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RELIABILITY AND LIFETIME PREDICTIONS FOR CERAMIC COMPONENTS

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INTRODUCTION

Ceramic materials are used extensively in non-nuclear components in the weapons stockpile including neutron tubes, stronglinks, weaklinks, batteries, and current/voltage stacks. Ceramics also perform critical functions in electronics, passively as insulators and actively as resistors and capacitors. Glass and ceramic seals also provide hermetic electrical feedthrus in connectors for many weapons components.

The brittle nature of ceramics makes them highly sensitive to the presence of flaws such as pores, grain boundaries, and machining damage. The fracture strength under inert or fast fracture conditions is inversely proportional to the square root of the flaw size. Large flaws are usually detected during processing and assembly, but subcritical flaws that exist in ceramics are difficult to detect. During the stockpile lifetime, these flaws can propagate to a critical size under mechanical/thermal loads, such as residual stresses, thermal cycling, handling (shock and vibration), etc. The propagation of these cracks is strongly dependent on the environment as water or other chemical reagents in the environment react with strained bonds at the crack tip.[1] This behavior is known as subcritical crack growth (SCG), static fatigue, or stress-corrosion cracking.[2] The crack velocity, v, as a function of the applied stress intensity, K, can be described over a range of stress intensities by the power law relationship, $v=AK^N$, where A and N are environmental fatigue constants. Subcritical crack growth may lead to delayed failure of the ceramic at stresses well below the strength values determined in fast fracture qualification tests.

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The primary goal of the present work is to predict the reliability and lifetime of ceramic components under conditions typical of the stockpile environment. We have studied the reliability and dynamic fatigue behavior of 94% alumina (Al_2O_3), which is likely the most common ceramic material in the stockpile. Measurements have been made on alumina samples manufactured by four vendors (Coors, Wesgo, AlSiMag, and Diamonite). These materials are expected to be a representative of typical product obtained from vendors who have supplied alumina during the past several decades.

In a stronglink electrical feedthru ceramic (94% alumina) and metals are joined by brazing. The thermal expansion mismatch between the two on cooling from the brazing temperature leads to residual stresses that may compromise the integrity of the component. Finite element analysis was performed using ABAQUS[i] software to determine the residual stresses generated in the ceramic during the manufacturing of this component. The predicted stresses were then used along with fast fracture strength data to predict the ceramic failure probability using CARES/LIFE[ii] software.

EXPERIMENTAL PROCEDURE

The fast fracture strengths of one hundred size B bend bars of each material were measured in four-point bending according to the procedure specified in ASTM C1161-90.[3] The cross-head displacement rate of 0.5 mm/min corresponds to a stressing rate of ~30 MPa/sec. The

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[i] Hibbitt, Karlsson, and Sorensen, Inc, Pawtucket, RI

[ii] Ceramic Analysis and Reliability Evaluation of Structures (CARES), NASA Lewis, Cleveland, OH

average strength and statistical parameters describing the strength variability (Weibull modulus, m and characteristic strength, σ_o) were calculated from the strength data.[4] The subcritical crack growth behavior was also measured using dynamic fatigue tests on four-point bend bars specified by the same standard (C1161-90). The stressing rate was varied between 10^{-2} and 10^3 MPa/sec. Measurements were made at low (0-3%) and high (95%) relative humidities to account for a range of environmental conditions that may exist in weapons systems. Failure times ranged from ~ 2.8×10^5 sec (3.3 days) to ~ 0.35 sec. Five bars were broken for each test. Plots of the strength vs. stressing rate provide the parameters N and A, which can be used along with the fast fracture parameters to predict the ceramic reliability and lifetime as a function of applied stress.

RESULTS

The fast fracture parameters are shown in Table 1. All four materials show similar strength variability as characterized by the Weibull modulus m. The characteristic strength, σ_o, which is a scaling parameter for strength, and the average strength differ slightly from each other likely due to compositional, grain size, and processing differences.

Table 1. Fast fracture parameters for 94% alumina (σ_{avg}=average strength, σ_o=characteristic strength, m=Weibull modulus).

