On the Method to obtain the Effective Elastic Modulus of Non-homogeneous ATF Cladding Materials

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1. Introduction

The development of new materials for a nuclear fuel cladding has been brought into focus worldwide due to the Fukushima accident in 2011. An accident tolerant fuel (ATF) became a popular term for that fuel of new cladding materials. Since a hydrogen explosion of the Fukushima accident was the most significant issue of the cladding, most of the goals of the ATF was given to the reduction of the hydrogen production during the accident evolution so that the coping time can be extended. One of the approaches is to apply a coating of a strong material on the conventional zirconium alloy tube [1,2]. On the other hand, completely different materials other than the conventional zirconium alloy, e.g. SiC [3] and FeCrAl [4], are also under developing to comply with the goal.

So far, many works for the ATF claddings are often devoted to the development of the fabrication technology. Few research works have been done for the mechanical behavior of the ATF claddings from the authors' best knowledge. However, to know it is also important for the mechanical design as well as failure assessment of a nuclear fuel rod. For instance, the elastic modulus and Poisson ratio of the cladding material are used in the elastic buckling formula, which is used to confirm the self-standing criteria of the nuclear fuel rod during the reactor operation.

The first step for the mechanical design and analysis of the ATF rod is to obtain the elastic properties (i.e., elastic modulus and Poisson ratio) of the ATF cladding materials. It is not a simple task because the ATF cladding material is far from a homogeneous material of the conventional zirconium alloy. A conventional test method (e.g., ASTM E8 [5]) is not appropriate to be applied for the ATF cladding materials because the mechanical behavior of present concern is in a radial direction of a cladding rather than a longitudinal one. So to speak, to apply a simple tension to a thin coated cladding (present case of the ATF) along the cladding axis could not give proper elastic properties owing to the different loading direction to which the cladding is actually subjected when deformed.

This implies it is necessary to have a proper method to find the elastic properties of a non-homogeneous material. The micromechanical analysis may be consulted, which has been investigated previously for the functionally graded material (FGM) [6]. Various models of the composite material could also be consulted. If an appropriate model is acquired, it can be used for the design and fabrication guidelines of the ATF cladding materials, which is the purpose of this work. As one of the approaches, it is tried here to develop a simple experimental technique using the theory of solid mechanics.

2. Derivation of Formulae

Primary idea of the present work is to consider a stress-strain relation (Hooke's law) in the case of a plane stress condition of a cylindrical tube. If we denote r, θ and z as the directions along the radial, circumferential (hoop) and axial directions of a tube, respectively, the Hooke law in the θ-z plane under the plane stress assumption can be written as follows.

$$\varepsilon_{\theta\theta} = \frac{1}{E}(\sigma_{\theta\theta} - \nu\sigma_{zz}), \qquad \varepsilon_{zz} = \frac{1}{E}(\sigma_{zz} - \nu\sigma_{\theta\theta}) \quad (1)$$

where E and ν are the elastic modulus and Poisson ratio, respectively. $\varepsilon_{\theta\theta}$ ($\sigma_{\theta\theta}$) and ε_{zz} (σ_{zz}) are the hoop and axial strains (stresses), respectively. It is noted that the radial component of the stress (σ_{rr}) is neglected in Eq. (1) when a plane stress condition is applied.

The plane stress condition can be assumed when a thin and long cylindrical tube is subjected to an internal pressure. In this case, the hoop and axial stresses are well known such as follows.

$$\sigma_{\theta\theta} = \frac{pr}{t}, \qquad \sigma_{zz} = \frac{pr}{2t} \quad (2)$$

where p is the internal pressure, r and t are the radius and thickness of the tube, respectively.

