Study on the FGM Models for Estimating the Elastic Properties of ATF Claddings

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1. Introduction

After the hydrogen explosion accident of the Fukushima nuclear power plant in 2011, a strong demand of developing an accident tolerant fuel (ATF) is vastly driven in the world. Fundamental target of the ATF is rested on the reduction of hydrogen production and the extension of the coping time during accident evolution. One of the realistic approaches is to use a different material rather than the conventional zirconium alloy such as SiC [1] and FeCrAl [2], or to apply a strengthening material such as the coating of Mo-Zr [3] or Cr [4], and the particle dispersion of the ODS (oxide dispersion strengthened) onto the zirconium alloy surface of a fuel cladding. Including these works, many researches on the ATF development have been done from a material science viewpoint. There are few works from the viewpoint of the mechanical design. Perhaps a paper by the present authors regarding the FeCrAl cladding thickness [5] is the first work in the mechanical design area.

The most important concern in the mechanical design standpoint is the self-standing criterion of a fuel rod inside the reactor under operation. It means that the cladding tube should not be collapsed (buckled) during reactor operation. To this end, the reactor internal pressure should be less than the critical buckling pressure, which is expressed as follows.

$$p_{cr} = \frac{E}{4(1-\nu^2)}\left(\frac{t}{r}\right)^3 \qquad (1)$$

where p_{cr} is the critical buckling pressure, E and ν are the elastic modulus and the Poisson ratio of cladding material, respectively. t and r are the thickness and radius of the cladding tube, respectively.

Eq. (1) has been critically used to design the thickness of an outer cladding tube of a dual cooled annular fuel, which has a considerably larger diameter than the conventional fuel rod. Beside the dimension parameters, the mechanical properties, E in particular, play a crucial role in the above critical buckling formula. Thus, it is very important to know the mechanical properties of the ATF cladding material in order to design its dimension. However, this study has not been done visibly so far from the authors' best knowledge. Only the resultant material properties might be presented during the ATF development without a prior design plan of mechanical strength. This drives us to develop a design method to acquire specific mechanical properties of an ATF cladding.

To achieve this aim, we firstly attempt to investigate the models of a functionally graded material (FGM) because the constituents and structure of the ATF cladding are similar to the FGM. As a first step, four different models well known in the FGM are investigated in this work. The features of each model are examined and presented. Tentative calculations are carried out to see the difference between the models. The effect of the volume fraction and higher moduli of the coatings and ODS (termed as strengthening material in this paper) is also studied. A possible reduction of the ATF cladding thickness is considered from an example calculation.

2. Investigation of Some FGM Models

2.1 Revisited Models of the FGM Moduli

The models investigated in this paper are listed below. All those assume that spherical particles are distributed in a statically homogeneous manner in a continuous matrix. In the models below, K and G designate the bulk and shear moduli, respectively. ν means the Poisson ratio. It is considered that the matrix is strengthened by the spherical particles, which are denoted by the subscripts 1 and 2, respectively. c designates the volume fraction, i.e. $c_1 + c_2 = 1$. Whereas, the effective modulus value is denoted by subscript o.

- The Mori-Tanaka (MT) model [6]

$$K_o = K_1\left[1 + \frac{c_2}{\dfrac{3c_1K_1}{3K_1+4G_1} + \dfrac{K_1}{K_2-K_1}}\right]$$

$$G_o = G_1\left[1 + \frac{c_2}{\dfrac{6}{5}\dfrac{c_1(K_1+2G_1)}{3K_1+4G_1} + \dfrac{G_1}{G_2-G_1}}\right]$$

- The Sasaki-Hirai (SS) model [7]

$$K_o = \frac{\dfrac{K_1c_1}{(3K_1+4G_1)} + \dfrac{K_2c_2}{(3K_2+4G_1)}}{\dfrac{c_1}{(3K_1+4G_1)} + \dfrac{c_2}{(3K_2+4G_1)}}$$

$$G_o = G_1\left[\frac{\dfrac{G_2c_2}{(7-5\nu_1)G_1+(8-10\nu_1)G_2} + \dfrac{c_1}{15(1-\nu_1)}}{\dfrac{G_1c_2}{(7-5\nu_1)G_1+(8-10\nu_1)G_2} + \dfrac{c_1}{15(1-\nu_1)}}\right]$$

