ALON® Optical Ceramic Transparencies for Sensor and Armor Applications

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Surmet continues to invest in and expand its manufacturing capability for ALON® products, as the market demand for this material increases. The biggest demand and opportunity continues to be in the area of transparent armor, however, the market for Reconnaissance (Recce) windows and sensor domes/windows, made from ALON, continues to grow at an impressive rate as well.

ALON® Transparent Armor's unsurpassed ballistic performance, combined with the robustness of ALON's manufacturing process and reproducibly high material quality make ALON the leading candidate for many future armor systems. Recent developments in the area of ALON® armor will be presented.

Advances being made in Surmet's production capability to support the very large quantities of material required by the transparent armor market also benefit the sensor market. Improvements in quality, quantity and manufacturability of ALON material, combined with improvements being made in optical quality, ensure a robust supply of high quality material for high volume window and dome applications. Recent advances in sensor transparencies will also be presented.

Introduction: ALON® Optical Ceramic

Aluminum Oxynitride (ALON® Optical Ceramic) is a transparent ceramic material which combines transparency from the UV to the MWIR with excellent mechanical properties. ALON has isotropic optical and mechanical properties by virtue of its cubic crystal structure. Consequently, ALON is transparent even in polycrystalline form and thus can be produced by conventional powder processing techniques. This combination of properties and manufacturability make ALON suitable for a range of applications including IR windows, domes and lenses; to transparent armor.

Properties of ALON® Optical Ceramic

Aluminum Oxynitride (ALON) has a defect cubic spinel crystal structure with the chemical formula of $Al_{(64+x)/3}O_{32-x}N_x$; where $2 \leq x \leq 5$. Nitrogen stabilizes the cubic spinel crystal structure over a wide composition range. Some physical and mechanical properties of ALON are summarized in Table 1

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Table 1. Typical Properties of ALON® Optical Ceramic

Properties	**Values**	**Properties**	**Values**
Density (g/cc)	3.688	Flexural Strength (MPa)	380-700**
Structure	Cubic Spinel: $Al_{(64+x)/3}O_{32-x}N_x$ $(2.75 \leq x \leq 5)$	Compressive Strength (MPa)	2677
Lattice Constant (Å)	7.946	Transmission Range (µm)	0.2 to 6.0
Typical Grain Size (µm)	250-400	*Index of Refraction (n, λ)	1.790 @ 0 .633 µm, 1.777 @ 1.06 µm 1.722 @ 3.39 µm, 1.653 @ 5 µm
Young's Modulus (GPa)	334	Dielectric Constant and Loss Factor (@1GHz)	k = 9.19, tanδ = 31×10^{-5}
Shear Modulus (GPa)	135	Specific Heat (cal/g-°C)	0.22
Poisson's Ratio	0.239	Thermal conductivity (W/m-°K)	9.62 @75°C; 7.11@270°C 6.3@540°C 7.11@830°C
Knoop Hardness (kg/mm^2)	1800 @200 g load	Thermal Expansion Coefficient /°C	30-200°C: 5.65×10^{-6} 30-400°C: 6.40×10^{-6} 30-600°C: 6.93×10^{-6} 30-900°C: 7.50×10^{-6}
Fracture Toughness (MPa-m½)	2.0		

*(*Refractive index is composition dependent, ** strength has been increased through super-polishing but is generally dependent on grinding and polishing)*

ALON® has excellent transparency (>80% transmittance) from the near ultraviolet, through the visible and through the midwave infrared (MWIR) region of the spectrum, as is shown in Figure 1(a). The refractive index varies between 1.81 and 1.67 over the range of wavelengths 0.2 to 5.0 µm as shown in Figure 1(b).