Substituting Eq. (2) to (1) yield the following formulae of E and ν.

$$E = \frac{pr}{2t}\left(\frac{3}{2\varepsilon_{\theta\theta} - \varepsilon_{zz}}\right), \qquad \nu = \frac{1 - 2\,\varepsilon_{zz}/\varepsilon_{\theta\theta}}{2 - \varepsilon_{zz}/\varepsilon_{\theta\theta}}. \quad (3)$$

Eq. (3) shows that E and ν are obtained from the hoop and axial strains that are measured during the elastic deformation of a tube during the exertion of the internal pressure. In addition, it does not depend on the material combination. Therefore, it can be used for the ATF cladding irrespective of its type, e.g. either a coated cladding with strengthening material onto the conventional zirconium alloy or a dispersion of strengthening material into it. Thus, E and ν of Eq. (3) may also be termed as the *effective* elastic modulus and Poisson ratio, respectively in the case of the ATF cladding materials.

3. Experiments

Before applying Eq. (3) for the ATF claddings, it was verified using as-fabricated nuclear fuel cladding of Zircaloy-4 whose properties are known as E = 99.3 GPa and ν = 0.37 in the open database [7]. Besides the Zircaloy-4 tube, the recently developed ODS (oxide dispersion strengthened) coated zirconium alloy tube for the ATF claddings [8] were tested to obtain the E and ν.

The length, outside diameter and thickness of the tube specimens of both materials were 200, 9.5 and 0.57 mm, respectively.

The tube specimen was plugged at one end and a pressure line was connected at the other end of the tube specimen using a swage lock. Thus, the tube can be extended as well as expanded during applying the internal pressure. The strain gauges of both axial and circumferential directions were pasted on the tube surface and at the middle of the tube length.

The applied internal pressure values were 25.53 and 31.91 MPa, which were determined using Eq. (2) such that $\sigma_{\theta\theta} \leq \sigma_{ys}$ where σ_{ys} being the yield strength of the Zircaloy-4 ($\approx$ 320 MPa). The experiments were conducted at room temperature air and repeated three times at each pressure condition. Fig. 1 shows the test apparatus and tube specimen with the strain gauges pasted.

Fig. 1. Device for applying pressure and tube specimen.

4. Results and Discussions

Fig. 2 shows the $\varepsilon_{\theta\theta}$ and ε_{zz} measured at each pressure condition. It is found that $\varepsilon_{\theta\theta}$ is greater than ε_{zz} by around five times. Although only two pressure values were applied in the experiment, $\varepsilon_{\theta\theta}$ and ε_{zz} should be linearly proportional to the pressure. The difference in strain between the bare Zircaloy-4 and ODS coated one is not obviously distinguishable. Thus, it is anticipated that the E and ν of the present ODS coated and bare Zircaloy-4 claddings would not be apparently different. However, it is expected that the strain will be meaningfully changed if either the thickness or modulus of the ODS coating is, or both are altered from the present values.

Figs 3 and 4 provide E and ν, respectively, calculated using the strain values of Fig. 2 and Eq. (3). Compared with the open database [7], the Poisson ratio is somewhat lower (ν = 0.324~0.337 for the bare Zircaloy-4; ν = 0.330~0.333 for the ODS coated) than that (ν = 0.37). However, the elastic modulus values are amazingly close (E = 98.2~102 for the bare Zircaloy-4 and E = 97~100 GPa for the ODS coated) to it (E = 99.3 GPa). Thus, it is addressed here that Eq. (3) can be applicable to estimate the elastic properties of the ATF cladding materials.

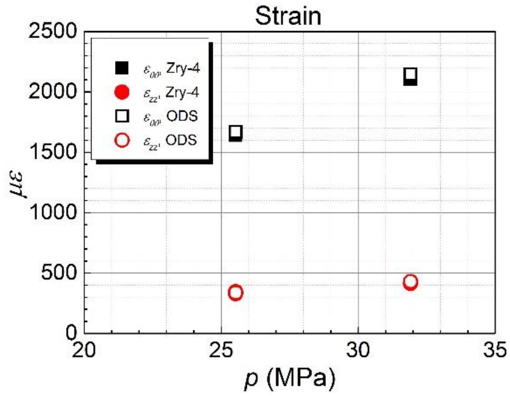

Fig. 2. Strain data.

