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The Thickness Concern of a FeCrAl Cladding against Buckling Failure

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1. Introduction

Owing to the hydrogen explosion of nuclear fuels at Fukushima 2011, it is widely attempted to develop an accident tolerant fuel (ATF) with using a different material other than the conventional zirconium alloy. The major target is to enhance the oxidation resistance and mechanical strength when compared to the current zirconium alloy under accident conditions [1-6]. A coated Mo-Zr cladding [2], a cladding coating [3,4], an iron-based alloy cladding [5], and a SiC_f/SiC cladding [6] are the typical examples.

Among them, the iron-based alloy (FeCrAl) cladding is brought into focus presntly. Although this material shows a good corrosion/oxidation resistance and high mechanical strength, it has some weak points regarding the melting point, tritium permeation, and neutron economy when compared to the zirconium alloy [5,7].

Among those, the clad thickness of the FeCrAl alloy is substantially decreased to improve the neutron economy, because the mass of fuel loading can be increased as well as the neutron cross-section caused by the FeCrAl cladding can be decreased through the thickness reduction [5]. This may violate the crucial requirement of a fuel cladding of PWR such as to avoid a collapse during reactor operation. Some candidates made of ODS-FeCrAl have a thickness of even as thin as 0.275 mm [8].

Concerning this, present work is carried out to investigate the minimum allowable thickness of the FeCrAl cladding by consulting the well-known formula of the elastic buckling of a tube [9]. In order to achieve this, a safety factor is incorporated considering the uncertainties of the mechanical properties such as the elastic modulus and Poisson ratio, and dimension tolerances of the thickness and diameter. In addition, the ovality of the cladding cross section is also considered. The APMT cladding of 9.5 mm diameter is used for an example calculation, and the minimum thicknesses are presented for various safety factors and ovality.

2. Formulae of Critical Buckling Pressure

2.1 Perfectly Circular Cylindrical Tube

The term, 'critical buckling pressure' is used for an external pressure, p_o (or the difference of external and internal pressures where the former is greater than the latter) at which a tube is abruptly collapsed. In the case of a long tube with a perfectly circular cross section, the critical buckling pressure has been derived in a general form such as follows [10].

$$p_{cr} = \frac{\eta E_s}{4\left(1-\mu^2\right)} \cdot \left(\frac{t}{r}\right)^3 \tag{1}$$

where, p_{cr} designates the critical buckling pressure of a perfectly circular tube, t and r are the thickness and mean radius of the tube, respectively. And,

$$\eta \equiv 1 - \frac{\left(1 - E_t/E_s\right)}{1 + \left(1 - 4\mu^2\right) E_t/\left(3E_s\right)}, \quad \mu \equiv \frac{1}{2} - \left(\frac{1}{2} - \nu\right)\frac{E_s}{E_t} \tag{2}$$

whence E_t and E_s are the tangent and secant moduli, respectively, to incorporate the inelastic behavior of the material, and ν is the Poisson ratio.

If the tube material exhibits a perfectly linear manner in its elastic range, $E_t = E_s \equiv E$, the elastic modulus, and $\mu = \nu$. In this case, Eq. (1) is written as a well-known form appears in mechanical design [9].

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

Because the thickness and radius have dimension tolerances, Eq. (3) may be rewritten conservatively as

$$p_{cr} = \frac{E}{4\left(1-\nu^2\right)} \cdot \left(\frac{t_{\min}}{r_{\max}}\right)^3 \tag{4}$$

where t_{min} and r_{max} are the minimum thickness and maximum radius incorporating the maximum of each tolerance, respectively.

2.2 Tube with Non-zero Ovality

If the cross section of a tube is not perfectly circular, e.g. if it has an oval shape, the tube will be collapsed before p_o reaches p_{cr} of section 2.1. The critical buckling pressure of an oval tube has also been developed [9]. It can be obtained from the following equation, the details of which can be found in [9].

$$q_{cr}{}^2 - \left\{\frac{\sigma_{ys}}{m} + \left(1 + 6mn\right)p_{cr}\right\} \cdot q_{cr} + \frac{\sigma_{ys}}{m} \cdot p_{cr} = 0 \tag{5}$$

where q_{cr} is the critical buckling pressure of a tube with an ovality, δ and σ_{ys} is the compressive yield strength. It is defined as $m = r/t$, $n = \delta/r$.

It should be noted that Eqs. (1) through (5) are derived assuming that the tube deforms within the elastic regime. This implies that p_{cr} and q_{cr} should be less than or equal to $\sigma_{ys}\cdot t/r$. If p_{cr} or q_{cr} exceeds $\sigma_{ys}\cdot t/r$, it should be set as $\sigma_{ys}\cdot t/r$ in the calculation. In addition, we will obtain two q_{cr}'s owing to the quadratic form of Eq. (5). Owing to the above reason, the lower value of the two q_{cr}'s will be the actual solution we need.

3. Application to FeCrAl Claddings

As for the mechanical properties of the FeCrAl cladding, the APMT cladding material is used here for an example calculation. Thus, E = 196 GPa, ν = 0.3, and σ_{ys} = 379 MPa at 320ºC [8,11]. The temperature of 320ºC is used for the condition of hot zero power, which can provide a conservative result because the pressure difference between the external and internal pressures of a fuel rod is the maximum and the mechanical properties are the smallest.

At present, p_o is set as 13.25 MPa reflecting the reactor and fuel rod internal pressures being 15.5 and 2.25 MPa, respectively. In addition, a cladding of 9.5 mm in diameter is presently considered because it is widely used for pressurized water reactor fuels.

To evaluate the minimum required thickness, it is necessary to have a safety factor, S against the buckling failure. This implies that, for instance, S = 1.0 if p_{cr} or q_{cr} is evaluated as 13.25 MPa. The thickness will increase corresponding to the increase of the safety factor as well as the ovality.

Consequently, the minimum thickness is obtained from Eq. (5) with applying p_{cr} = Eq. (3), $q_{cr} = S\cdot p_o$ and a specified value of the ovality. As a result, Eq. (5) produces two solutions. The larger one is to be adopted as the minimum thickness.

Table 1 gives the variation of the minimum thickness when the safety factor is 1.0-3.0, and the ovality is 0-1%. It may be noted that, for conservatism, the safety factor and ovality should be larger than unity and null, respectively. The mechanical properties incorporating the maximum cladding temperature may give more conservatism.

4. Conclusions

Corresponding to the material change from the conventional zirconium alloy to the iron-based alloy for the cladding of an ATF, the thickness tends to be reduced in order to compensate the decrease of the neutron economy. However, the fuel cladding should withstand the reactor internal pressure during operation and avoid an abrupt collapse, which demands a design method to determine the minimum allowable thickness.

Table 1. Min. thickness of the APMT cladding of 9.5 mm in diameter to avoid the elastic buckling failure

Safety factor, S	Ovality, n (%)	t_{min} (mm)
1.0	0	0.30
	0.5	0.35
	1	0.39
2.0	0	0.38
	0.5	0.50
	1	0.57
3.0	0	0.50
	0.5	0.65
	1	0.74

This is achieved in the present work with the APMT (FeCrAl) cladding of the ATF cladding material. The safety factor and ovality are incorporated in this study to give conservatism. As a tentative result for the case of 0.5% ovality and the safety factor of 2.0, the thickness needs to be around 0.50 mm at least.

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