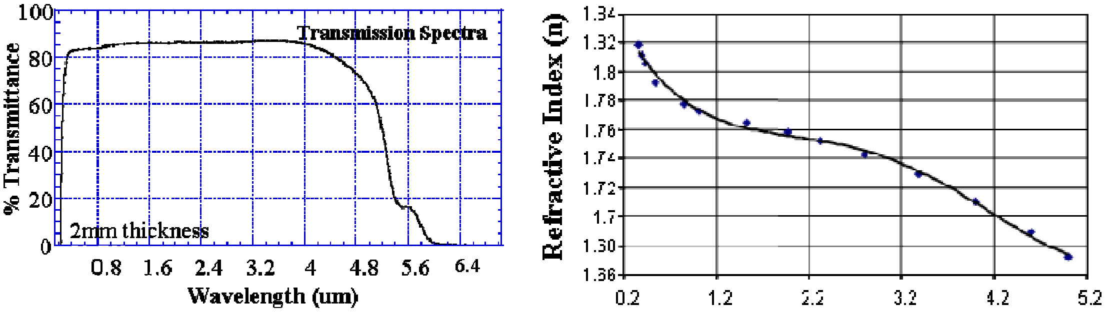

Figure 1. (a) Optical transmission spectrum, and (b) refractive index of ALON® over a range of wavelengths.

Applications

Recce windows

Sensor windows typically require <λ/10 wavelength transmitted wavefront uniformity, over any area of the window equal to the size of the sensor aperture, at the shortest wavelength of interest. The apertures for such systems are commonly 12-in diameter or larger, and operate at visible wavelengths. Such requirements are obviously very demanding, and put very tight requirements on the window material blanks from which these windows are fabricated. Furthermore, large apertures require large windows, so Recce windows typically require the highest material quality achievable on the largest windows that can be made. To date, Surmet has produced window blanks as large as 17x30-in for Recce applications, with excellent optical performance

The ability to produce large (~17x30-in), crack-free window blanks itself is difficult. Even in opaque ceramics it is difficult to produce parts of this size. Producing transparent material, with demanding optical tolerances of this size significantly magnifies the difficultly of the undertaking. Small variations in process conditions across window blanks of this size can easily lead to large stresses, and which can lead to cracking and breaking. Furthermore, small variations in materials properties across these blanks will lead to non-uniform optical properties, so the uniformity of materials properties across these large blanks must be excellent. Consequently, it is easy to understand why these windows are so difficult to produce.

Surmet has made significant investment in its manufacturing facilities and processes in order to produce large ALON blanks of sufficiently high quality to be used for Recce applications. As recently as a year ago windows of this size were produced in batch sizes of ~10 per production cycle. However, recent expansion of our manufacturing processes and capabilities has increased this number to ~30 such large sized parts in a single production cycle today, an increase of nearly 3x. This increase is reflected below in figure 2 showing a photograph of 11- 15x27-in plates, repeated three times to reflect the 3x increase in capacity

Figure 2: Three photograph of 11 large ALON blanks produced for Recce applications representing the nearly tripling of Surmet production capacity for these windows.

In terms of optical quality, the first issue that had to be addressed was non-uniformities in the material itself. These non-uniformities manifested themselves as striae as is shown below in figure 3a. These striae are variations in the index of refraction of the ALON material itself. Through careful control of the material processing we have been able to significantly reduce the striae in the parts as is shown in the shadowgraph in figure 3b.

Figure 3a and 3b shadowgraphs of old (left) and new (right) ALON material.

The striae in the early windows was found to correlate with particular aspects of the manufacturing process. The ability to establish this correlation allowed us to then modify the process to virtually eliminate the striae. Recently two large (~15x27-in) ALON® windows were provided to Goodrich Optical Systems in Danbury, CT for evaluation of optical inhomogeneity using their 24-in diameter Zygo interferometer. The results of their measurements are shown below in figure 4.

