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Design optimization of multi-layer Silicon Carbide cladding for light water reactors

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HIGHLIGHTS

- SiC cladding designs are optimized with a multi-layer structural analysis code.
- Layer radial thickness fraction that minimizes cladding fracture probability exists.
- The demonstrated procedure is applicable for multi-layer SiC cladding design.
- Duplex SiC with the inner composite fraction ~0.4 is optimal in a reference case.
- Increasing composite thermal conductivity markedly decreases SiC cladding stress.

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ABSTRACT

A parametric study that demonstrates a methodology for determining the optimum bilayer composition in a duplex SiC cladding is discussed. The structural performance of multi-layer SiC cladding design is significantly affected by radial thickness fraction of each layer. This study shows that there exists an optimal composite/monolith radial thickness fraction that minimizes failure probability for a duplex SiC cladding in steady-state operation. An exemplary reference case study shows that the duplex cladding with the inner composite fraction ~0.4 and the outer CVD-SiC fraction ~0.6 is found to be the optimal SiC cladding design for the current PWRs with the reference material choice for CVD-SiC and fiber reinforced composite. A marginal increase in the composite fraction from the presented optimal designs may lead to increase structural integrity by introducing some unquantified merits such as increasing damage tolerance. The major factors that affect the optimum cladding designs are temperature gradients and internal gas pressure. Clad wall thickness, thermal conductivity, and Weibull modulus are among the key design parameters/material properties.

1. Introduction

Silicon Carbide (SiC) is considered as a potential alternative for the current zirconium-based alloy (zircaloy) cladding. SiC exhibits a number of attractive features as a light water reactor (LWR) cladding material. It is a well-known high temperature refractory material that exhibits excellent high temperature and irradiation tolerance (Carpenter et al., 2007, 2010; Stempien et al., 2011; Snead et al., 2007, 2011; Snead, 2013; Katoh et al., 2014a). Its high temperature steam reaction rate is a few orders of magnitudes slower than that of zircaloy, essentially eliminating safety issues associated with structural integrity degradation by oxidation (Lee et al., 2013a, 2013b, 2016; Terrani et al., 2014; Pint et al., 2013). These are advantageous features from the safety point of view. Yet, even in operation, SiC cladding is more transparent for thermal neutrons than Zr (Dobisesky et al., 2011; Bloore et al., 2013), which implies minimal, if any, departure from the current LWR core designs.

Despite of the proven advantageous features of SiC, its deployment in LWRs requires to assure reliable operation against its inherently brittle fracture mode. Today, a consensus is being made on the critical importance of understanding its fracture as a cladding material, and improving its structural integrity (Lee and Kazimi, 2015; Ben-Belgacem et al., 2014; Lee et al., 2015b). A recent work conducted at Massachusetts Institute of Technology (MIT) (Lee and Kazimi, 2015) proposed a duplex cladding of the inner fiber-reinforced composite (SiC_f/SiC) layer and the outer CVD-SiC layer. This cladding design is found to markedly reduce

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steady-state cladding failure probability compared to the conventional triple-layered cladding design that employs the inner CVD-SiC monolith, SiC_f/SiC composite, and thin environmental barrier overcoat (Lee and Kazimi, 2015; Carpenter et al., 2010; Stempien et al., 2011; Snead, 2013). Failure modes of SiC cladding considered in this study are limited to the loss of gas-tightness due to the cracking caused by mechanical, thermal, and swelling induced tensile stresses. They can occur by (1) the loss of gas tightness due to through-thickness cracking or (2) the loss of load bearing capabilities. Either of the two results in fission gas releases. The former can still take place without violating the later, i.e.; dispersed matrix cracking in the SiC cladding made of sole SiC_f/SiC composite. The later (2) automatically implies occurrence of the former (1) by losing structural integrity. Hence, in this study, successful cladding design targets to prevent both. Even at today's highest allowable burnup level, the duplex cladding is anticipated to give steady-state fuel failure probability (P_f) less than $\sim 10^{-4}$ ($P_i = 20$ MPa) whereas the triple-layered cladding design is predicted to almost certainly fail ($P_f \sim 1$) (Lee and Kazimi, 2015). Such a marked difference in steady-state cladding failure probability with different layer designs illuminates the following two key points:

(1) Triple-layered SiC is an imprudent design based on incorrect qualitative reasoning for the presence of each layer, which was conducted in the early phase of the concept development.
(2) The cladding layer design holds key to improving structural integrity of SiC cladding.

