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Multiaxial ratcheting behavior of zirconium alloy tubes under combined cyclic axial load and internal pressure

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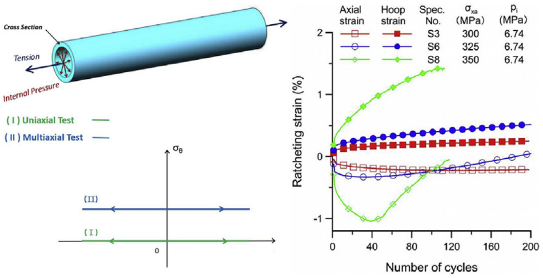
HIGHLIGHTS

- Uniaxial and multiaxial ratcheting behavior of the zirconium alloy tubes are investigated at room temperature.
- The ratcheting depends greatly on the stress amplitude or internal pressure.
- The interaction between the axial and hoop ratcheting mechanisms is greatly dependent on the internal pressure level.
- The ratcheting is influenced significantly by the loading history of internal pressure.

GRAPHICAL ABSTRACT



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ABSTRACT

In this study, a series of uniaxial and multiaxial ratcheting tests were conducted at room temperature on zirconium alloy tubes. The experimental results showed that for uniaxial symmetrical cyclic test, the axial ratcheting strain ε_x did not accumulate obviously in initial stage, but gradually increased up to 1% with increasing stress amplitude σ_{xa}. For multiaxial ratcheting tests, the zirconium alloy tube was highly sensitive to both the axial stress amplitude σ_{xa} and the internal pressure p_i. The hoop ratcheting strain ε_θ increased continuously with the increase of axial stress amplitude, whereas the evolution of axial ratcheting strain ε_x was related to the axial stress amplitude. The internal pressure restricted the ratcheting accumulation in the axial direction, but promoted the hoop ratcheting strain on the contrary. The prior loading history greatly restrained the ratcheting behavior of subsequent cycling with a small internal pressure.

1. Introduction

Zirconium alloy tube has been widely used as fuel cladding in both light and heavy water reactors [1]. The extensive applications in nuclear industry of zirconium alloy tubes are mainly due to a combination of perfect properties of low neutron absorption cross-section [2,3], high corrosion resistance [4], strong creep resistance and excellent mechanical strength during the operating conditions [5].

Reactivity Initiated Accident (RIA), caused by a control rod ejection or drop, is a common design basis accident that could enhance cladding degradation and increase the possibility of

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cladding failure [6]. When a RIA occurs, the fuel pellet expanded abruptly due to the combined effect of thermal load, mechanical load, and neutron irradiation. The resulting fuel pellet expansion leads to pellet - cladding - mechanical interaction (PCMI), which forces the fuel cladding to deform from equal-biaxial tension to plane-strain tension [7–11], and the failure strain of fuel cladding in multiaxial stress state decreased significantly compared to that in uniaxial stress state [12]. In other words, the results obtained from uniaxial tests will underestimate the risk factor, which tends to be unsafe to evaluate the reliability of the nuclear fuel cladding. To solve the problem, many multiaxial testing methods have been proposed in recent years. The ring compression test was directly performed on the cladding tube and relevant finite element simulation was straight-forward. The ring of cladding tube under the plane-strain condition was perfectly consistent with that in RIA [13]. Although the ring compression testing method provided an attractive level of stress biaxiality, it was difficult to define a general failure criterion from testing response [8]. The expansion due to compression (EDC) test was carried out by inserting a polymer pellet into the cladding sample. The stress state in EDC test was close to that of uniaxial hoop test. Simulations based on the finite element method (FEM) have been proved powerful in investigating fracture and fatigue behaviors of advanced structural materials [14–16], so it is necessary to implement the FEM to accurately estimate the stress state and strain path for EDC tests [17]. However, the most important shortcoming for EDC test was that the accuracy of FEM simulation cannot be verified directly from the experiments. The burst test, which can be classified into a plane-strain state, was indeed more accurate compared to those structural testing methods mentioned above [9]. However, without considering the effect of axial stress on the ultimate failure of cladding tube, the burst test method was not effective to provide a sound and safe prediction. Therefore, multiaxial experiments considering the real stress state of fuel cladding tube in active service should be carried out.

