Polycrystalline Alumina for Advanced Infrared Windows and Domes

CeraNova Corporation
85 Hayes Memorial Drive
Marlborough, MA 01752

Contact: Mark V. Parish, Ph.D.
Phone: (508) 460-0300 [x12]
Fax: (508) 460-0325
Email: mparish@ceranova.com
Website: www.ceranova.com

AIM-9X Sidewinder

Command: NAVAIR
Topic: N04-234

PROBLEM STATEMENT

Missile domes are one of the most demanding applications for ceramics because severe aero-thermal heating occurs as a missile accelerates to its programmed velocity. These rapid heating rates require materials with excellent thermal shock resistance, in order to avoid premature failure. Thermal shock resistance is a function of both intrinsic properties (e.g., thermal conductivity) and extrinsic properties (e.g., strength). Ceramic materials suitable for missile dome applications must possess excellent physical properties in conjunction with high transmission over a broad wavelength range.

As surveillance and tactical missions become more vital and missile speeds increase, there is a need to improve the performance of infrared (IR) systems to provide higher quality images. Increasing missile velocities coupled with higher sensor performance requires commensurate improvements in window and dome performance, including aerodynamic (ogive) shapes. Ogive domes enable a combination of increased range, speed, and payload due to reduced drag. The ogive shape also offers improved rain impact resistance and a greater unvignetted field of view. CeraNova's fine-grained polycrystalline alumina (CeraLumina™) is the most promising candidate material to fulfill the requirements for a successful ogive missile dome. CeraLumina™ possesses the required performance benefits of sapphire, yet can be fabricated using a cost-effective near-net shape processing method.

CeraLumina™ could be used as a direct replacement for sapphire in several existing window and dome applications, e.g. AIM-9X Sidewinder.

WHO CAN BENEFIT?

Near-term and long-term dome and window applications exist for CeraLumina™ in IR missile systems. The AIM9X Sidewinder is the most likely system for initial demonstration of CeraLumina™ as a hemispheric dome. In the near term, CeraLumina™ could be used also as a direct replacement for sapphire in other existing short and medium range missiles.

With funding from AFOSR, CeraNova is forming and evaluating polycrystalline alumina for an advanced propulsion application. This application requires the infrared transparency, excellent mechanical properties, and high chemical inertness of CeraLumina™.

Due to its fine-grained microstructure, high density, and very low defect concentration – resulting in excellent mechanical properties – coupled with low specific gravity, CeraLumina™ could provide benefits as an armor material, e.g. for lightweight ballistic protection in small arms protective insert (SAPI) armor. Conventional, larger grained alumina is already used for some SAPI armor, and CeraLumina™ may have even better ballistic performance. Preliminary ballistic testing is in progress. The potential application of CeraLumina™ as an infrared transmitting material and as a lightweight, high strength armor material would benefit all branches of the DoD.

BASELINE TECHNOLOGY

Single crystal Al_2O_3 (sapphire) remains the material of choice for the most demanding dome applications, due to its excellent combination of mechanical, thermal, and optical properties. However, sapphire has proven expensive due to the time and cost involved in growing large single crystals and machining dome shapes from the crystal boules. Also, sapphire is a single crystal and its properties are a function of crystal orientation. Consequently, the mechanical and optical properties of single crystal sapphire domes vary with position on the curved dome surface. Compensating hardware and/or software solutions are required to correct for this variability in optical properties.

Other polycrystalline materials, such as AlON and spinel, have good optical properties, and are under consideration for IR dome and window applications. However, these materials are fabricated with large grains (>100μm) that can lead to decreased mechanical strength.

The cost of manufacturing a sapphire hemispheric dome, including growth of the single crystal boule, machining the basic shape, grinding and polishing the interior and exterior surfaces, is estimated to be at least $20K. CeraNova polycrystalline alumina can be formed to near-net shape which significantly reduces the manufacturing time of the basic shape and essentially eliminates the time and cost associated with machining and shape grinding sapphire domes.

TECHNOLOGY DESCRIPTION

Polycrystalline alumina has the potential for providing aerothermal performance better than sapphire, yet offers the benefits of lower cost powder based manufacturing. Polycrystalline alumina has the same intrinsic properties as sapphire, but its mechanical properties are enhanced by processing to a very fine grain size (≤500nm). The resulting material has high thermal shock resistance and nearly equivalent optical properties in the MWIR.

CeraNova has demonstrated transparent polycrystalline alumina using a powder processing method for shape forming. The sintered material is 100% dense, has a submicron grain structure, high transmittance (Figures 1 and 2), and low scattering in the infrared (Table 1).

Figure 1.
Transparent CeraLumina™ disk (~2mm thickness) with high in-line transmittance.