It is noteworthy that the zircaoly cladding performance has been gradually improved by its composition and coolant chemistry optimization since its first deployment in 1960s. The cladding design optimization directions lie in its key failure causes. That, in case of zircaloy, its chemical affinity with water, hydrogen and irradiation induced embrittlement are the key degradation mechanisms, for which chemical remedies should be used. Hence, for the zircaloy cladding, it was the chemistry related – optimization that led the gradual improvements of the fuel failure rates and accident tolerance over the years. SiC cladding today is a parallel example. For SiC cladding, loss of gas-tightness due to cracking by tensile stress is the dominant failure mechanism, for which the tensile stress managements should be considered.

Tensile stress managements in SiC cladding can be done in a few different ways. Advancing composite architecture, and reducing residual stresses in the manufacturing stage are the two common methods that could be done on the material level. Yet, considering relatively high maturity of today's SiC composite manufacturing technologies, potential for their advancements is considered marginal. A greater improvement can be found from the cladding layer optimization. Indeed, today in the SiC cladding development community, an increasing attention is given to the design work. That, the feasibility of the SiC cladding concept for LWRs should be addressed with the consideration of its designs. Yet, an essential ingredient for the design of a new cladding material is a basic understanding of the material behavior. Thanks to well understood material properties of both monolithic (Snead et al., 2007) and fiber-reinforced composite SiC (Katoh et al., 2007, 2010, 2011, 2013, 2014b; Newsome et al., 2007), today we can ever accurately model the stress distributions of the SiC cladding.

This study is dedicated to demonstrate a methodology for determining the optimum bilayer composition in a duplex SiC cladding. It is important to note that an optimal cladding design for steady-state operation is likely to be different from that of accident conditions. An ideal cladding design optimization should, however, assure its ever most reliable performance in steady-state operation while demonstrating accident coping capability. Hence, in this work, the scope of our exploration is limited to the steady-state performance. Once the steady-state optimization is finalized, a marginal departure from the proposed design may be allowable in the direction of improving its accident performance, which we find worthy of exploring in the future.

2. Design goals and lessons from previous studies

Design optimization of SiC cladding should be conducted to achieve its key functional roles. They are summarized as follows:

- Hermeticity of fission gases

Required gas tightness of cladding is a basis for the need of monolithic CVD-SiC layer. Dispersed matrix cracking SiC_f/SiC in the course of fiber elastic deformation may prevent the use of the sole composite layer as the cladding structure.

- Load-bearing capability

SiC cladding is subject to stresses arising from (1) mechanical loading by pressure difference, (2) differential thermal expansion across the cladding thickness, and (3) differential irradiation-swelling induced expansion across the cladding thickness. Radiation swelling in SiC depends on temperature and quickly saturates with 0.1–1 dpa for temperature ranges of 200–800 °C. Unlike thermal expansion, SiC swelling is greater for the lower temperature. As a consequence, swelling induces tensile stresses in the inner (hotter) region of the cladding and compressive stress in the outer (colder) region (Lee and Kazimi, 2015). SiC cladding layer compositions should be designed to minimize the overall tensile stresses.

- Heat transferring capability

Increasing thermal conductivity of multi-layered SiC cladding is desirable. A lower thermal conductivity of a cladding material increases fuel temperature. A higher fuel temperature increases fission gas releases and fuel pellet expansion, which eventually undesirably raises the cladding stress level. Thermal conductivity of CVD-SiC (~9.5 W/m K at ~1 dpa (Snead et al., 2007; Lee and Kazimi, 2015; Katoh et al., 2011) is far higher than that of SiC_f/SiC (~1.5 W/m K at ~1 dpa) (Katoh et al., 2010, 2011). Hence, a larger relative fraction (in terms of radial thickness) of CVD-SiC is more desirable from the heat transferring point of view.

- Water reaction protection

Previous studies (Filipuzzi et al., 1994; Yin et al., 2001; Ogbuji, 1998) found that high-temperature steam oxidation tolerance of SiC_f/SiC is found to be markedly impaired when steam ingresses through matrix cracks. The pyrolytic carbon coating of SiC fiber is submissive to high temperature steam reaction, which causes loss of its nominal mechanical behavior. This fact mandates to place a protective coating on the cladding outer surface to block steam ingression. In a multi-layered SiC cladding structure, CVD-SiC could function as both steam ingression barrier and load-bearing structure. Impact tolerance is missing from the list because this study primarily concerns failures by tensile stresses.

Previous analyses showed that swelling strain of SiC cladding in the steady-state operation is significant (Lee and Kazimi, 2015; Ben-Belgacem et al., 2014). In the triple-layered cladding design, irradiation swelling causes strong tensile stresses in the inner monolithic CVD-SiC, which seriously challenges the hermeticity