Lifetime Predictions for Alumina Ceramics Used in Nuclear Weapons Stockpile Components
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Introduction

Ceramic materials are used extensively in non-nuclear components in the weapons stockpile including neutron tubes, firing sets, radar, strong link and weak link assemblies, 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 feedthroughs 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 (those flaws too small to cause fracture under rapid loading) exist in all ceramic parts that are too small to be detected during initial testing and inspection. Mechanical loading due to residual stresses, thermal cycling, and handling (shock and vibration), along with environmental assistance due to the presence of reactive substances (especially moisture), are the driving forces for subcritical flaws to slowly grow to a critical size during stockpile lifetime. Residual stresses are our main concern and they are present because of the thermal expansion mismatch between the ceramic and the metal that it is joined to in a component. 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 most of the range of stress intensities of interest by the power law relationship, $v=AK^N$, where A and N are environmental fatigue constants.

Subcritical crack growth leads to delayed failure (cracking) of the ceramic-containing component at stresses well below the strength values determined in fast fracture. A strength decrease of the ceramic due to SCG may compromise the function of components. On the assumption that introducing new ceramic parts into all existing weapons components is not a viable near-term means of achieving high reliability, weapons safety and reliability will rely solely on the ability to accurately predict the service life of components in the weapons stockpile, allowing component design engineers to replace vulnerable components before they fail.

The primary goal of the ceramic material lifetime prediction program is to provide the enhanced surveillance program with the capability to specify the reliability and lifetimes of glass and ceramic-containing components under conditions typical of the stockpile environment. We have studied the reliability and subcritical crack growth (SCG) behavior of 94% alumina (Al_2O_3), which is likely the most common ceramic in the stockpile. Measurements have been made on aluminas manufactured by four war reserve qualified vendors (Coors, Wesgo, AlSiMag, and Diamonite). These materials are expected to be representative of typical product obtained from vendors who have supplied alumina for weapons components during the past several decades.

Experimental Procedure

The fast fracture strengths of one hundred size B bend bars 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 average strength and statistical parameters describing the strength variability (Weibull modulus, m and characteristic strength, σ_0) were calculated from the strength data.⁴ The subcritical crack growth behavior was measured using dynamic fatigue tests. The stressing rate was varied between 10^{-2} and 10^3 MPa/sec. Measurements were made at low (0-3%) and high relative humidities (95%) to account for the range of environmental conditions that exist in weapons systems. Failure times ranged from $\sim 2.8 \times 10^5$ 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 reliability and lifetime as a function of the applied stress.

Results and Discussion

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_0 , which is a scaling parameter for the strength, and the average strength show that the materials have *slightly* different strengths. These differences are likely due to compositional, grain size, and processing differences.

¹ S. M. Wiederhorn, "Influence of Water Vapour on Crack Propagation Soda-Lime Glass," *J. Am. Ceram. Soc.*, Vol. 50, p. 407, (1967).

² B. R. Lawn, *Fracture of Brittle Solids*, Cambridge University Press (1993).

³ ASTM C1161-90. Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature.

⁴ W. Weibull, "A Statistical Distribution Function of Wide Applicability," *J. Appl. Mech.*, 19, p. 293 (1951).

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

AlSiMag 94			Coors AD94			Wesgo Al500			Diamonite			All 94% Al ₂ O ₃		
σ_{avg}	σ_o	m	σ_{avg}	σ_o	m	σ_{avg}	σ_o	m	σ_{avg}	σ_o	m	σ_{avg}	σ_o	m
295 ±17	301	22	317 ±18	322	21	298 ±21	306	18	335 ±18	341	23	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 how higher humidity enhances the strength degradation. The parameters A and N in the power law relation $v=AK^N$ can be determined using a least squares fit to the data in Fig. 1.⁵ The values are shown in Table 2.