In general, the accumulative plastic strain, which is termed as ratcheting strain, takes place and accumulates in the axial and hoop directions when the zirconium alloy tubes are subjected to cyclic stress [18]. Ratcheting accumulates inelastic deformation progressively cycle by cycle, giving rise to irreversible damage of structure and material [19–21]. Due to the factors of non-proportional hardening and diverse loading complexity, multiaxial ratcheting displays more harmfulness compared to uniaxial ratcheting [22]. Therefore, the multiaxial ratcheting behavior of thin-walled tube subjected to cyclic stress and internal pressure was studied extensively in recent years. Corona et al. [23] studied on carbon steel 1018 and 1026 tubes under the strain-symmetric cycling combined with a constant pressure. They found that the symmetric axial strain cycling with a constant pressure led to a continuous hoop ratcheting accumulation. The increase of both axial strain amplitude and hoop stress resulted in increasing hoop ratcheting strain rate. Shi et al. [24] conducted ratcheting test on thin-walled elbow tubes of Z2CND18.12N under reversed in-plane bending moments and a constant internal pressure. They found that the hoop ratcheting strain obviously occurred at the 45° position while the axial ratcheting strain was considerably low. Yoshida [25,26] conducted a series of biaxial creep-ratcheting interaction tests subjected to axial symmetrical cyclic straining combined with a constant internal pressure. The effects of stress rate and stress ratio on ratcheting in biaxial loading paths were investigated. Mattos et al. [27,28] presented the ratcheting behavior of elasto-plastic thin-walled tubes under internal pressure and subjected to cyclic axial loading. They found that the tube exhibited a progressive accumulation of deformation in the hoop direction. However, no experimental tests were used to verify the predictions. Jiao and Kyriadides [29–31] performed ratcheting and wrinkling of tubes under combined axial cycling and internal pressure. They investigated whether a tube that developed small-amplitude wrinkles can be subsequently collapsed by persistent axial cycling. The onset of buckling and collapse was the emphasis of their research, and thus only the scenario of pressurized tubes under compressive loading conditions was concerned. Although uniaxial ratcheting behaviors of zirconium alloys have been investigated widely [32–36], experiments concerning about multiaxial ratcheting of zirconium alloys have hardly ever been carried out, especially for axial-hoop multiaxial ratcheting behavior. Therefore, the multiaxial ratcheting behavior of zirconium alloys is necessary to be discussed and analyzed.

EBSD (electron-backscattered diffraction) technique has a significant influence on the study of materials deformation and failure analysis by examining grain size, grain boundary, local and bulk texture and individual grain orientation. In general, local strain contour maps were often used to analyze plastic deformation at the micron length scale, which could highlight local strain variations in the deformed specimen [37]. The microstructural characterizations and deformation behavior of zirconium alloys have been revealed using EBSD. Clear texture existed in the zirconium alloy tubes caused by fabrication process. Moreover, the variation of bulk texture was observed clearly in the deformed zirconium alloy tubes subjected to multiaxial mechanical loading [38,39].

In this study, a series of studies on uniaxial and multiaxial ratcheting behavior of zirconium alloy tubes were carried out at room temperature. The study will provide some preliminary data concerning about the ratcheting behavior of zirconium alloy tubes under combined axial cycling and a constant internal pressure at room temperature. The results would be helpful to establish a precise constitutive model and improve the accuracy of prediction on reliability of fuel cladding. However, the effects of high temperature and irradiation are not considered in the paper, which limits the applications of experimental data directly to practice. Further studies on these issues are still in progress and will be published in future.

2. Experiments

Table 1 shows the chemical compositions of the zirconium alloy tubes. All specimens used in tests were cut into tubes with an outside diameter of 9.5 mm, an inside diameter of 8.3 mm and a length of 120 mm. Each end of the tubular specimen was inserted into a hollow steel cylinder to prevent the tubular end being crushed by clips. The outside diameter of the hollow steel cylinder is very close to 8.3 mm, but with a minimum clearance of 0.02 mm to ensure it can be plugged into the tube. The inside diameter of the hollow steel cylinder is 3 mm, and the length is 20 mm.

Axial stress was applied by a uniaxial electric-hydraulic actuator with a capacity of 20 kN, whereas internal pressure was imposed by a self-designed servo-hydraulic actuator with a capacity of 30 MPa. A dynamic closed-loop multiaxial testing controller was used to manipulate two actuators simultaneously or independently. The signals of the axial and hoop strain during the test were detected by a biaxial strain gauge. A data acquisition system was employed to monitor and store the signals of load, displacement, internal pressure, axial and hoop strain, etc. 200 data points per cycle were also

Table 1
Compositions of zirconium alloy tube (wt.%).

Zr	Nb	O	Fe	C	S
Bal.	0.8–1.2	0.09–0.18	0.015–0.06	0.0025–0.012	0–0.0035