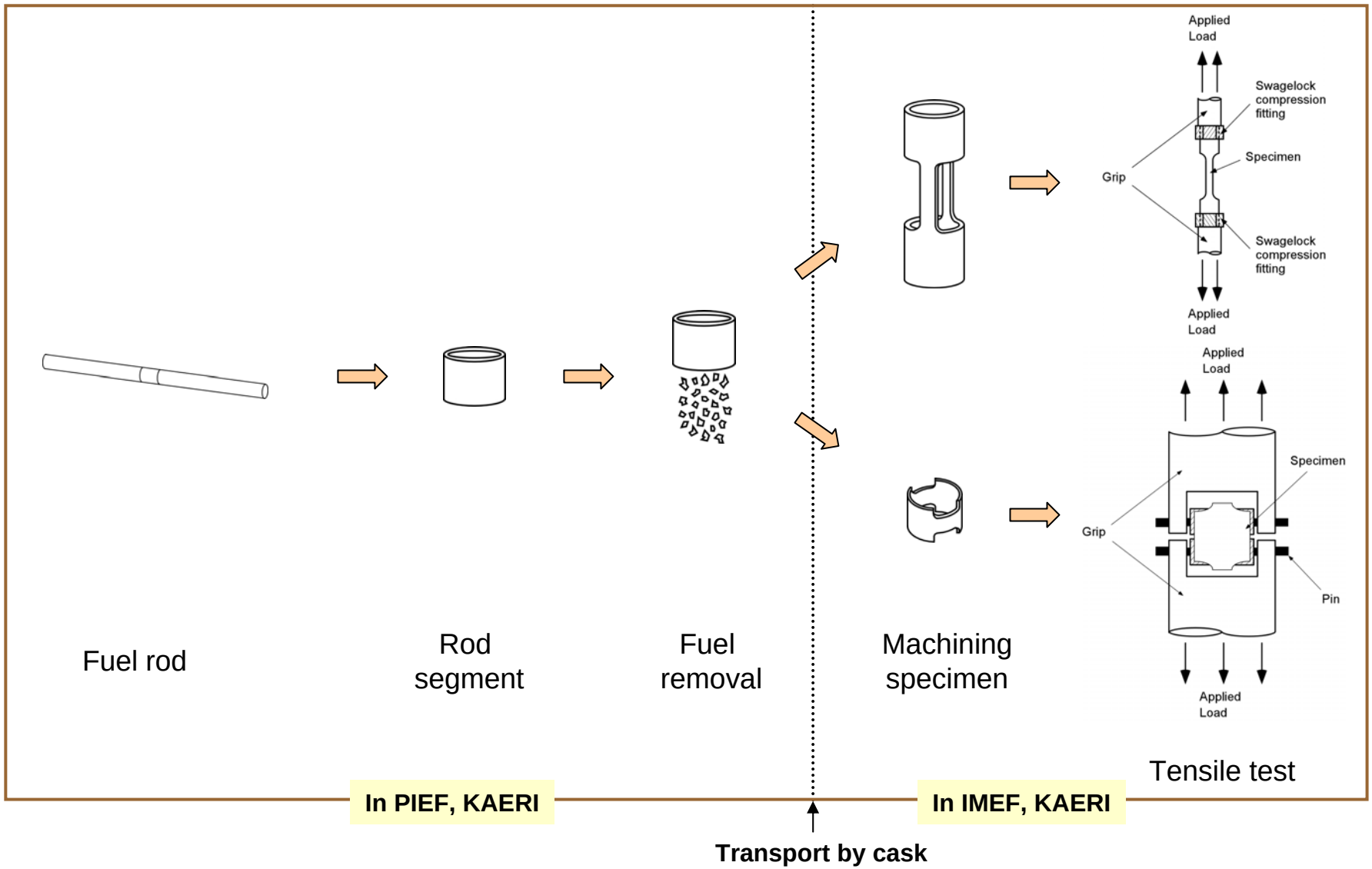
: Average burnup = about 57GWd/tU



Dimensions of fuel rod to be tested

Unit: mm

Schematic of tensile test procedure



Test conditions & Apparatus

1. Axial & hoop tensile test conditions

: To generate data relevant to the loading and thermal conditions of LOCA and RIA

(1) Temperature range = R.T. ~ 800 ^{o}C

(2) Heating rate = 5 ^{o}C/s (LOCA-relevant test), 100 ^{o}C/s (RIA-relevant test)

(3) Initial strain rate = 0.001/s ~ 0.01/s (LOCA-relevant test), 1/s (RIA-relevant test)

2. Testing machine

: Instron servohydraulic system, Model 8562

3. Heating apparatus

: Radiant and resistive furnace with 3 heating zones

: Transient heating apparatus is still under development.