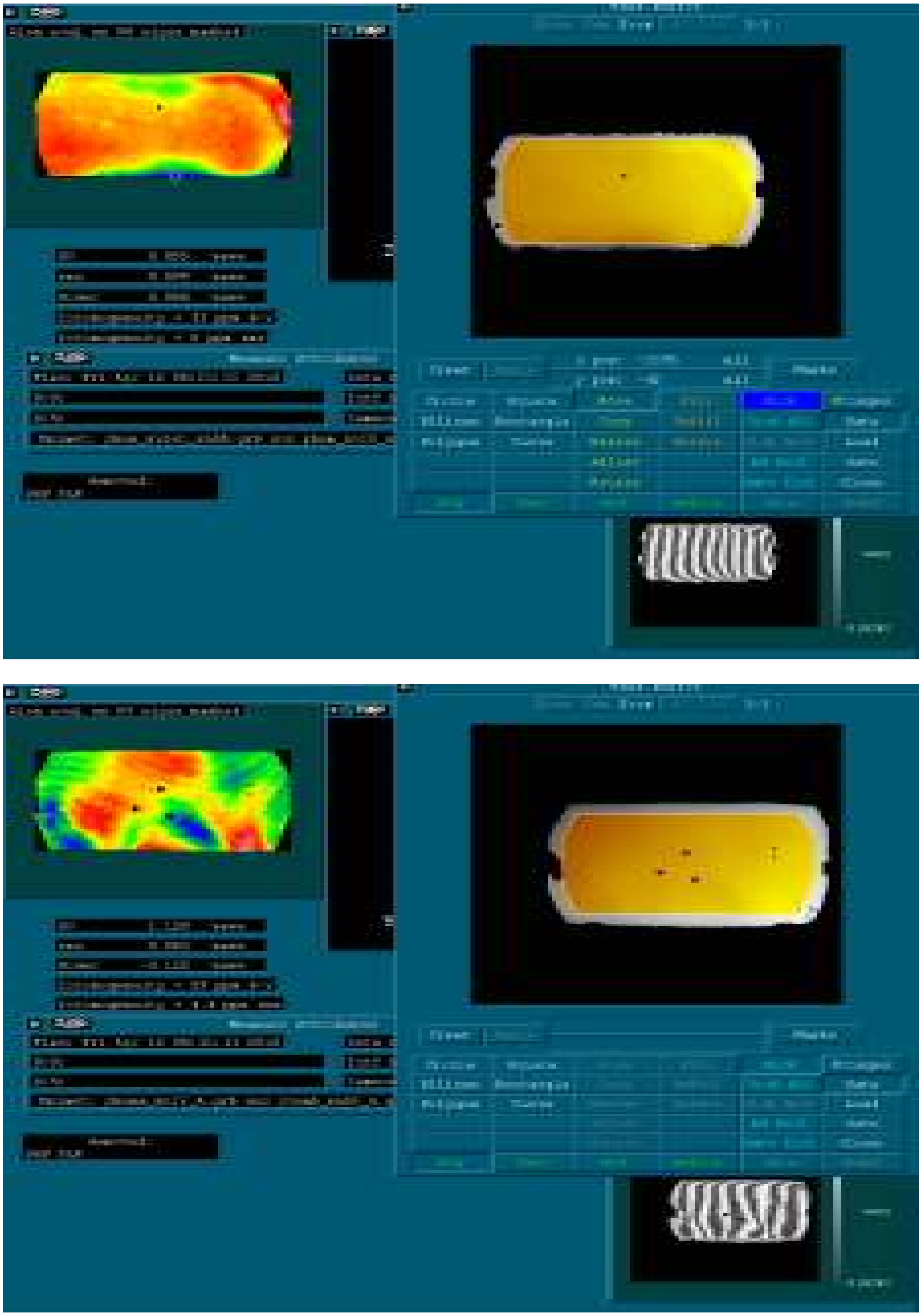

Figure 4: Inhomogeneity measurements of ALON® Windows S/N 08 and 09 made using Goodrich's Zygo interferometer with a 24-in aperture. The inhomogeneity of these windows was measured to be only 5 and 4.4 ppm respectively over the entire aperture

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The next issue that had to be addressed was the effect of small amounts of residual stresses in the large blanks, and the effect that this stress had on the transmitted wavefront through stress induced birefringence. Initial large ALON windows were found to have significant residual stresses resulting in a measureable level of stress induced birefringence which varied across the face of the window. It was found that this level of residual stress was impacting the achievable transmitted wavefront error of large recce windows and the material manufacturing process was optimized to reduce residual stresses. Figure 5 shows in-process results of this effort in which residual stresses were substantially reduced.

