Transparent Ceramics Enable Large, Durable, Multifunctional Optics

Aluminum oxynitride and magnesium aluminate spinel are mechanically strong, hard and scratch resistant; they are also chemically durable.
Both exhibit broadband transmittance from near-UV to mid-IR.

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Single-crystal sapphire has been the material of choice for defense and other applications that require extremely durable optics, but aluminum oxynitride (ALON) and magnesium aluminate (spinel) have emerged for use when those applications need optics in large sizes or with complex geometries.

Table 1 lists the key physical properties of each material. Both have cubic spinel crystal structures that make them transparent in their polycrystalline form, which means they can be produced using conventional ceramic powder processing techniques. Powder processing allows them to be produced in large sizes, complex geometries and large volumes that otherwise would be very difficult or impossible.

While their crystal structures are similar, some of their mechanical and optical properties are different. ALON's high hardness, modulus and strength are especially suited for transparent armor; spinel's extended transmission in the mid-infrared wavelength region (Figure 1) makes it applicable for many IR optics uses.

How they are made

The manufacturing processes for ALON and spinel are similar to the processes used for any other ceramic materials. However, because these materials need to be transparent, purity and process control are quite a bit more challenging. Between the two, the ALON process is much more robust, has higher yields and produces parts of better quality compared to spinel.

Unlike single-crystal sapphire, versatile ceramic green-forming techniques allow ALON and spinel components to be formed into near-net shapes prior to heat treatment, saving energy and significantly reducing machining costs. The processing steps (Figure 2) for both materials involve:

(1) Powder synthesis.
(2) Green body formation (shaping).
(3) Heat treatment.
(4) Optical fabrication.

Table 1. Key properties of ALON and spinel.

Property	ALON	Spinel	Unit
Chemical Formula	$Al_{23-1/3X}O_{27+X}N_{5-X}$	$MgAl_2O_4$	–
Density	3.69	3.58	g/cc
Flexure Strength	300 to 700	70 to 350	MPa
Knoop Hardness	1870	1650	Kg/mm^2
Refractive Index (at Wavelength 0.5 µm)	1.80	1.723	–
Absorption Coefficient (at 3.39-µm Wavelength)	0.1	0.018	cm^{-1}
Transmission Wavelength Range*	0.25 to 6	0.25 to 6.5	microns
Refractive Index Homogeneity (~4-in. Aperture)	~5	<10	ppm
Typical Haze (in the Visible Range)*	<2	<10	%
Typical Optical Clarity (in the Visible Range)*	>98	>95	%

*Varies depending on thickness and processing conditions.

Images courtesy of Surmet Corp.

Green bodies can be created by one of a number of forming methods, including cold isostatic pressing, die pressing, injection molding and slip casting. Green bodies have the consistency of chalk and are only partially dense. They are then subjected to a number of heat treatment steps which bring them to full optical transparency. Commercially available ALON components are made using sinter/hot isostatic pressing (HIP) processes. They are virtually inclusion free and generally known for their high optical clarity, low haze, being tint free and – most importantly for many critical applications such as reconnaissance and sensor windows – good refractive-index homogeneity over large areas. Spinel can also be produced using the same basic heat treatment approach.

Another production method for spinel components uses a uniaxial hot pressing followed by hot isostatic pressing (HP/HIP) approach. In this process, a liquid phase sintering aid such as LiF is generally needed. Unfortunately, many studies have shown that the LiF-based approach leads to serious grain-boundary weakness issues, resulting in low strength and also problems in attaining a high level of RI homogeneity.

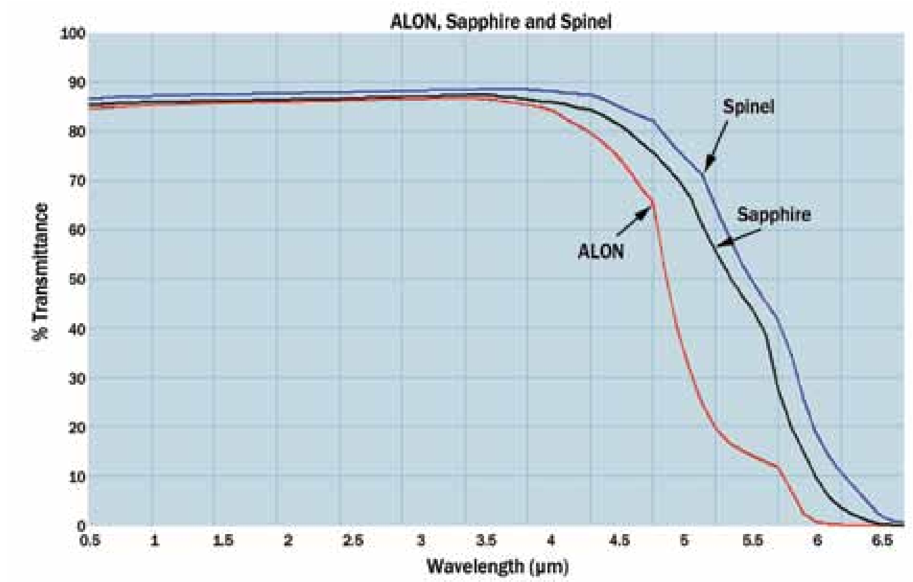

Figure 1. Transmittance spectra of ALON, spinel and single crystal sapphire at 2-mm thickness (without antireflection coatings).

