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Fracture strength and principal stress fields during crush testing of the SiC layer in TRISO-coated fuel particles

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HIGHLIGHTS

- A continuous stress vs. force function is defined by modifying the analytic solution.
- FEA simulations with nonlinear geometry show improvements over analytic solutions.
- During the test there are three different stress regimes defined by divot size.
- SiC asphericity is a likely cause of numerical results deviating from empirical data.
- Modeling true shell geometry is the factor of greatest concern in improving accuracy.

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ABSTRACT

Diametrical compression testing is an important technique to evaluate fracture properties of the SiC layer in TRISO-coated nuclear fuel particles. This study was conducted to expand the understanding and improve the methodology of the test. An analytic solution and multiple FEA models are used to determine the development of the principal stress fields in the SiC shell during a crush test. An ideal fracture condition where the diametrical compression test best mimics in-service internal pressurization conditions was discovered. For a small set of empirical data points, results from different analysis methodologies were input to an iterative Weibull equation set to determine characteristic strength (332.9 MPa) and Weibull modulus (3.80). These results correlate well with published research. It is shown that SiC shell asphericity is currently the limiting factor of greatest concern to obtaining repeatable results. Improvements to the FEA are the only apparent method for incorporating asphericity and improving accuracy.

1. Introduction

Tri-isotropic (TRISO) coated fuel particles are at the center of numerous nuclear energy designs and concepts, such as high temperature gas reactors (HTGRs) and fully ceramic micro-encapsulated (FCM) fuels [1,2]. The SiC layer in the TRISO coating functions as a spherical pressure vessel, preventing unintended release of fissile materials. Its structural integrity is imperative to the overall safety rationale that supports the use of HTGRs, FCM fuel elements, and other designs which use TRISO-coated fuel particles.

The SiC layer is applied using chemical vapor deposition (CVD). Its mechanical properties are dependent on the texture of the base onto which it is applied [3]. The SiC exhibits brittle fracture and the bulk of the fissile material is contained so long as no crack penetrates the full thickness of the shell. Thus, understanding principal stress fields and fracture strengths of this application-specific CVD SiC shell is important.

A typical modern TRISO particle (Fig. 1) features a SiC shell which is ~800 μm in diameter and only ~35 μm thick, and therefore mechanical testing is challenging.

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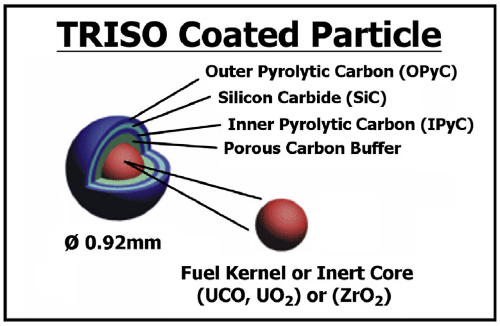

Fig. 1. A cutaway view of a TRISO-coated particle showing the overall size, options for core materials, and order of TRISO applied layers [4].

Numerous destructive test methods have explored the fracture of SiC isolated from the TRISO assembly [3,5,6]. Recent work has focused on diametrical compression of SiC hemispheres [7,8]. A key limitation of this method is that fracture inducing stress is generated on only a small portion of the shell. Results are sensitive to local geometry conditions and scaling functions must be used to predict full shell strength. However, this method has been less tedious than internal pressurization and it is suitable for high temperature testing [9,10].

Fig. 2 illustrates the basic principles of the test method. A soft metal, such as brass, is typically used as the crush plate.

While each layer of the TRISO particle is ideally spherical, manufacturing processes result in SiC shells which have unique aspheric geometries (Fig. 3(a)). In existing analysis methodologies, a test article (Fig. 3(b)) is represented as a uniform hemisphere with an outside radius (R) and thickness (t) [7,8].

The divot left in the soft crush plate (Fig. 4) has previously been considered to be perfectly circular (Fig. 4(a)), with a radius (r_0) that defines the contact area through which load is applied to the SiC test article [7,8]. For analyses which allow for asphericity, crush plate divots may be considered ellipses (Fig. 4(b)), with their minor radius (r_a) and major radius (r_b) measured from the centroid of the divot area.