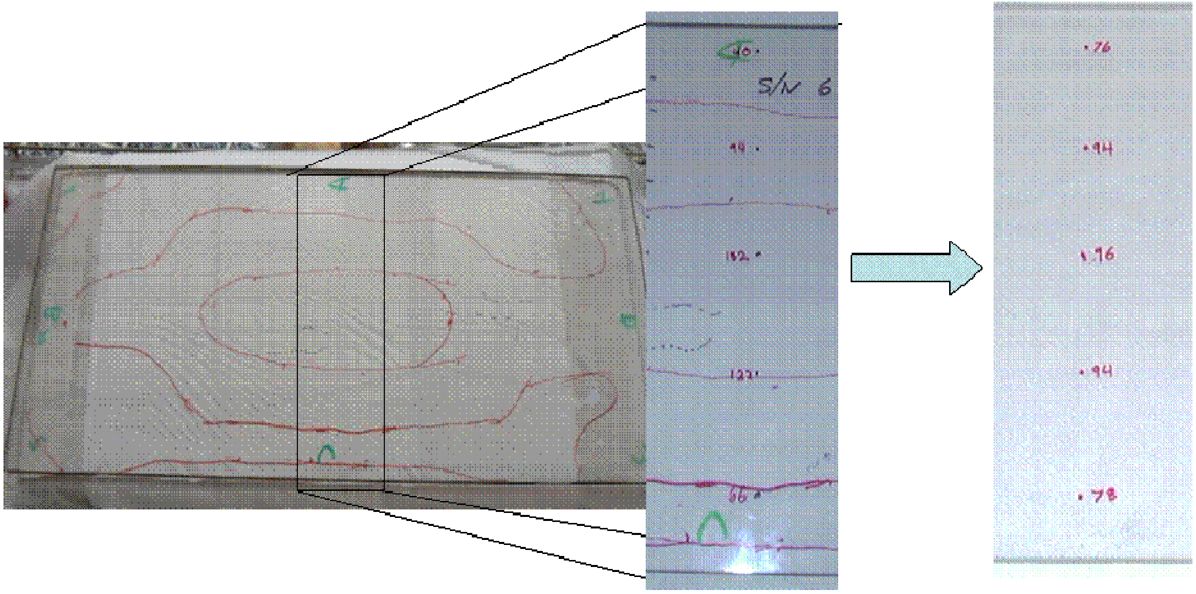

Figure 5: Comparison of stresses within large ALON plate produced by old (left) and new (right) processes. Section shown is a 2-in wide strip across the ~15-in width of 15x27-in ALON plates. Measured values from a Babinet Compensator are written on the face of the windows. The new window shows substantially reduced deviation from the stress-free state (value of 92) than the old on the left.

Similarly low levels of stress were measured by Goodrich on windows S/N 08 and S/N 09 using their babinet compensator. The results on these windows is shown below in figure 6.

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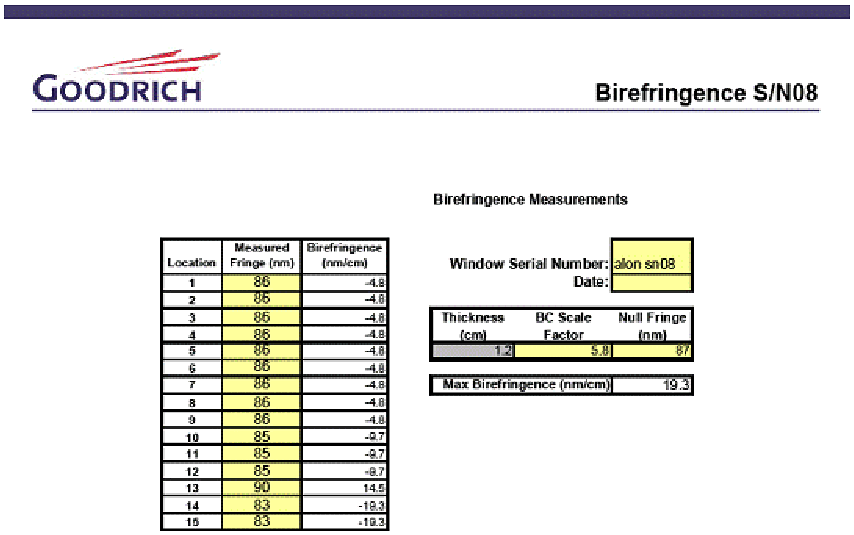