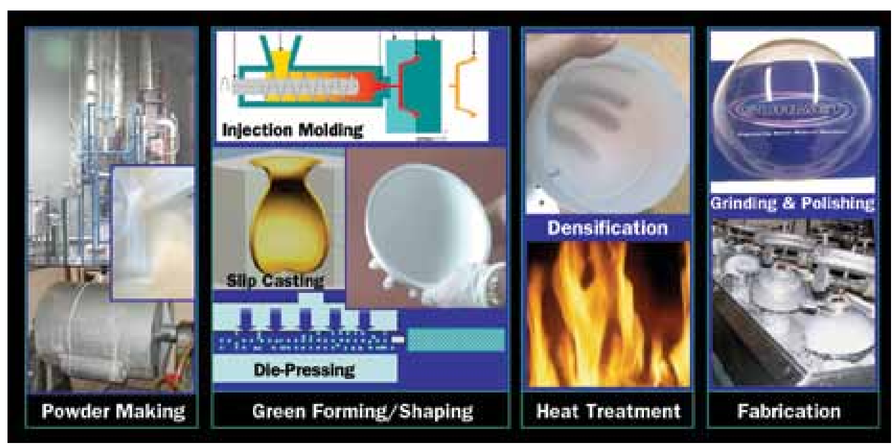

Figure 2. Typical process steps involved in manufacturing ALON and spinel transparent ceramics.

Complex geometries, multifunctional features

Optical ceramic components with complex 3-D geometries are required for many applications, including infrared (IR) military optics. Hemispherical and hyper-hemispherical domes, tangent ogive domes, complex lenses and curved windows are some of the complex geometries possible with powder-based ALON and spinel optical ceramics (Figure 3). Applications that use such components include tri-mode (laser, IR and radiofrequency) seeker systems, IR countermeasure systems and aircraft-targeting pod systems.

Manufacturing components with such complex geometries from single-crystal sapphire is uneconomical because of the costs involved in growing boules and subsequent machining of these shapes from the boules. Like sapphire, ALON and spinel ceramics still need grinding and polishing, but their near-net shape formability in the green stage eliminates huge machining/optical fabrication costs.

Embedded internal architecture within ALON optical ceramic components offers the potential for additional functionality. Some examples of multifunctional components are (Figure 4):

- Domes or windows with embedded grids or meshes for EMI (electromagnetic interference) shielding.
- Domes or windows with embedded antennas.
- Domes or windows with built-in recesses and internal electrical connections for sensors.

Additionally, compliant and integrated internal structures can be tailored to enhance mechanical properties such as toughness, structural integrity or ballistic performance of the component.

ALON-based GRIN optics

Although polymer and glass-based gradient index (GRIN) optics have been around for quite some time, ALON-based GRIN optics are relatively new and currently under development in a DARPA-funded research program at Surmet. GRIN-based lenses have a refractive index profile that varies gradually within the material in a controlled fashion. In compari-

Figure 3. Examples of ALON and spinel components with complex geometries.

Powder-processing methods allow ALON/spinel components to have complicated geometries and/or internal architectures.

son to regular lenses, which depend upon curvatures machined into their surfaces to bend light, GRIN optics can also use controlled gradients within the material itself to bend the light. This can be used with or without surface curvature to produce lenses.

This additional control can lead to substantial miniaturization and weight reduction in optical systems as well as reduction in optical aberrations caused by spherical lenses.

When the refractive index varies through the thickness of a lens, it is called axial gradient. Typical applications of such lenses include photographic objectives, because of their significantly low chromatic aberration compared to aspheric lenses. The index profile can also be varied radially (Figure 5), and this type of lens offers both aberration correction and the ability to change the focal length of the lens. ALON-based GRIN optics can be fabricated with significantly large refractive-index gradients (Δn), ranging up to 0.04 in both axial and radial profiles. This is achievable in ALON either by changing the composition and/or by adding suitable dopants.

Unlike many glasses and polymers, which are only transparent in visible wavelengths, ALON GRIN lenses are transparent in the visible- through mid-IR range. Furthermore, they offer exceptional du-

Figure 4. Examples of ALON components with embedded internal architectures.

rability in terms of scratch resistance, strength and high temperature resistance over glasses and polymers. This opens up many other potential applications for ALON GRIN lenses such as image systems for laser range finders, night-vision goggles and unmanned aerial vehicles.

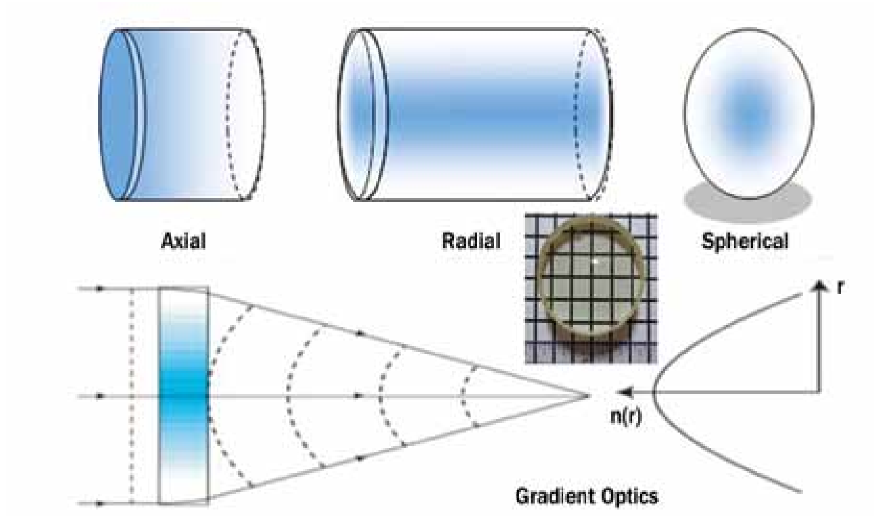

Figure 5. Graphical illustration of GRIN profiles (an ALON GRIN sample is shown in the inset).

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