Material	**σ_{avg} (MPa)**	**σ_o (MPa)**	**m**
AlSiMag 94	295 ± 17	301	22
Coors AD94	317 ± 18	322	21
Wesgo Al500	298 ± 21	306	18
Diamonite	335 ± 18	341	23
All 94% Al_2O_3	324 ± 24	320	16

The dynamic fatigue data are shown in Fig. 1 for the two materials that exhibit the lowest and highest strengths over the range of stressing rates. The Diamonite data are shown for both humidity levels to show the deleterious effect of high humidity. The fatigure parameters A and N can be determined using a least squares fit to the data in Fig. 1.[5] The values are shown in Table 2.

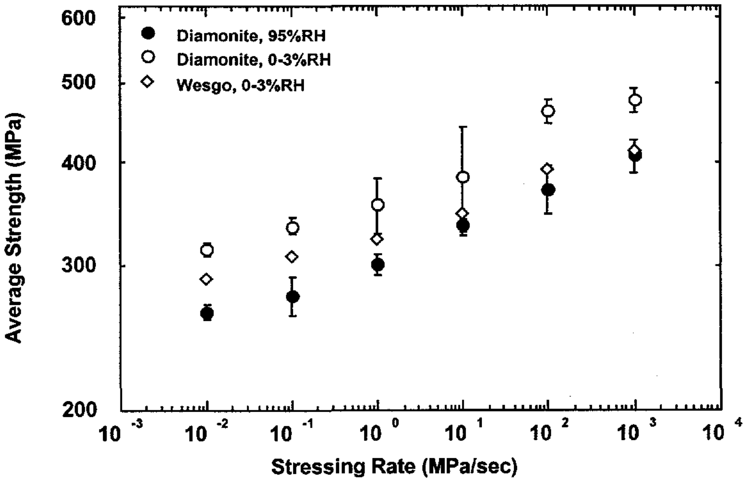


Fig. 1. Fracture strength vs. stressing rate.

Table 2. Dynamic fatigue parameters for 94% alumina at 0-3 and 95% relative humidity

%RH	AlSiMag 94		Coors AD94		Wesgo Al500		Diamonite	
	N	A	N	A	N	A	N	A
0-3	34.8	$3.42\text{x}10^{-29}$	33.8	$3.20\text{x}10^{-28}$	30.3	$5.4\text{x}10^{-24}$	24.8	$1.89\text{x}10^{-23}$
95	36.2	$6.64\text{x}10^{-25}$	26.3	$8.90\text{x}10^{-22}$	24.5	$7.4\text{x}10^{-19}$	24.4	$2.92\text{x}10^{-21}$

The results in Table 2 fall within the range of values found for other aluminas.[6,7] Using these parameters and the fast fracture parameters in Table 1, the nomograph for lifetime predictions in Fig. 2 can be constructed. This plot shows the predicted time to failure for a given failure probability, F (for values between 0.00001 and 0.1) for the Wesgo material at both humidity levels. For a given failure probability, two types of questions can be answered using this plot.

1. For a given level of residual stress in the ceramic, what lifetimes can be expected?
2. What stress level is permissible for a given lifetime?

For example, for a twenty year lifetime and a failure probability of one in a thousand, stresses of 92 and 116 MPa can be sustained at relative humidities of 95% and 3% respectively.

