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ADVANCED CERAMIC COMPOSITE FOR HIGH ENERGY RESISTORS; CHARACTERIZATION OF ELECTRICAL AND PHYSICAL PROPERTIES

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There is a need to characterize and apply advanced materials to improve the performance of components used in pulse power systems. One area for Innovation is the use of bulk electrically conductive ceramics for non-inductive, high energy and high power electrical resistors. Standard Ceramics, Inc. has developed a unique silicon carbide structural ceramic composite which exhibits electrical conductivity. The new, conductive, bulk ceramic material has a controlled microstructure, which results In Improved homogeneity, making the material suitable for use as a non-Inductive, high energy resistor. The new material has higher density, higher peak temperature limit, and greater physical strength compared with bulk ceramics currently used for pulsed power resistors.

This paper describes characterization of the material's physical and electrical properties, and relates them to Improvements in low-Inductance, high temperature, high power density, and high energy density resistors. An improvement of 3 to 5 times in energy and power density, as compared to existing components, would be expected, derived from specific properties such as good thermal conductivity, high strength, thermal shock resistance and high temperature capability. The bulk resistor approach we propose offers high reliability through better mechanical properties and simplicity of construction.

Key words: ceramic, composite, resistors, physical & high energy

INTRODUCTION

Bulk ceramic resistors have been used since the 1930's for pulsed power and other high energy or high power applications. The technology for producing these resistors has not changed much in this period of time. The advantages of using bulk ceramic In pulsed power applications is the ability for the material to absorb a large amount of energy for a given package size. This is due to the fact that nearly the entire mass of the package is the resistive element.

Current bulk ceramics consist mainly of either carbon-alumina or silicon-clay materials. whose shortcomings include high thermal resistance, low strength, and high porosity. The physical characteristics directly Impact the energy density and power density of the finished component, resulting In larger, less-efficient, costlier resistors. For example, current bulk resistors require 8 long cooling time between energy pulses, which limits the allowable duty cycle of the system. Thus, the material shortcomings lead to bulkier, more expensive systems.

New bulk resistor materials need to be developed and characterized. Standard Ceramics, Inc. has developed Electrically Conductive Silicon Carbide (ECSC), 8 proprietary advanced composite. ECSC may offer Improvements in cost and package size by Increasing power and energy density.

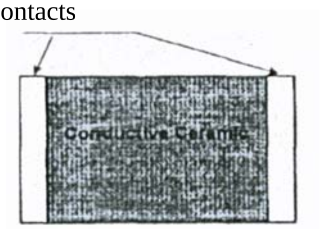

Fig. 1 Bulk resistor concept

THE PROGRAM

A grant from the New York Energy Research and Development Authority, (NYSERDA) provides partial funding for a program to demonstrate ECSC for use in bulk resistors, with the balance funded privately. The goal of this program is to characterize important properties, Investigate manufacturing issues, and finally, demonstrate prototype components in actual applications. A characterization of relevant physical, electr1caI, thermal, and mechanical properties of selected current and advanced ceramics for use in non-Inductive high-energy resistors will be accomplished.

TARGET APPLICATIONS

The materials properties Improvement would translate into very high peak-to-average power capability, allowing reduced size and weight, and Improved reliability for snubber circuit, Inrush limit, and braking resistors now needed for high frequency energy conversion circuits. As well, the high energy capacity would benefit pulse power systems with reduced size and shorter recycle time through better cooling.

The program goal is a process to manufacture the material and energy conversion package for highly reliable, non-Inductive ceramic composite resistors for use In energy conversion systems, energy storage systems, power sources, and pulsed power systems.

Experience with the failure mechanisms associated with current components highlights some important characteristics already diagnosed as Important to the resistor application. These are identified In Table I.

Table I Important Properties of Electrically Conductive Ceramics

Physical	Thermal
Density Microstructure Grain Size Pore Size	Thermal Conductivity Heat Capacity Thermal expansion Coefficient
Mechanical	Electrical
Young's Modulus Flexural Strength Thermal Shock Resistance (TCR)	Resistivity Thermal Coefficient of Resistance (TCR) Voltage Coefficient of Resistance

CURRENT BULK RESISTORS

Available bulk resistors are widely used in pulsed power applications, and are mainly of the carbon-alumina type. Thermal conductivity is typically 4.18 W/m(C (1) . The low thermal diffusivity results In a long thermal time constant, requiring cooling times of up to an hour or more after a maximum energy pulse, with low average power. Mounting the resistor to a heat sink can aid in cooling, but the low thermal conductivity of the ceramic is still the limiting factor. This is a major hurdle in using bulk ceramic in practical pulsed power applications.

Lower relative density is one contributor to the low thermal conductivity of the current materials. Current carbon-alumina material is approximately 80% dense, depending on carbon loading. With voids in the material, the number of thermal paths are reduced, resulting in a lower thermal conductivity. Nominal bulk density for the current material is 2.25 g/cc2.

