STATISTICAL STRENGTH OF CVD PyC

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INTRODUCTION

Nuclear fuel particles of the type used in the High-Temperature Gas-Cooled Reactor (HTGR) consist of spherical fuel kernels that are surrounded by chemical vapor deposited (CVD) coatings for retaining fission products within the particle. The first coating is a porous pyrolytic carbon (PyC) called the buffer layer, which is intended to absorb the energy from fission product recoils and to provide void volume to accommodate gaseous fission products.

The structural coating surrounding this substrate is a triple-layered composite material consisting of pyrolytic silicon carbide sandwiched between dense PyC layers as in the so-called TRISO fissile particles.

The structural performance of these coating layers under irradiation is of paramount importance in retaining fission products. In order to evaluate the structural performance of these coatings, material models, including both constitutive behavior and strength (failure) are required. This abstract discusses the strength model used at General Atomics in the fuel particle stress and performance analysis.

MECHANICAL STRENGTH OF PyC

Mechanical properties of CVD PyC derived from propylene with a range of structures have been measured by testing several small strip specimens in three-point bending [1]. Mean strength in the plane of deposition is listed in Table 1 as a function of sink-float density, deposition rate, and specimen volume. A column designated as BAF is included. BAF (Bacon anisotropy factor) is a measure of the degree of anisotropy as derived from analysis of PyC structures using X-ray or optical diffraction techniques [1,2].

WEIBULL STRENGTH PARAMETERS

Strength data for PyC fuel particle coatings have been analyzed in [1] using a two parameter Weibull volume flaw model for groups of specimens, where groups are different sizes and coating rates. The Weibull parameter, m, varies from 7.6 to 29. Because the Weibull parameter varies, the units of the characteristic strength, in stress×(length)$^{3/m}$, also varies, so that derivation of a single best fit Weibull parameter and characteristic strength is difficult. The strength data in [1] are re-analyzed here to obtain a unique set of Weibull parameters for use.

The results in Table 1 indicate that the Weibull modulus, m, is essentially independent of the coating rate and weakly dependent on the density. A relationship between m and BAF can be established as

$$m=10.1-0.587\times BAF.$$

The model accounts for >80% of the variance. For isotropic PyC (BAF=1.0), m=9.5.

The characteristic strength, σ_0, in Table 1 cannot be statistically analyzed because of the different units from batch to batch due to differences in m values. In this case, σ_0 can be divided by $[V/2(m+1)^2]^{1/m}$ to remove the volume effect, where V is the total volume between two outer supports in the three-point bend test. The resulting strength is denoted by S_0, with the unit of stress, which is essentially equal to the mean strength.

The strength vs density relationship given in [4] is used to adjust the strength in Table 1 to a reference density of 1.9 g/cm^3. The resulting strength is further adjusted to a reference volume of $1.65\times10^8\,\mu m^3$. This yields the following adjusted S_{t0} (MPa) set corresponding to the BAF order appeared in Table 1: 384.1, 402.5, 363.3, 167.3, 408.2, 363.1, 296, 294.3, 396.6, 269.4, 243.3. S_{t0} is found to be dependent on BAF:

$$S_{t0}=2918.7\times BAF^2-2666\times BAF$$

with 96.4% of the variance being accounted for by the model.

To convert S_{t0} to σ_0, one needs to multiply it by $[V/2(m+1)^2]^{1/m}$, where $V=1.65\times10^8\,\mu m^3$ and m corresponds to a given BAF, m=9.5 for BAF≈1.0. Hence,

$$\sigma_0=154.46\times BAF^2-141.1\times BAF\ \ (MPa\cdot m^{3/9.5})$$

in the parallel direction. This is also assumed to apply in the perpendicular direction for near isotropic PyC, since it is extremely difficult to measure the strength of PyC in the thin perpendicular direction (~40 μm thick). In addition, the maximum radial stress in the perpendicular direction is usually much smaller than the maximum tangential stress in the parallel direction. The contribution to the failure probability by the radial stress is several orders of magnitude smaller than that by the tangential stress.

CONCLUSION

Material strength for thin PyC layer prepared by CVD in a fluidized bed is reviewed and evaluated. The Weibull statistical strength theory assuming volume flaws is proposed to model the failure strength. A consistent set of Weibull parameters is derived as a function of degree of anisotropy. The model can be used to predict the performance of the fuel particle under various loading conditions.

REFERENCES

1. J. Kaae, Nucl. Techn., 35, 1977.
2. R. Price, J. Appl. Physics, 6, 1965.
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4. J. Kaae, Carbon, 9, 1971.

Table 1
WEIBULL PARAMETERS OF PROPYLENE-DERIVED PyC's DETERMINED IN THREE-POINT BENDING

Specimen Number	Density (Mg/m^3)	BAF_0	Coating Rate (μ/min)	Specimen Volume ($10^8\,\mu m^3$)	Number of Specimen Tested	Mean Strength (MPa)	Weibull (m)	σ_0 ($MPa\cdot\mu m^{3/m}$)
5781-65	1.94	1.041	1.50	1.653	12	384.0	8.9	1866
5781-69	1.94	1.039	1.61	1.643	12	402.7	10.2	1563
5781-29	1.98	1.025	9.20	1.667	10	362.8	8.1	2115
6251-89	1.95	1.019	11.90	2.867	8	155.6	7.6	1111
5781-33	1.85	1.037	1.22	1.290	6	417.6	11.9	1286
5781-39	1.88	1.037	1.51	1.330	10	371.2	9.8	1509
5901-9	1.83	1.016	3.36	1.961	6	293.5	20.2	553
6411-11	1.83	1.012	10.40	3.065	6	288.1	29.0	352
6251-39	1.65	1.007	4.50	1.029	12	328.0	28.9	490
6251-41	1.67	1.008	11.15	1.211	12	233.0	10.0	903
6251-87	1.63	1.007	27.60	2.614	12	186.3	15.5	449