Scale Up of Large ALON® Windows

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Aluminum Oxynitride (ALON® Optical Ceramic) combines broadband transparency with excellent mechanical properties. ALON's cubic structure means that it is transparent in its polycrystalline form, allowing it to be manufactured by conventional powder processing techniques. Surmet has established a robust manufacturing process, beginning with synthesis of ALON® powder, continuing through forming/heat treatment of blanks, and ending with optical fabrication of ALON® windows. Surmet has made significant progress in our production capability in recent years. Additional scale up of Surmet's manufacturing capability, for larger sizes and higher quantities, is currently underway.

ALON® transparent armor represents the state of the art in protection against armor piercing threats, offering a factor of two in weight and thickness savings over conventional glass laminates. Tiled and monolithic windows have been successfully produced and tested against a range of threats.

Large ALON® window are also of interest to a range of visible to Mid-Wave Infra-Red (MWIR) sensor applications. These applications often have stressing imaging requirements which in turn require that these large windows have optical characteristics including excellent homogeneity of index of refraction and very low stress birefringence.

Surmet is currently scaling up its production facility to be able to make and deliver ALON® monolithic windows as large as ~19x36-in. Additionally, Surmet has plans to scale up to windows ~3ftx3ft in size in the coming years. Recent results with scale up and characterization of the resulting blanks will 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.

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 (ppm/°C)	30-200°C: 5.65 30-400°C: 6.40 30-600°C: 6.93 30-900°C: 7.50
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).

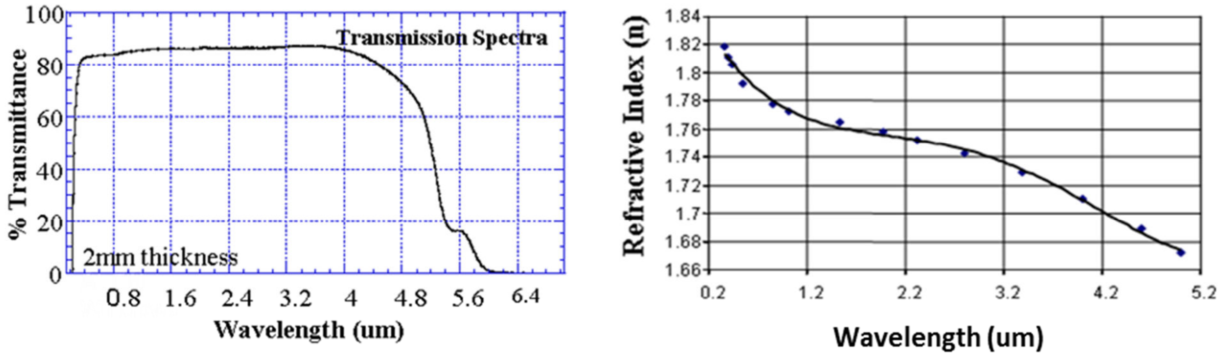


Figure 1: (a) Optical transmission spectrum, and (b) refractive index of ALON® Optical Ceramic over a range of wavelengths

ALON® Optical Ceramic is produced using conventional powder processing techniques shown in Figure 2 below.