The microstructure of carbon-alumina Inherently reduces the thermal conductivity. While carbon has a relatively high thermal conductivity, the alumina and the clay used for bonding the alumina both have lower thermal conductivity.

Not being near theoretical maximum density also leads to poor strength. In many cases, when resistivity is changed the density of the material also changes, particularly in some carbon-alumina resistors. The lower resistivity materials tend to be weaker and more prone to laminar fracturing during production. Laminar fracturing can result in decreased thermal performance, local "hot-spots", and decreased physical strength.

The combination of low thermal conductivity and low fracture strength are primary contributors to lower thermal shock resistance (TSR). TSR is directly proportional to both of these quantities.

Peak temperature of typical carbon-alumina resistors Is 150°C continuous, and 250 °c to 300°C for peak temperature excursion. Silicon bonded resistors have a 3500C peak temperature31. Beyond these values, resistance changes of greater than +5% are common.

STATUS OF DEVELOPMENT OF CURRENT ECSC

Improvement in thermal conductivity was a key issue for this developmental work on the ECSC. Many facets of a resistor's performance are dependent on this property, as noted above. Thermal conductivity was determined using laser flash measurements on thin discs of ECSC material. These tests were carried out at Alfred University. Results indicated a thermal conductivity between 116 and 126 W/m(C. The average of the test results was 122.5 W/m(C. This Is an Improvement of 29 times the typical thermal conductivity of current bulk resistor material.

Resistivity of the ECSC Is an important factor is determining whether or not the material is suitable for use in pulse power applications. The resistivity of TSC was expected to be in the 0.01 ohm-cm to 20 ohm-cm range. The factors affecting resistivity include composition, density, and the sintering process. The more dense the material, the lower the resistivity. Typica1 bulk densities range from 3.02 to 3.05 g/cc. Disc-shaped test slugs were made using various combinations of raw SiC powder, sintering temperature, sintering time, and sintering additives. These slugs then had brass terminations bonded to the faces of the discs, using an electrically conductive nickel-filled epoxy. The results of the measurements indicated a resistivity range of 0.9 to 48.16 ohm-cm (See Table II), though this is not an exhaustive compilation of combinations.

Table II . Resistivity Data

Batch number	number of samples	Average resistivity (ohm-cm)
151a	3	12.92
152a	3	25.37
153a	3	35.62
154a	3	48.16
155a	3	12.42
151b	4	0.90
152b	3	1.94
153b	3	1.50
154b	4	1.83
155b	4	1.59

Thermal shock resistance (TSR) is determined using the approximation (4);

$$R^f = \frac{K\sigma_f(1-\mu)}{E_a} \approx \frac{K\sigma_f}{E_a}$$

Where, K is the thermal conductivity (W/mº(c), σ_f is the fracture strength (N/m^2), E is Young's Modulus (N/m^2), and a is the thermal expansion coefficient (m/mº (c).

The poisson ratio, (, is approximately the same for the ceramics in question, including carbon-alumina and silicon carbide. Because of this, the (1-) factor can be eliminated when making comparisons between the various types of ceramics. For ECSC, this value, ignoring the Poisson ratio term, is 2.48 x 104(w/m). The corresponding number for carbon-alumina is approximately, depending on percentage of carbon loading, 1.09 x 102 (W/m), which is an order of magnitude less.

The peak temperature of ECSC is much higher than carbon-alumina. Structural properties remain Intact at continuous temperatures of 1200(C, while the electrical properties of ECSC have been tested to remain within 0.5% of their Initial values at temperature of 200(C continuously, with some of the change due to contact oxidation. Based on the lack of change in the structure of the material, the peak temperature for use as a resistor is expected to be near 1200(C. This Increase In the maximum temperature means that the material, when used as a resistor, can absorb more energy in a single pulse, since the allowable peak temperature is higher. Also, smaller resistors can be used to absorb amounts of energy where a much larger carbon-alumina or clay bonded silicon resistor would need to be used. Thus, resistors for high energy pulses could be made much smaller.

NEXT PHASE-CONCLUSION

The results of this investigation In to the feasibility of using ECSC as a bulk resistive material have indicated that ECSC is a viable material for this purpose, and has improved performance parameters, particularly improved thermal conductivity, which is directly related to improved power density, improved temperature capability, which is directly to Improved energy density, and a suitable resistivity range.

Further investigation is planned in several areas, as the next phase of the project. The thermal shock resistance will be determined via quench tests, and a test will be developed to determined the shock resistance of an upward temperature change. The results of these two test can then be correlated.

Temperature coefficient of resistance will also be determined over a suitable range of temperatures, and voltage coefficient of resistance will also be measured. Bonding techniques for obtaining the best electrical contact will also be explored in further detail. Possible methods for bonding Include flame spray metal1zatlon. plasma deposition, and plating.

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