GOODRICH

Birefringence S/N08

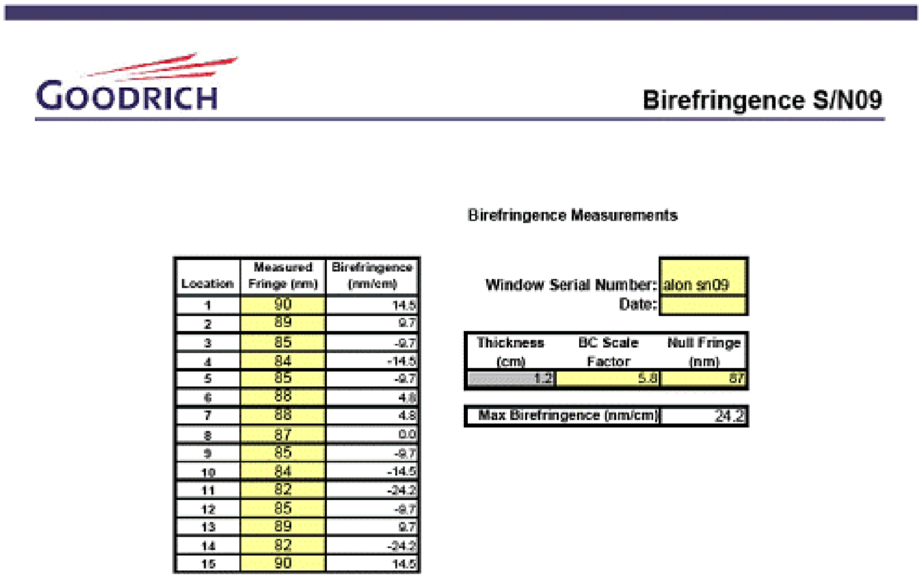
Birefringence Measurements

Location	Measured Fringe (nm)	Birefringence (nm/cm)
1	86	-4.8
2	86	-4.8
3	86	-4.8
4	86	-4.8
5	86	-4.8
6	86	-4.8
7	86	-4.8
8	86	-4.8
9	86	-4.8
10	85	-9.7
11	85	-9.7
12	85	-9.7
13	90	14.5
14	83	-19.3
15	83	-19.3

Window Serial Number: alon sn08
Date:

Thickness (cm)	BC Scale Factor	Null Fringe (nm)
1.2	5.8	87

Max Birefringence (nm/cm): 19.3



GOODRICH

Birefringence S/N09

Birefringence Measurements

Location	Measured Fringe (nm)	Birefringence (nm/cm)
1	90	14.5
2	89	9.7
3	85	-9.7
4	84	-14.5
5	85	-9.7
6	88	4.8
7	88	4.8
8	87	0.0
9	85	-9.7
10	84	-14.5
11	82	-24.2
12	85	-9.7
13	89	9.7
14	82	-24.2
15	90	14.5

Window Serial Number: alon sn09
Date:

Thickness (cm)	BC Scale Factor	Null Fringe (nm)
1.2	5.8	87

Max Birefringence (nm/cm): 24.2

Figure 6: Stress Birefringence measurements for windows S/N 08 and 09 as reported by Goodrich.