→ Perform the tests after rapid or slow heating up to the test temperature

Ring tensile specimen

1. Ring specimen

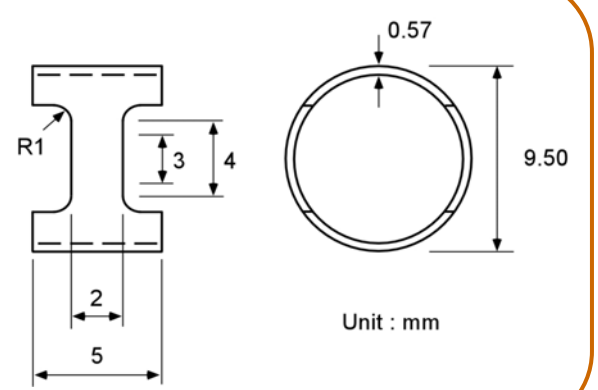
(1) Design requirements

: Deformation is limited in the gage section.

: Maximizing uniform uniaxial hoop strain in the gage section

(2) Dimensions

Determine the mechanical properties in hoop direction of the cladding



Ring specimen

Ring tensile specimen & half cylinder

Ring specimen & half cylinder

Preparation of specimen (1)

1. Removal of fuel in hot cell

: Both mechanical(grinding or drilling of the fuel) and chemical(dissolution of the fuel) techniques will be used to remove the fuel.

: Special care should be taken to prevent damage of the cladding wall.

(1) Mechanical technique

: Drilling the pellets → Remove small fuel particles with nylon-brush

(2) Chemical technique

: A rod segment is placed in a nitric acid(HNO_3) bath for 1~2 days.

- Cleaning

: The cladding segment is ultrasonically cleaned in alcohol.

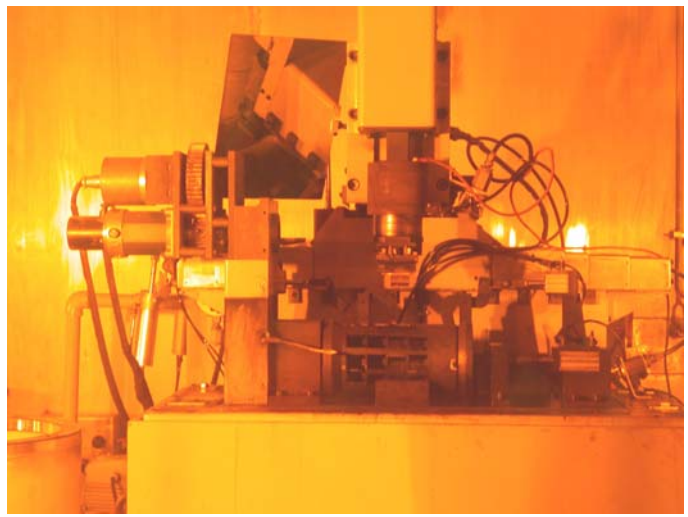
Preparation of specimen (2)

2. Specimen fabrication in hot cell

(1) Using diamond files or emery papers, the oxide on the outer surface of the cladding is partially removed to establish an electrical circuit for specimen fabrication, if needed.

: Particular care is taken not to remove any hydrides on the outer surface of the cladding.

(2) Electrical discharge machine(EDM) will be used.



Grip (1)

2. Hoop loading grip

(1) Design requirements

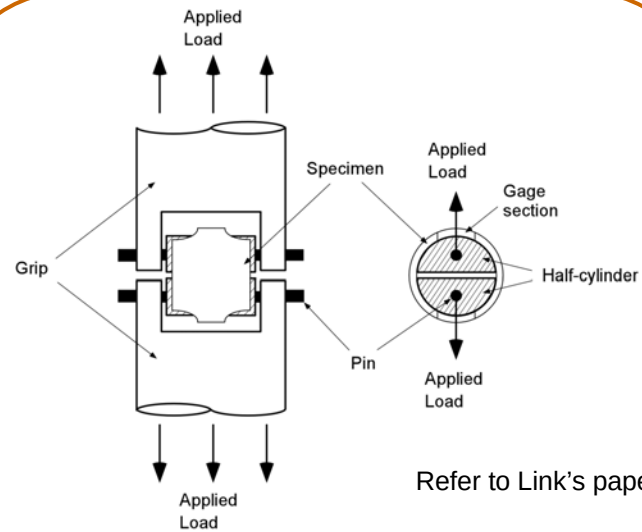
: Prevent specimen bending at the gage section