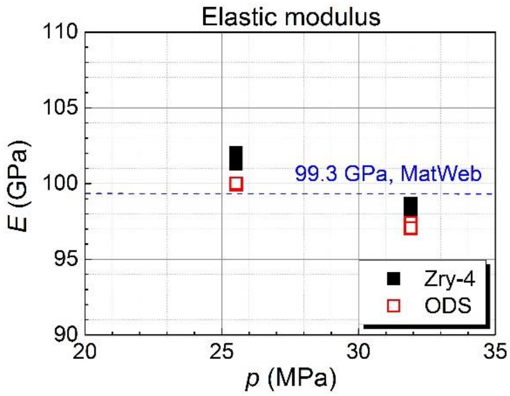

Fig. 3. Elastic modulus evaluated from Eq. (3).

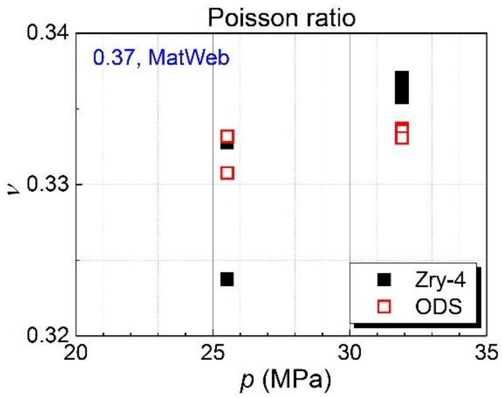

Fig. 4. Poisson ratio evaluated from Eq.(3).

Nevertheless, there may be an issue because E of the ODS coated is a bit lower than that of the bare Zircaloy-4. An apparent increase of the tensile strength was found in the ODS coated cladding compared with the Zircaloy-4 cladding (by $\approx$ 10% and $\approx$ 15% at the room temperature and 380°C conditions [8]. The increase in strength was readily expected because a strengthening material (Y_2O_3) was coated and dispersed into the Zircaloy-4.

However, Fig. 3 does not show such an increase in the elastic modulus. It shows the opposite result even though it is tiny. This is, we think, partly attributed to the allowance range of the strain gauges used. It may also include the accuracy of alignment of the strain gauges, possible significant radius of curvature of the circumferential strain gauge. Of course, the nature of E and ν are different from that of the tensile strength. Nevertheless, it is thought that more experiment with a caution is necessary to understand the present result.

On the other hand, the thin tube assumption for the present tube specimen dimension may be another issue of the present method. Definitely, Eq. (2) was derived when the thickness is very small compared with the radius (or diameter) such that the ratio, t/r (or t/d, $d = 2r$) is as small as reasonably acceptable for the validation of the assumption. In fact, a criterion of t/d does not exist in a numeric value.

For this issue, the following Eq. (4) of the critical stress, σ_{cr} at the onset of elastic buckling of may be considered.

$$\sigma_{cr} = \frac{E}{(1-\nu^2)}\left(\frac{t}{d}\right)^2 \tag{4}$$

From Eq. (4), $t/d \le \sqrt{\left(\sigma_{ys}(1-\nu^2)/E\right)}$ where σ_{ys} is the yield strength here, can produce the numeric value of the thin tube assumption because $\sigma_{cr} \le \sigma_{ys}$ should be satisfied in the elastic regime. If σ_{ys} = 320 MPa is used together with E = 99.7 GPa and ν = 0.37, $t/d \le 0.053$. The present tube dimension of t/d (= 0.06) is a little larger than that. This will also be investigated in detail with more experiments with different materials and various dimensions.

5. Conclusions

A method of estimating the effective elastic modulus and Poisson's ratio of the nuclear fuel claddings was developed using a thin tube theory and corresponding plane stress assumption. A simple formula was derived, which is composed of the strains in the circumferential and axial directions measured from an internally pressurized fuel cladding. A bare Zircaloy-4 tube as well as recently developed ATF cladding of the ODS coated were used for the verification tests. The elastic modulus showed an excellent agreement with the known value in the open database [7], while the Poisson ratio was somewhat different from it. If the verification is sufficiently done with more experiments, the elastic properties of the ATF claddings can be easily obtained using the present method whatever the composition of the cladding material will be. This implies that the method can also be efficiently used for the design of a new ATF cladding material.

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