Specialty Domes

The maturity of the production processes for producing ALON® optical ceramic facilitates producing blanks in a wide variety of shapes, sizes and geometries. This includes the ability to form blanks by one of a large number of ceramic forming techniques including cold isostatic pressing, slip and gel casting as well as die pressing.

The wide variety of forming technique combined with the ability to machine the green ALON blanks prior to firing (i.e., green machining) allows ALON to be produced, reproducibly and reliably for a wide variety of applications. Examples of such specialized domes are shown in figure 7, below:

*http://www.nanotechsys.com/images/PDFs/Conformal_Dome_Fabrication.pdf

Figure 7: Photographs of a variety of ALON domes, including a hyper-hemispherical dome, Tangent ogive domes and a hemispherical dome with embedded grids.

The maturity of the ALON manufacturing process allows ALON® blanks to be produced in these as well as other complicated geometries. In addition to excellent control over geometry and dimension, we have demonstrated the ability to maintain excellent control over the quality of the material being produced. The optical homogeneity of a 7-in hemispherical ALON dome is shown in figure 8 below:

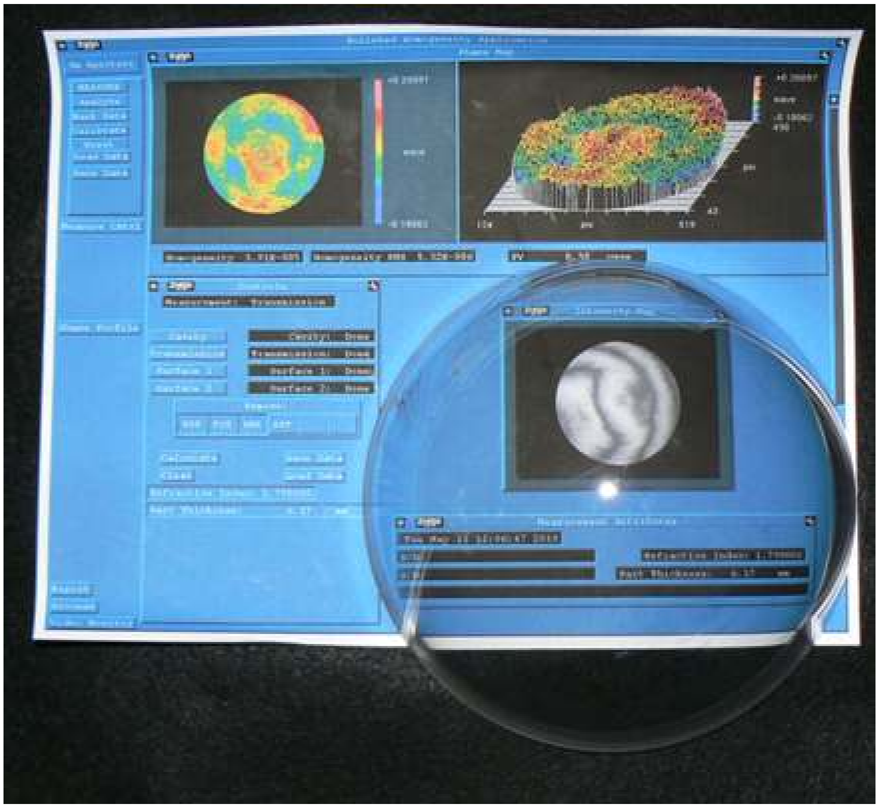


Figure 8: photograph of a 7-in hemispherical ALON dome over a measurement of its transmitted wavefront and homogeneity. This dome has an inhomogeneity of only ~5ppm over a 3.4-in aperture.

Surmet's ALON has demonstrated a level of homogeneity that is consistent with the requirements of many future seeker systems.

Windows for Laser communications (Lasercom) Applications

Lasercom systems are under development to meet the growing requirements for transmitting high volumes of data, rapidly into and out of the battlefield. Lasercom has demonstrated the ability to transmit information far more rapidly that convention radio frequency (RF) links alone.