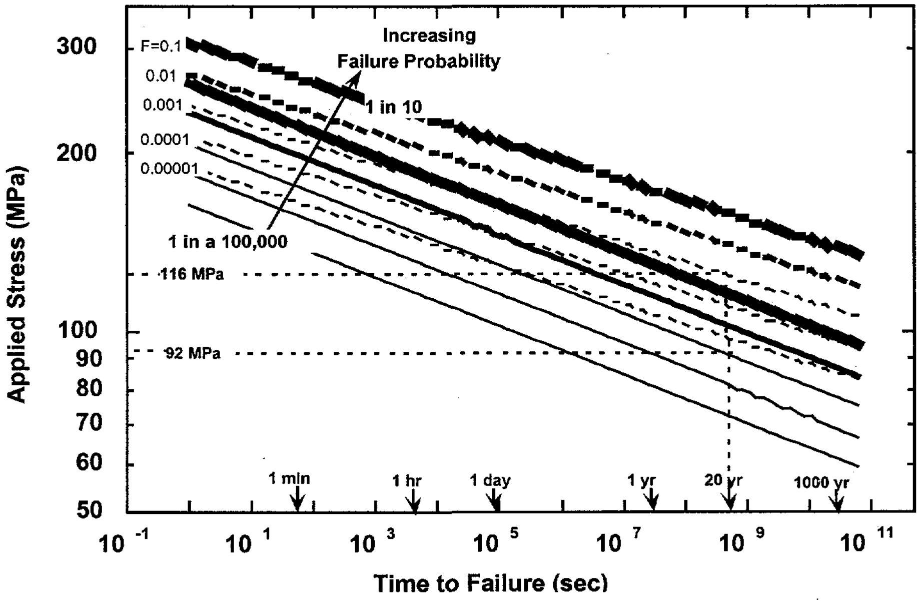


Fig. 2. Lifetime predictions for different failure probabilities, F. Solid lines = 95%RH, Dashed lines = 0-3%RH.

FINITE ELEMENT ANALYSIS OF COMPONENTS

Residual stresses generated in various materials in a feedthru during manufacturing were predicted using commercially available ABAQUS software. The connector is comprised of 94% alumina, Kovar, stainless steel, and silver braze alloy. The connector and the finite element mesh are shown in Fig. 3. The alumina and Kovar are brazed at 980°C using a silver braze. During the brazing process and subsequent cool-down to room temperature, residual stresses are generated due to the differential thermal contractions of the alumina, silver braze, Kovar contact, washer, and sleeve, and the stainless steel header. The component was modeled using axisymmetric thermal/solid elements CAX4. Kovar was modeled as a temperature dependent elastic-plastic material. The stainless steel header was not expected to plastically deform and was modeled as a linear elastic material. The silver braze was modeled using the hyperbolic creep model in ABAQUS.

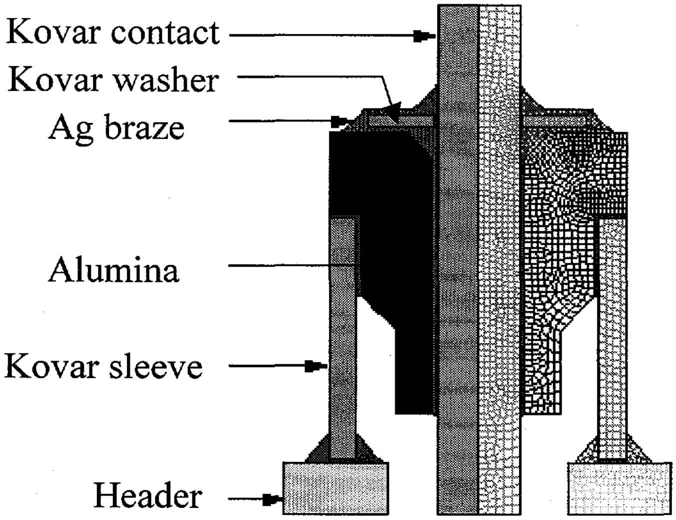
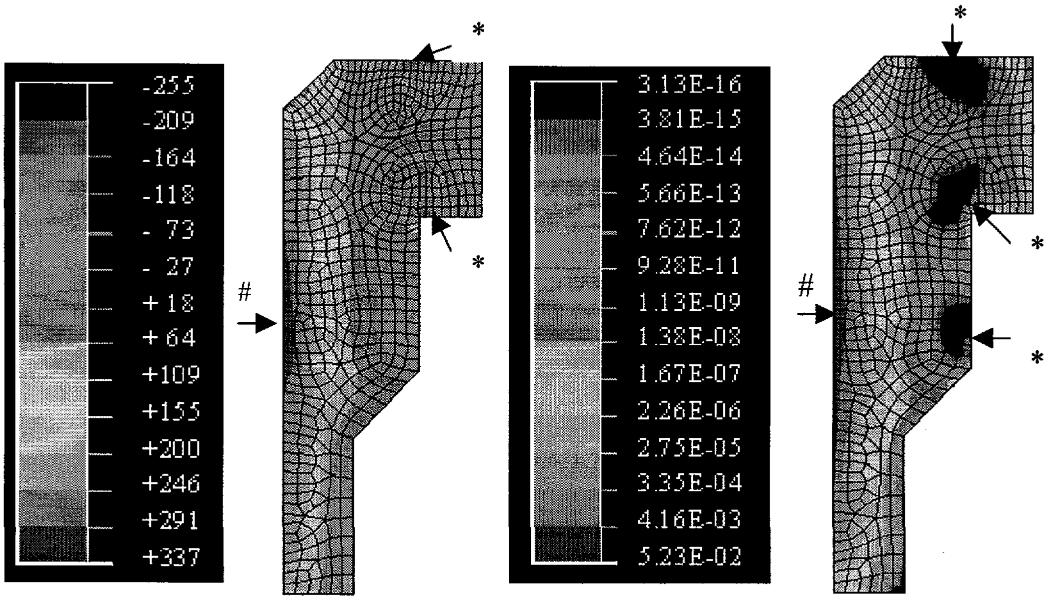