- The Teraki et al (TR) model [8]

$$K_o = c_1K_1 + c_2K_2 + c_1c_2\frac{(K_1-K_2)(1/K_1-1/K_2)}{\dfrac{c_1}{K_1}+\dfrac{c_2}{K_2}+\dfrac{c_2}{(3K_2+4G_1)}}$$

$$G_o = c_1G_1 + c_2G_2 + c_1c_2\frac{(G_1 - G_2)(1/G_1 - 1/G_2)}{\frac{c_1}{G_1} + \frac{c_2}{G_2} + \frac{9K_1 + 8G_1}{6G_1(K_2 + 2G_2)}}$$

- The Christensen (CH) model [9]

$$K_o = K_1 + \frac{c_2(K_2 - K_1)}{\left\{1 + \frac{(K_2 - K_1)}{(K_1 + 4/3\,G_1)}\right\}}$$

$$G_o = G_1 - \frac{15c_1G_1(1-\nu_1)(1 - G_2/G_1)}{\{7 - 5\nu_1 + 2(4 - 5\nu_1)\,G_2/G_1\}}$$

It is immediately found that the effective elastic modulus (E_o) is not directly given from the above models. However, it is necessary to use it for the design of the cladding tube dimension (Eq. (1)). The relationship between K and E, or G and E may be applied to obtain E, in the case of an isotropic and homogeneous material, such that

$$E = \frac{K}{3(1-2\nu)} = \frac{G}{2(1-\nu)}. \tag{2}$$

It may be said that Eq. (2) can also be used for the anisotropic and non-homogeneous FGM with using an effective Poisson ratio, which is defined as follows [10].

$$\nu_o = c_1\nu_1 + c_2\nu_2. \tag{3}$$

2.2 Some Findings from the Models

Before using the above formulae for an actual ATF cladding material, the feature of the above models are investigated. Without any doubt, each author spent an exhaustive and tedious arithmetic work to derive the models. Therefore, they may have some errors. The most basic confirmation is to check if the effective modulus has that of material 1 when $c_2 = 0$. Opposite case should also be found, e.g. $K_o = K_2$ when $c_1 = 0$. All the above models confirmed it. Besides this, parametric calculations were done and we found the following features.

i) The MT and SS models always give the identical values of K_o and G_o
ii) The TR model always gives the identical values of K_o of the MT and SS models; It also gives the identical values of G_o of the MT and SS models only when $\nu_1 = \nu_2$; If $\nu_1 \neq \nu_2$, G_o from the TR model is different from that obtained from the MT and SS models
iii) The CH model always gives different values of K_o and G_o of the MT, SS and TR models regardless of the difference in the Poisson ratio of the two materials.

Besides above features of i) through iii), it is interesting to see that E_o obtained from K_o is different from that from G_o when the relationship of Eq. (3) is used. This may be attributed to the anisotropic and non-homogeneous feature of the FGM, especially for the Poisson ratio (Eq. (3)). E_o from K_o is always smaller than E_o from G_o irrespective of the model difference. Therefore, it is decided here to use the formula of E directly consists of K and G without incorporating ν, in the case of isotropic and homogeneous material, such as

$$E_o = \frac{9K_oG_o}{(3K_o + G_o)}. \tag{4}$$

In order to increase the strength of the conventional fuel cladding, which is made of a zirconium alloy, the material for the strength enhancement may well have higher modulus than the zirconium alloy. To see the influence of the strengthening material on the modulus enhancement, the above-mentioned models were used for calculations. Example calculation results are given in Fig. 1.