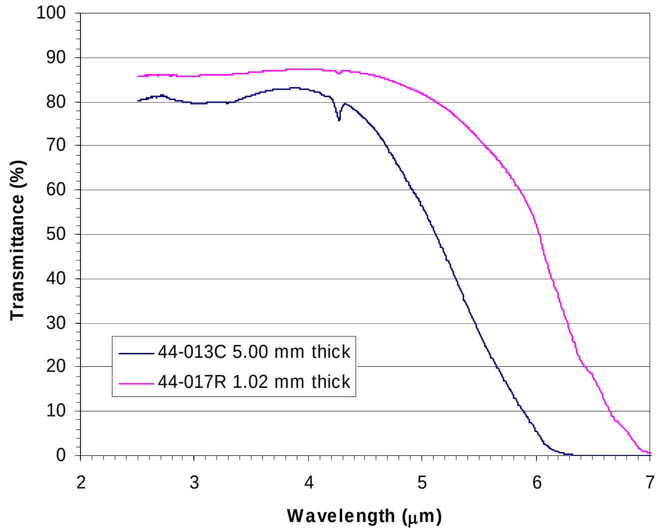

Figure 2. In-line transmission (MWIR) for CeraLumina™ 1mm and 5mm thickness.

Table 1. Total integrated optical scatter at 3.39 µm for CeraNova polycrystalline alumina.

	1.02 mm thick	5.00 mm thick
Percent scatter in forward hemisphere	0.10 ± 0.007	0.21 ± 0.006
Percent scatter in backward hemisphere	0.06 ± 0.03	0.16 ± 0.006

Testing performed at NAVAIR China Lake.

Advanced mechanical property measurements by third parties have shown that, compared to sapphire, CeraLumina™ has a) higher hardness and toughness (Table 2), b) comparable thermal shock resistance (laser thermal shock tests performed by Aerospace Corporation), and c) equivalent rain impact resistance at normal incidence (Figure 3). In addition, biaxial flexure testing of CeraLumina™ disks gave measured strengths approaching 1GPa and Weibull modulus (a measure of material reliability) greater than 6.

Table 2. Hardness and Toughness for Several IR Materials

Material	**Hardness (Kgf/mm^2)**	**K_{Ic} (MPa m$^{1/2}$)**
Spinel	1349 ± 45	2.22 ± 0.20
AlON	1558 ± 44	2.96 ± 0.21
Sapphire	1692 ± 111	2.54 ± 0.17
CeraNova PCA	2284 ± 53	3.30 ± 0.12

*All materials tested at the Center for Optics Manufacturing, University of Rochester (NY) under equivalent conditions.

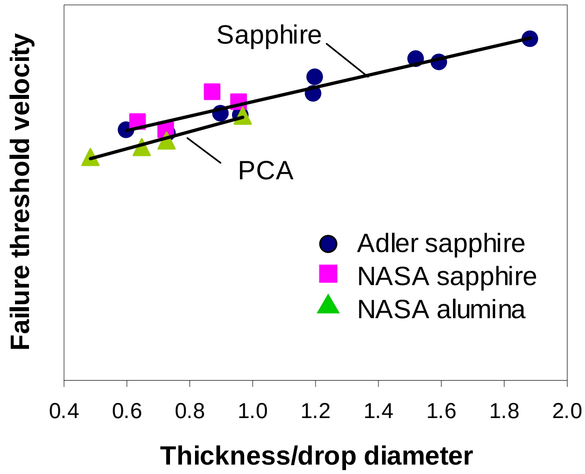

Figure 3. Results of single drop water impact tests (normal incidence) show similar performance for polycrystalline alumina and sapphire. All tests were conducted at NASA-Marshall Space Flight Center. "Adler sapphire" is data generated previously by Adler using the same test equipment. "NASA sapphire" is sapphire tested by NASA to compare with Adler's data. "NASA alumina" is CeraLumina™ tested by NASA.

Table 3. Biaxial flexure strength and Weibull modulus for CeraLumina™.

Weibull Modulus	Average Strength	Median Strength	Std. Dev.	Number of Samples
6.56	967.3 MPa	978.2 MPa	161.9 MPa	28

Tests performed at the University of Dayton Research Institute.

The advantages of CeraLumina™ vs. sapphire include lower cost, facility of molding into required shapes, and improved mechanical and thermomechanical properties, leading to improved aerothermal performance. Features and benefits are summarized in Table 4.