Durable transparencies are required to transmit at laser wavelengths (e.g., 1.55 μm), for such systems. These transparencies must maintain their transparency despite being subjected to severe environmental loading, including sand erosion. ALON® windows have been produced for several lasercom systems, including the FALCON terminal being developed by ITT under funding for by AFRL. A photograph of a FALCON window assembly with ALON® windows is shown below in figure 9.

Figure 9: photograph of an ITT FALCON terminal with a window assembly with ALON® windows.

The FALCON terminal was used in a lasercom demonstration between two counter maneuvering aircraft, separated by distances as great as 132 Km, at data rates as high as 2.25 GB/sec.

Transparent Armor

Transparent ceramic materials such as ALON® Optical Ceramic, spinel and sapphire offer a quantum leap in ballistic performance over conventional glass laminates. Each of these materials has been shown to provide protection against armor piercing rounds at about one half the weight and thickness of conventional glass laminates. However, the relatively high cost (compared to glass) and availability of these materials are currently the largest obstacles to their wide spread use. While these materials will always be more expensive than glass, the ability to substantially decrease the cost and increase the production volume will determine if any of these materials will be viable towards transparent armor market. It is precisely in these areas that ALON® Optical Ceramic has an advantage over spinel and sapphire.

Comparison of ALON and Spinel for Transparent Armor

While Surmet produces both ALON and spinel, we market only ALON for transparent armor applications based upon cost and producibility advantages. While both ALON and spinel are produced by conventional powder processing techniques (Figure 7), and the processes for producing these two materials are very similar, ALON has several advantages over spinel in terms of producibility:

- The process for ALON is more robust and mature, and less susceptible to lot to lot variations.
- Surmet produces its own ALON powder
  - at a significantly lower cost than that of spinel powder
  - without the lot to lot variation often seen in commercially available spinel powders
- The process yields for ALON are currently higher than for spinel

For these reasons we are able to produce larger lots of ALON® material at a consistently high quality, than are currently possible for spinel. These same factors make ALON a more affordable option than spinel.

Figure 7: Schematic of process for producing ALON by powder processing

Comparison of ALON to Sapphire for Transparent Armor

While ALON is made by conventional powder processing techniques (Figure 7), sapphire is grown by melt based single crystal growth techniques. This limits the size (particularly thickness and width) that can be grown in reasonable cycle time and at affordable price. Furthermore, there is little economy of scale for single crystal growth techniques. If you want to double your capacity, you must double the number of crystal growers. By comparison, there is a considerable economy of scale for powder processing based production equipment. Dramatic improvements in throughput, and cost savings, can be attained through the use of larger furnaces.

ALON can easily and affordably be produced in thicknesses well above 0.3 in. (the currently supplied standard sapphire layer thickness). ALON® transparent armor thus holds an advantage particularly against armor piercing (AP) threats larger than 30 caliber round (12.7 mm, 14.5 mm, etc.) and against improvised explosive devices (IEDs). For threats larger than 30calAP, this sapphire layer thickness falls below the commonly used rule of thumb for hard faced armor. Thus, ALON® transparent armor is expected to provide a more efficient solution against larger AP and IED threats. While thicker sapphire layers can be produced, it is not likely that it can be done cost effectively, as thicker layers require much slower crystal growth rates.

Figure 8 below shows a photograph of an monolithic ALON window that is ~1.3-in thick.