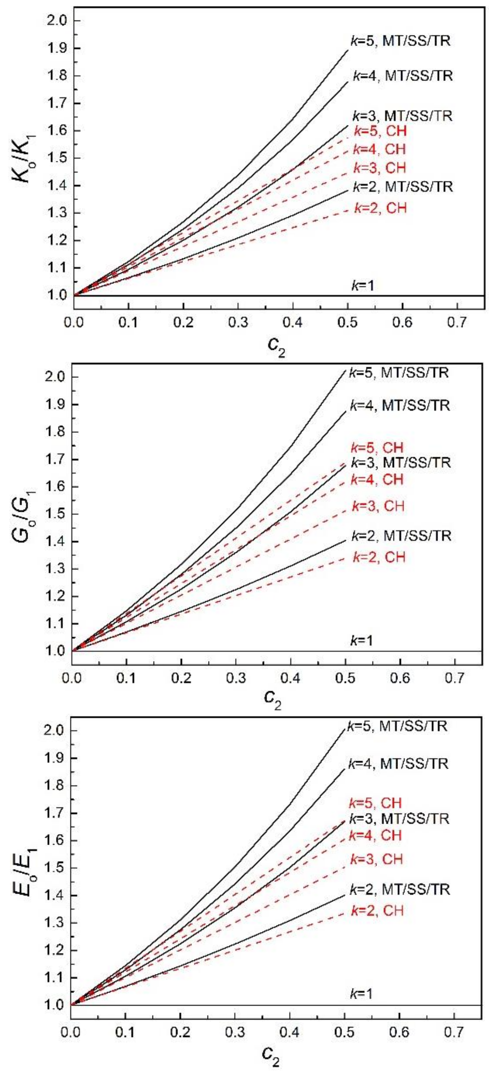

Fig. 1. Variation of the effective bulk (K_o), shear (G_o) and elastic moduli (E_o) in terms of the volume fraction of the strengthening material, c_2, evaluated from various models.

Fig. 1 illustrates the variation of K_o, G_o and E_o when $k \equiv E_2/E_1 = K_2/K_1 = G_2/G_1 = 1 \sim 5$ and the volume fraction of the strengthening material, $c_2 = 0 \sim 0.5$. $\nu_1 = \nu_2 = 0.3$

was assumed here. E_1 was set as 80 GPa for a reference value of the zirconium alloy of a conventional fuel cladding. As already stated, the MT, SS and TR models gives identical K_o, G_o and E_o under the condition of $\nu_1 = \nu_2$.

The CH model always gives lower values than the others do. It is shown that the increase of the modulus is reduced during the increase of k. This means that we cannot expect the strengthening of the FGM in proportion to the modulus of the strengthening material. It is reasonable to see that the modulus of the FGM increases when more strengthening material is included in the matrix. From these findings, the present result such as Fig. 1 can be used to determine the modulus of the strengthening material and its volume fraction to obtain an FGM of a specific modulus.

3. Application to the Cladding Thickness Design

When the elastic modulus increases, the thickness of cladding tube can be reduced corresponding to Eq. (1). Therefore, when $E_o = m \cdot E_{zry}$ (zry stands for a zirconium alloy of the fuel cladding), the thickness of the FGM cladding, $t_o = t_{zry} \cdot (m)^{-1/3}$. For instance, if $k = 3$ and $c_2 = 0.3$, $E_o/E_{zry} = m = E_o/E_1 = 1.355$ (for MT, SS, TR models) that results in $t_o/t_{zry} = 0.904$. So the cladding thickness can be reduced by 10% from the original thickness. It may provide more margin for the oxide layer deposition as well as loading of more fissile material in a fuel rod.

4. Conclusions

The elastic modulus obtained from each of the bulk and shear moduli of the presently investigated models gives different values with each other if incorporating the Poisson ratio, which implies the inapplicability of the relationship between the elastic, bulk and shear moduli of the FGM incorporating the Poisson ratio in an isotropic and homogeneous manner. The irregular result in using the Poisson ratio is also observed during comparing the modulus values of each model: three (MT, SS and TR) out of four models give the same result only if the Poisson ratios of the matrix and strengthening material are the same. This drives us to use a formula consisting the bulk and shear moduli without incorporating the Poisson ratio (Eq. (4)) to evaluate the elastic modulus.

As is expected, each modulus increases from the matrix modulus as the modulus and/or the volume fraction of the strengthening material increase. However, the increase rate of the effective moduli is not proportional to the ratio of the moduli between the matrix and strengthening material. It gradually decreases as the ratio increases. The present approach will be used to design of the strengthening material for an ATF, e.g. a reduction of its cladding thickness.

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