Fig. 3. Finite element mesh of the axisymmetric feedthru.

In the analysis, the feedthru was considered stress free at 960°C, the melting temperature of silver. The connector was then cooled to 20°C and the residual stress state was calculated. Results of the analysis indicated that high residual stress would be generated in the alumina near the center of the Kovar contact pin as shown in Fig. 4(a). A maximum principal stress of 336 MPa oriented in a radial direction was predicted. This stress is presumably caused by the Kovar contact contracting more than the alumina on cooldown from the stress-free temperature.

RELIABILITY PREDICTION USING CARES/LIFE

CARES/LIFE is a software package developed at NASA Lewis that predicts the failure probability of a monolithic ceramic component[8]. It couples commercial finite element programs--which resolve a component's temperature and stress distribution--with reliability evaluation and fracture mechanics routines for modeling strength-limiting defects. The failure probability of the stronglink feedthru was determined using fast fracture strength data and stresses calculated by finite element analysis. In the CARES/LIFE analysis, Weibull's principal of independent action (PIA) was used as the fracture criterion. Fig. 4 shows contour maps of principal stress and failure probability for various elements in the alumina using the strength distribution of Diamonite samples. The overall failure probability of the ceramic component was 0.009. The corresponding values for AlSiMag and "All" samples were 0.164 and 0.034 respectively.



(a)

(b)

Fig. 4: (a) Principal stresses (in MPa) and (b) risk of rupture (log scale) of alumina in stronglink feedthru. # and * indicate maximum and minimum values in the figures.

CONCLUSIONS

Fast fracture and dynamic fatigue measurements have been made for 94% alumina samples from four vendors. There are only slight differences in the fast fracture behavior of these materials; however, their subcritical crack growth (SCG) behavior is significantly different likely due to differences in the composition of the glass phase in alumina. As expected, high humidity conditions produce a greater degree of strength degradation. Finite element analysis was performed to determine the residual stresses generated in a ceramic component during assembly. The analysis indicated that high residual stresses are generated in the ceramic in stronglink feedthru during cooling from the brazing process. Using the statistical strength parameters and results from the finite element analysis, the reliability of ceramic component was predicted using NASA CARES/LIFE program. The failure probability of the component was found to be very strongly dependent on the slight differences in sample strength distributions.

Lifetime predictions are only as good as the material data and the estimate of the residual stresses in the ceramic. Residual stress estimates are obtained using finite element models of the component along with our best measurements and/or estimate of the properties of all the materials in that component. Additionally, the low K threshold in the subcritical crack growth behavior of alumina is not accounted for in the power law description. There are also issues relating to whether the behavior measured with test bars is representative of the behavior of the ceramic in a component and whether the properties of alumina are different near interfaces with other materials, such as at a braze joint between alumina and Kovar. In addition, alumina is prepared for brazing using a metallization procedure that is likely to change its mechanical performance. One additional caveat is that the residual stresses that drive cracks often drop off very rapidly away from the interface in which case the crack may never reach the critical size.

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