: Minimize the friction between specimen and grip

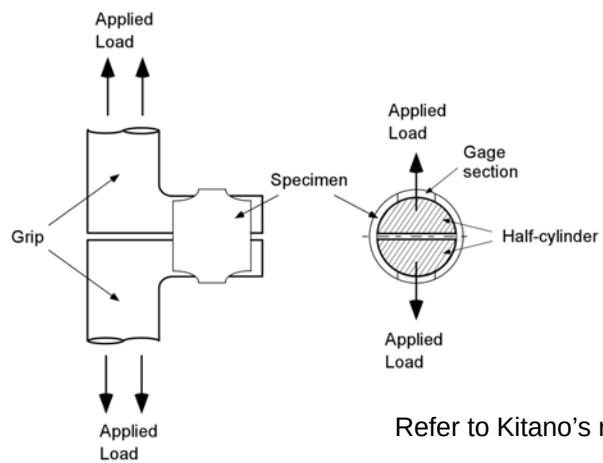
(2) Grip

: The gage sections of the specimens will be oriented at the top and bottom of the half-cylinder, such that a constant specimen curvature is maintained during deformation.

: The interface was lubricated with Teflon tape and graphite lubricant at the beginning of each test.



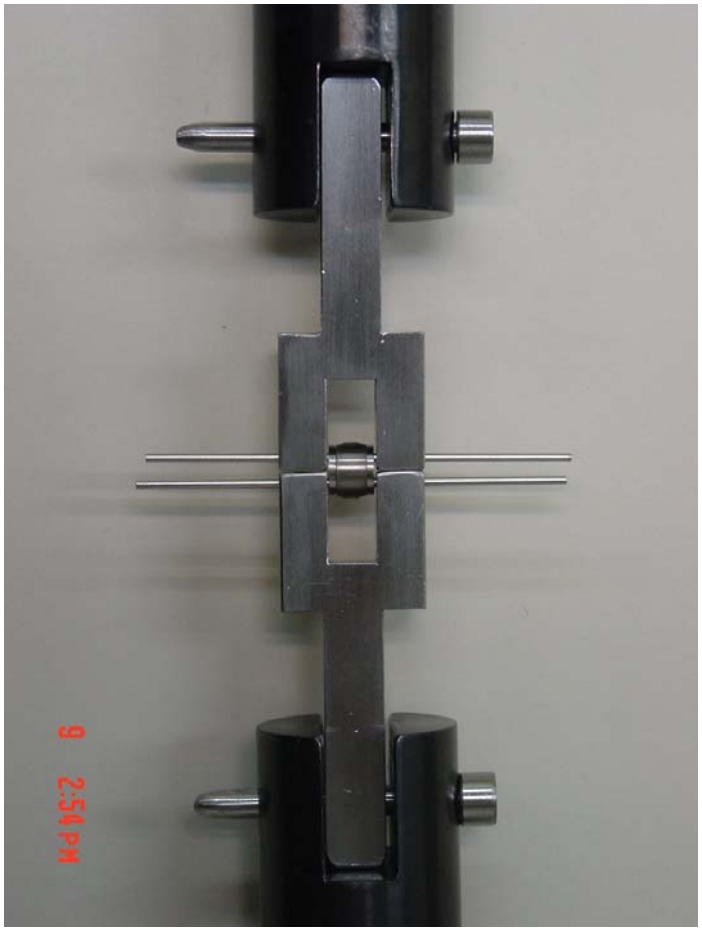
Refer to Link's paper



Refer to Kitano's report

Ring tensile test

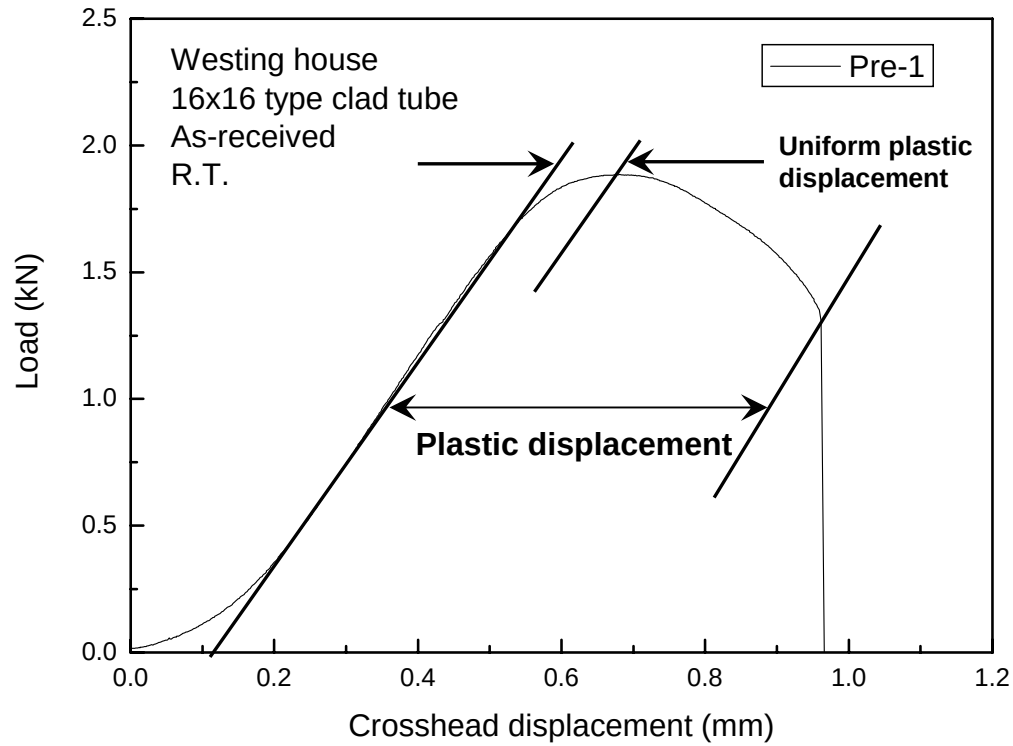
Grip (2)



Jig design 1

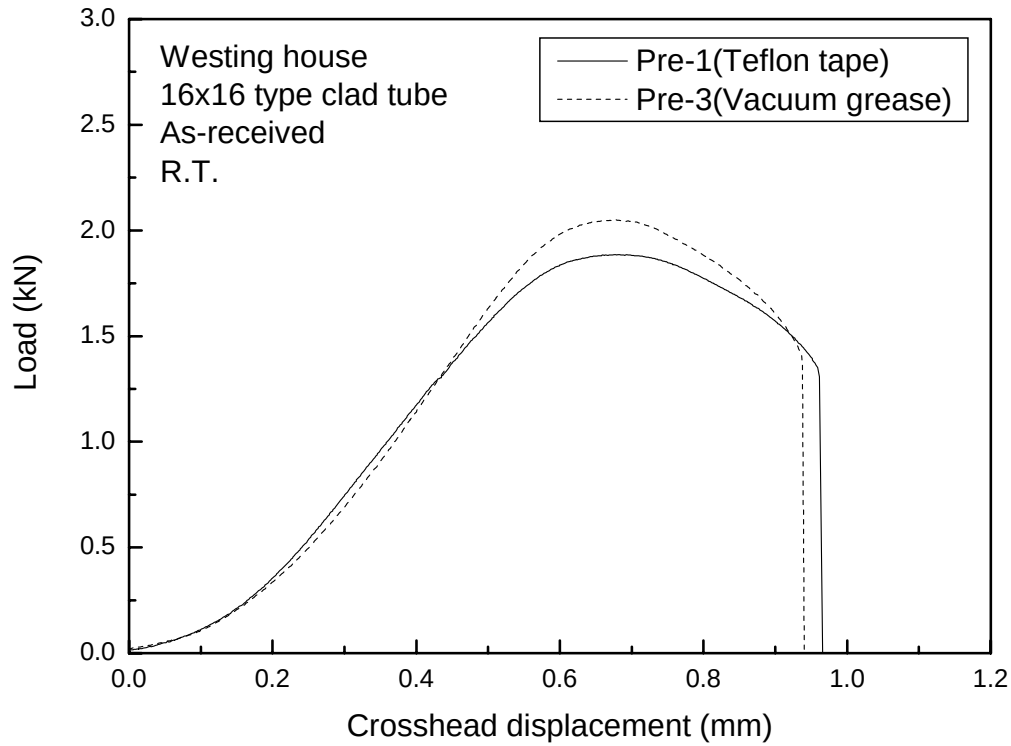
Jig design 2

The results of preliminary tests (1)