Table 4. Features, Advantages, and Benefits of CeraLumina™ vs. Sapphire

Property / Feature	**Sapphire** single crystal alumina	**CeraLumina™** fine grain polycrystalline alumina
Optical	High transmission in the MWIR; very low scattering; dependent on crystal direction	Transmission and scattering nearly equivalent to sapphire; optically isotropic.
Mechanical	Dependent on crystal direction	Isotropic, with higher hardness and toughness than sapphire.
Thermal Shock	Best MWIR dome material.	Equivalent to sapphire.
Rain Impact	Good; dependent on crystal orientation.	Equivalent to sapphire at normal incidence; potential improvements at other incident angles; isotropic.
Manufacturability	Long times required to grow large crystals; dome shapes must be machined from large crystals – adds to cost.	Powder based manufacturing using established ceramic processing enables near-net shape – reduces machining time and cost.
	Cannot produce "deep concave" (ogive) shapes economically from single crystal boules.	Ogive shapes can be manufactured to near-net shapes with powder based manufacturing.

The ability to cost-effectively produce an ogive dome is a revolutionary new capability. The size and geometry of ogive domes make machining these shapes from single crystal sapphire prohibitively expensive. However, this future need could be addressed using the lower cost, near-net shape forming methods employed by CeraNova to process polycrystalline alumina. An aerodynamic shape made from CeraLumina™, with a durable material at the nose, could survive in hypersonic flight.

CURRENT STATE OF DEVELOPMENT

Both hemispheric and ogive dome shapes have been produced from CeraLumina™ using CeraNova's near-net shape forming technology. Figure 4 shows a fully polished hemispheric dome with good transparency in both the visible and the infrared, and a full-scale, fully dense ogive dome blank (unpolished) of polycrystalline alumina.

At present, techniques to grind and polish such deep concave shapes to the required precise optical tolerance are under development. CeraNova recently installed two pieces of fabrication equipment to grind and polish both hemispheric and ogive domes. The eSX 150 grinder and the UltraForm polisher (purchased from OptiPro Systems) have multi-step programmable 5-axis CNC grinding and polishing capability for the fabrication of highly precise, complex optical surfaces. CeraNova is working closely with OptiPro to modify the equipment as necessary to ensure that it is capable of fabricating deep concave shapes to the tolerances required for Navy applications.

CeraNova also has ongoing collaborations with several other organizations investigating new methods for grinding and polishing domes, and with organizations developing and evaluating new techniques for metrology of ogive domes.

Figure 4. Full size, fully dense, unpolished ogive dome blank and fully dense, polished hemispheric dome of CeraLumina™ polycrystalline alumina. (Base diameter of hemisphere is approximately 70mm.)

The current TRL for this technology is 3. CeraNova's current Phase II polycrystalline alumina IR dome programs include complete preparation (through final polish) of hemispheric domes and full size ogive domes. These tasks are scheduled for completion in Fall 2010 and will increase the TRL to 4.

Improvements to the baseline material continue as improved techniques and materials are incorporated. Evaluation of optical and mechanical properties is ongoing. Advanced rain impact tests are in progress, including distorted drop tests and tests.

Fully polished hemispheric domes for qualification testing will be available Spring 2010. We expect qualification testing to be conducted by Prime Contractors who would use domes in their missile systems. Eventual insertion/deployment of CeraNova domes in missile systems will require ongoing collaboration among CeraNova, Prime Contractors, and NAVAIR. A full scale, fully dense polished ogive is expected by Fall 2010.

Technical challenges include scale-up of the processing technology to full-size domes, and processing reproducibility and reliability to ensure fine grain size, high density, and no defects. These are being addressed in current in-house programs including the equipment and procedures that will be necessary for appropriate quantity and quality of manufacturing scale-up. Machining and metrology of ogive domes is a particular challenge which will involve development of new methods and equipment. A comprehensive evaluation of cost / performance benefits and trade-offs versus sapphire domes is planned.

REFERENCES

NAVAIR TPOC: Tel. 760-939-1649

ABOUT THE COMPANY

CeraNova Corporation, a privately held company, was founded in 1992 to be a leader in the development and manufacture of advanced ceramic products for targeted markets. CeraNova Corporation has extensive experience in processing and characterization of ceramics and ceramic composites. Primarily involved in R&D and pilot-scale manufacturing of innovative, high technology materials, CeraNova seeks application partners and commercialization opportunities for the technology it develops. In 1996 CeraNova spun off a sister company, Specific Surface Corporation. This separately funded venture was undertaken to manufacture, under license, ceramic filters for particulate filtration. CeraNova employees have experience in developing sound business plans, in raising capital and in commercializing technology.

For the past seven years, CeraNova has directed increasing effort toward the development of transparent, fine-grained oxide ceramics. Sensor window and dome applications requiring transparency in the infrared are the current emphasis of CeraNova's development efforts for fine-grain alumina. However, CeraNova continues to explore other applications and markets for this material including those that can benefit from its unique and advantageous optical, mechanical, and thermal properties. Markets and applications being evaluated include lamp envelopes for high intensity lighting, SAPI armor, window materials for advanced propulsion systems, orthodontia brackets, industrial pump seals, and high performance automotive components.