Diametrical compression generates tensile hoop stress on the inner surface of the shell underneath the contact area. This is similar to the tensile stress that internal pressurization generates on the entire inner surface of the SiC shell for a whole TRISO particle during in-service conditions [11]. Some previous researchers have utilized max. principal stress at the shell inner apex (σ_t) together with r_0 to define localized fracture when using Weibull statistical methods to scale up test results to full shell fracture strength (σ_{fi}^F) [7,8]. Others have employed the more complex scaling function used herein [9]. The end result of either method is an empirically defined Weibull two-parameter statistical distribution for failure probability.

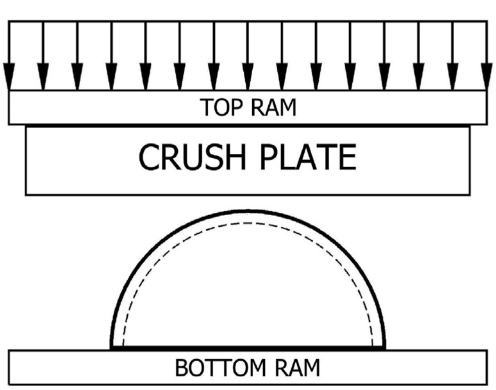

Fig. 2. Diagram of the diametrical compression crush test. The SiC shell rests freely on the fixed bottom ram. The crush plate is attached to the top ram, which moves at a rate controlled by reaction force. The crush plate is thick enough to ensure that the top ram does not affect the contact pressure distribution between the SiC shell and crush plate.

With the intention of improving existing diametrical compression testing and expanding the understanding of test mechanics, there are several questions the present study seeks to investigate:

- How do different calculation methods affect results for max. principal stress at the inner apex of the SiC shell?
- How does the max. principal stress field develop during a diametrical compression test?
- How does shell asphericity affect the principal stress fields?
- What is an appropriate local fracture strength and effective local area to use in a Weibull scaling of the fracture condition?
- What key factor(s) can be identified as limiting accuracy and/or precision?

2. Experimental test procedure

The TRISO-coated fuel particles were procured from Babcock and Wilcox (363 North Sam Houston Pkwy E, Houston, TX 77060) with the same lot and sample number. The particles contained surrogate ZrO_2 kernels (i.e. AGR-coated zirconia beads).

Mechanical test specimens were created by mounting the particles in hot wax and then grinding and polishing to the midplane using 320, 800, and 1200 grit SiC paper. ZrO_2 cores which had not fallen out were removed with tweezers. The hemisphere particles were heated to 800 °C in air to burn off PyC layers and wax. The resulting SiC hemisphere shells were sonicated in Alconox and DI water, then in isopropyl alcohol, before being air dried. Test articles were immersed in buffered oxide etchant, triple rinsed with DI water, and stored for later measurement and testing. Additionally, test articles were placed in an acetone bath and air dried immediately prior to crush testing.

After preparation, geometric parameters of each individual SiC hemisphere were taken using a scanning electron microscope and ImageJ image processing software. Thickness was determined from the mean of 8 measurements made on the polished surface. The outer radius of the shell was calculated from the cross sectional area. Hemisphere height was used to adjust measurements to the midplane [12], producing R and t, which are used in some analyses to represent each test article as a perfect hemisphere of uniform thickness.

Diametrical compression crush testing was performed in a screw-driven tensile test machine (Fig. 2). The top ram had a 3 mm thick polished Brass 260 plate attached to it [7,8]. A load cell (10 lbf) was located under the bottom ram and crosshead travel was force controlled to 3 N/min. The bottom ram was surrounded with tape to contain test article pieces after fracture. Tests were manually stopped when the audible "pop" of a breaking test article was heard and the real time load cell monitor displayed a drastic reduction in force.

Post-test, divot measurements were taken from the brass crush plate in a manner similar to pre-test SiC shell measurements. Circular divot radius (r_0) was calculated from cross sectional area. Elliptical divot radii (r_a, r_b) were measured from the centroid of the cross sectional area to the edge of the divot.

3. Calculations

Calculations were performed to create a correlation between the