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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
3	34.8	3.42×10^{-29}	33.8	3.20×10^{-28}	30.3	5.4×10^{-24}	24.8	1.89×10^{-23}
95	36.2	6.64×10^{-25}	26.3	8.90×10^{-22}	24.5	7.4×10^{-19}	24.4	2.92×10^{-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 a component, what lifetimes can be expected?
2. What stress level is permissible for a given lifetime?

At a failure probability of $F=0.001$, results are shown in Table 3 for Question 1 with residual stresses of 69 and 100 MPa (10 and 14.5 ksi), and for Question 2 for a 20 year lifetime. A maximum residual tensile stress of 69 MPa has been used for many years at Sandia as a design guideline for alumina. Twenty years is the expected stockpile lifetime.

⁵ T. Fett, and D. Munz, "Lifetime Prediction of Ceramic Materials Under Constant and Cyclic Load," pp. 161-174 in *Life Prediction Methodologies and Data for Ceramic Materials*, ASTM STP 1201, C. R. Brinkman and S. F. Duffy, Eds., American Society for Testing and Materials, Philadelphia, 1994.

⁶ T. Fett, W. Hartlieb, K. Keller, B. Knecht, D. Munz, and W. Rieger, "Subcritical Crack Growth in High-Grade Alumina," *J. Nucl. Mater.*, 184, pp. 39-46, (1991).

⁷ L-Y. Chao and D. K. Shetty, "Time-Dependent Strength Degradation and Reliability of Alumina Ceramic Subjected to Biaxial Flexure," pp. 228-249, in *Life Prediction Methodologies and Data for Ceramic Materials*, ASTM STP 1201.

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

Table 3. Lifetimes for a given residual stresses and acceptable residual stress levels for a lifetime of twenty years (both for a failure probability of 0.001, Wesgo alumina).

% Relative Humidity	t_f for $\sigma_{res}=69$ MPa (10 ksi)	t_f for $\sigma_{res}=100$ MPa (14.5 ksi)	σ_{max} for $t_f=20$ yr
0-3	2.8×10^{16} sec (8.9×10^6 yr)	3.6×10^{11} sec (11,260 yr)	116 MPa
95	5.1×10^{11} sec (16,300 yr)	5.6×10^7 sec (1.8 yr)	92 MPa

Lifetime predictions are only as good as the material data and the estimate of the residual stresses the ceramic is subjected to. Residual stress estimates are obtained using finite element models of the component along with our best estimate of the properties of all the materials in that component. What is not accounted for in this method for obtaining lifetime predictions is that there is a low K threshold in the subcritical crack growth behavior that 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 this situation the crack may never reach a critical size. This situation makes the predictions shown in Fig. 2 conservative.

We are currently interfacing finite element model predictions of stresses in ceramic-containing components⁸ to the NASA CARES/LIFE code for ceramic lifetime predictions.⁹ This will allow us to identify components in which the ceramic is likely to be vulnerable and regions of the ceramic that should be examined to determine if subcritical crack growth is occurring. We are currently examining returned hardware and accelerated aging units to validate our predictions.

Conclusions

Fast fracture and subcritical crack growth measurements have been made for four 94% aluminas. 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 of the alumina. The SCG behavior determines whether the alumina will fail at low loads before replacement. High humidity conditions produce a greater degree of strength degradation. The fracture parameters measured for 94% alumina were used to predict lifetimes for a given residual stress level and to determine an acceptable stress for a given lifetime. Stresses less than 92 MPa at high humidity and less than 116 MPa at low humidities are required to ensure a lifetime of at least twenty years.

⁸ Sandia National Labs Internal Memorandum, Date: Oct. 29, 1996, From: M. K. Neilsen, To: S. L. Monroe, Subject: Thermal Stress Analysis of MC2969 Connectors.

⁹ N. N. Nemeth, L. M. Powers, L. A. Janosik, and J. P. Gyekenyesi, CARES/LIFE - Ceramics Analysis and Reliability Evaluation of Structures. Users and Programmers Manual, NASA Lewis Research Center, Cleveland, OH, March 1993.

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