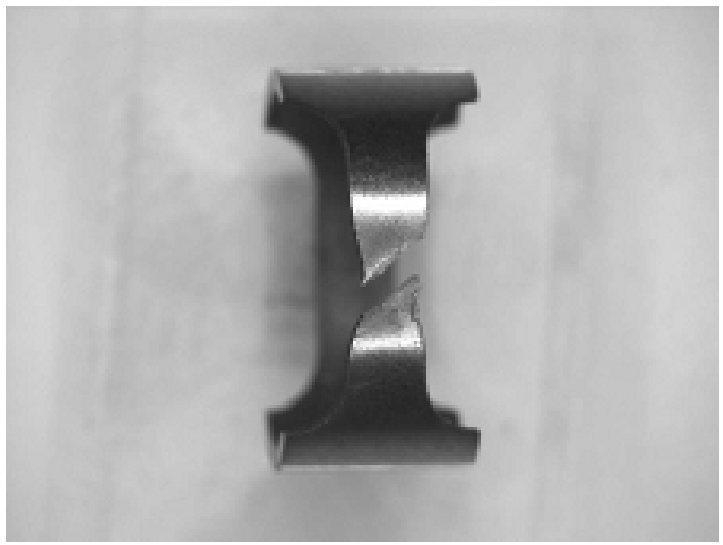
L-D Curve

The results of preliminary tests (2)

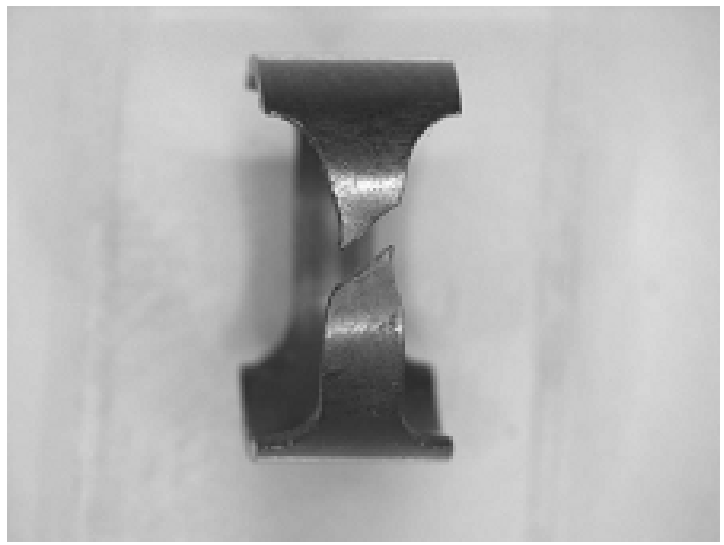


Friction Effect

The results of preliminary tests (3)



(a) Pre-1(Teflon tape)



(b) Pre-3(Graphite lubricant)

Morphology of fractured ring specimens

Summary (1)

To investigate the mechanical properties in the transverse direction of high-burnup fuel cladding tubes

1. Ring tensile test conditions
   : Temperature range, heating rate & strain rate relevant to the loading and thermal conditions of LOCA and RIA

2. Specimen design
   : Hoop tensile specimen - Ring specimen (5 mm)
   : Gauge length = 3 mm, gauge width = 2 mm

3. Preparation of specimen
   : Fuel removal - Mechanical and chemical techniques
   : Specimen fabrication - EDM

Summary (2)

4. Grip design

: Hoop loading grip - Grip with 2-pieces of half-cylinder

: The diameter of half-cylinder = 8.08 mm

: Two types are considered

5. Determination of mechanical properties

: Mechanical properties(yield strength, ultimate tensile strength, uniform elongation, total elongation) in hoop directions

It was confirmed that our design for the ring tensile tests are applicable to the tests in hot cell for the mechanical properties of Zr alloy cladding tubes

Further Study

The experimental variables
of the non-irradiated Zr cladding tubes

1. Cladding tube material
   : Zircaloy-4, ZIRLO, M5
2. Oxidation
   : Steam oxidation experiments with TGA (1200°C)
   : ECR =0, 5, 10, 15, 17, 20, 25 %
3. Hydrogen content
   : Hydrogen charging (400°C)
   : 0, 100, 200, 400, 500, 600, 1,000 ppm
4. Test temperature
   : RT, 135, 200, 400, 600, 800°C
5. Strain rate
   : 0.001, 0.01, 1/s