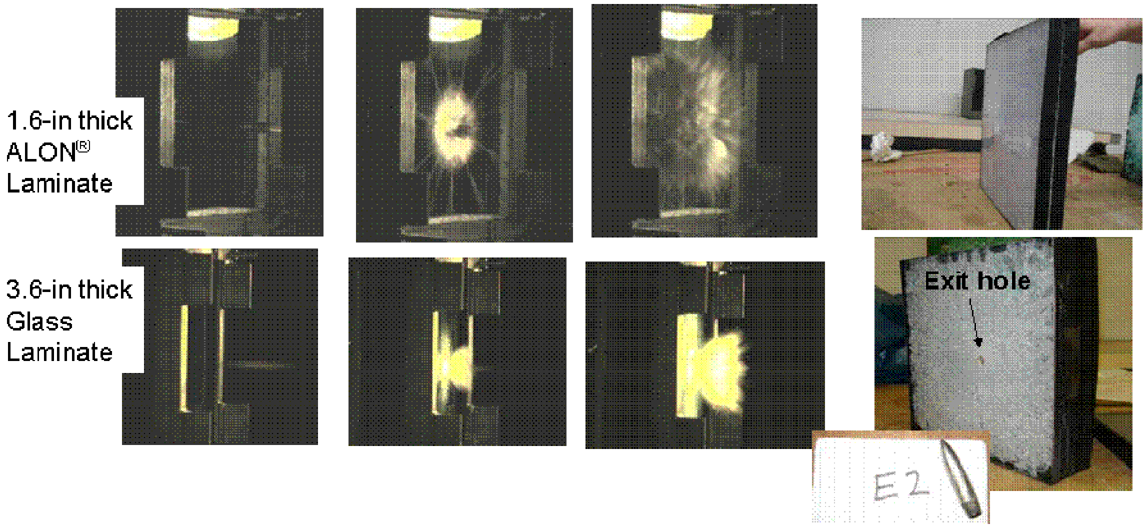
Figure 8 photograph of 1.3-in thick ALON window from the front and side.

Results on 50 Cal AP Testing on ALON® Armor

Recently, we have concentrated much of our testing on higher level threats such as 50 cal AP threats. This is in large part due to the interests of our particular customer base, and in part to the recognition that it is easier to justify the relatively higher cost of ALON transparent armor for higher level threats where the benefits are more substantial.

While much of the testing that we have performed in the recent past is customer specific and consequently quite sensitive, and is some cases classified, one set of testing was performed specifically for, and shown on the Discovery Channel show 'How Stuff Works' (January 8th , 2009 episode). In this testing the performance of ALON transparent armor laminates was compared to the performance of conventional glass laminates. In particular, an ALON laminate nominally 1.6-in thick, with an areal density of ~19 psf was compared to a glass laminate nominally 3.6-in thick and with an areal density of approximately 43 psf. Both samples were shot with 50 cal M2AP rounds at the University of Dayton Research Institutes (UDRI) ballistic test range. High speed video (~5000 frames/sec) was taken of the impacts on these two types of laminates.

A sequence of high speed images of the 50 cal M2AP rounds on the ALON® and glass laminates is shown below in figure 9.



Bullet penetrated glass laminate, and 5 phone books

Figure 9: Sequence of high speed images of 50 cal M2AP round impacting 1.6-in thick ALON® laminate (top) and 3.6-in glass laminate (bottom). The laminates are also shown after impact, with the exit hole clearly visible in the glass laminate. Also shown in the bottom right is the bullet that penetrated the glass laminate.

ALON® armor is now in production for a few aerospace applications with small to medium quantities. One of these applications required that we obtain FAA certification. It is also being evaluated for a number of high volume transparent armor applications including Gunner Protection Kits (GPKs). Recently, ALON, spinel and sapphire were tested side by side by the Army for GPK windows. While all three materials met the minimum test requirements, the ALON windows demonstrated substantially higher V50 performance than either the spinel or sapphire windows.

Figure 10: Photographs of gunner protection kits with transparent armor windows

Surmet is continuing to work with Engineers at Picatinny Arsenal to insert ALON armor windows into GPKs for various armored vehicles.

Surmet has recently obtained security clearances for its HQ facility in Burlington, MA and key personnel working there. These clearances allow us to work closely with our customers on classified armor programs.

Summary

The demand for ALON® Optical Ceramic products continues to grow. Its excellent mechanical and optical properties combined with its producibility make it the material of choice for a number of military and commercial applications. These applications include: Recce windows, specialty domes, Lasercom windows and transparent armor. Investments continue to be made to expand our production capacity for ALON® Optical Ceramic.

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