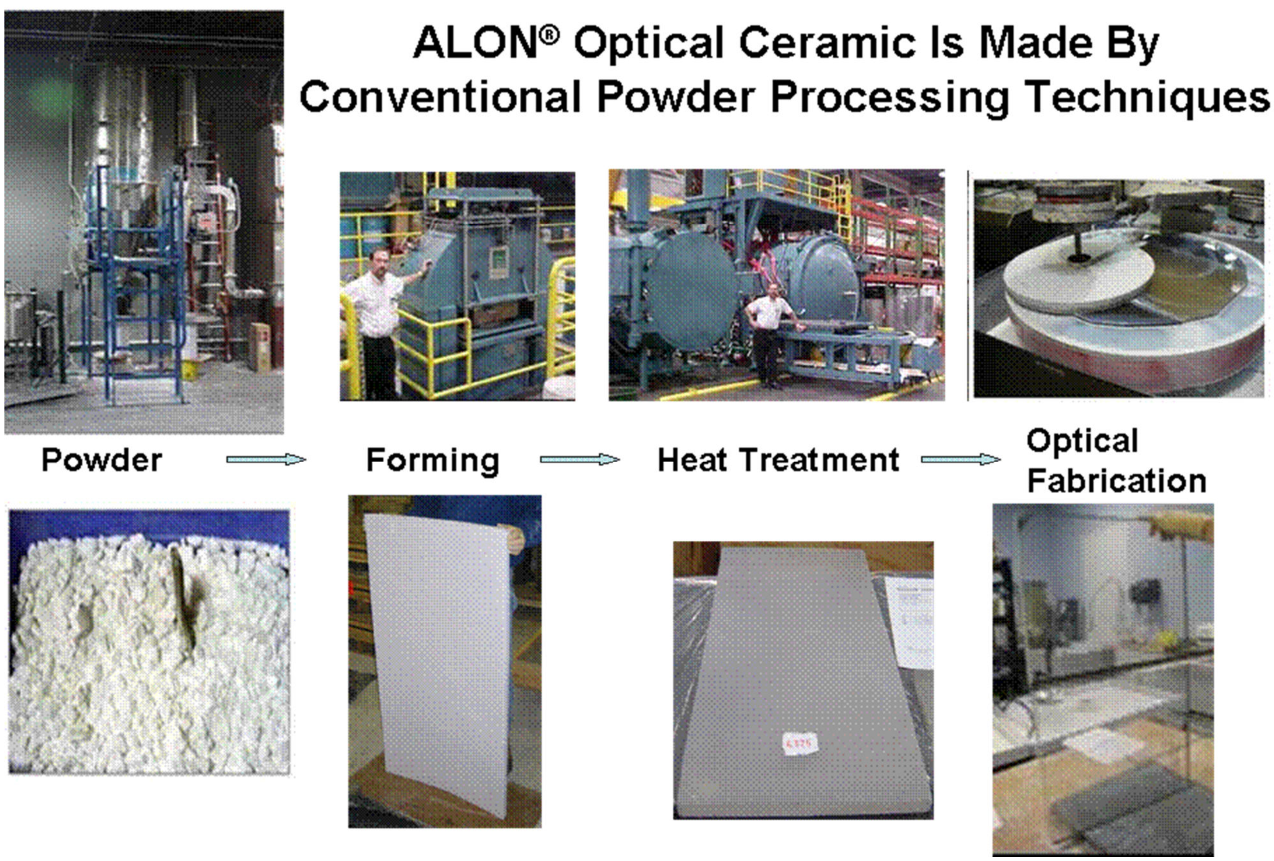


Figure 2: Schematic of process for producing ALON by powder processing

Surmet produces its own ALON® Powder from commercially available precursors. The powder is then formed into a green body using one of a number of forming techniques including: cold isostatic pressing (CIP), die pressing, injection molding or slip casting. The green body is approximately 50% dense and has the consistency of chalk (Figure 3). The green body is then subjected to series of heat treatment processes to densify it and remove residual porosity creating a fully optically dense blank. The blank is then ground and polished to transparency.

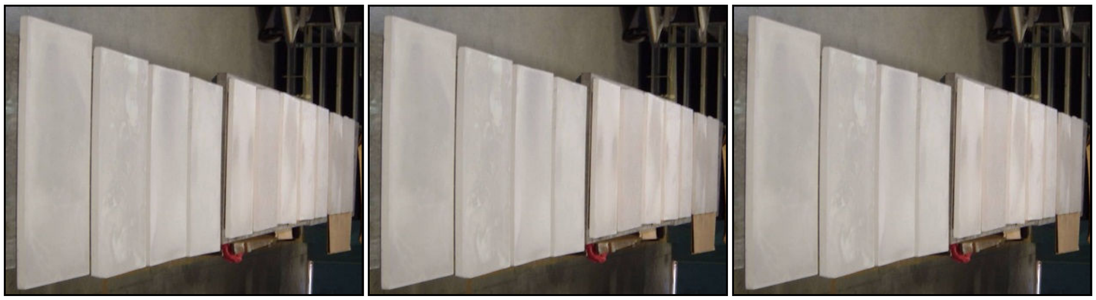


Figure 3: Three photographs of 11 large ALON® blanks produced for Recce applications representing the nearly tripling of Surmet production capacity for these windows

Surmet now routinely produces blanks as large as 15x27-in for production programs. We are now able to produce over 30 such blanks in a single production batch, and are scaling up to much larger sizes.

As of spring 2012, the largest plates Surmet had produced were nominally 16x32-in in size, Figure 4.

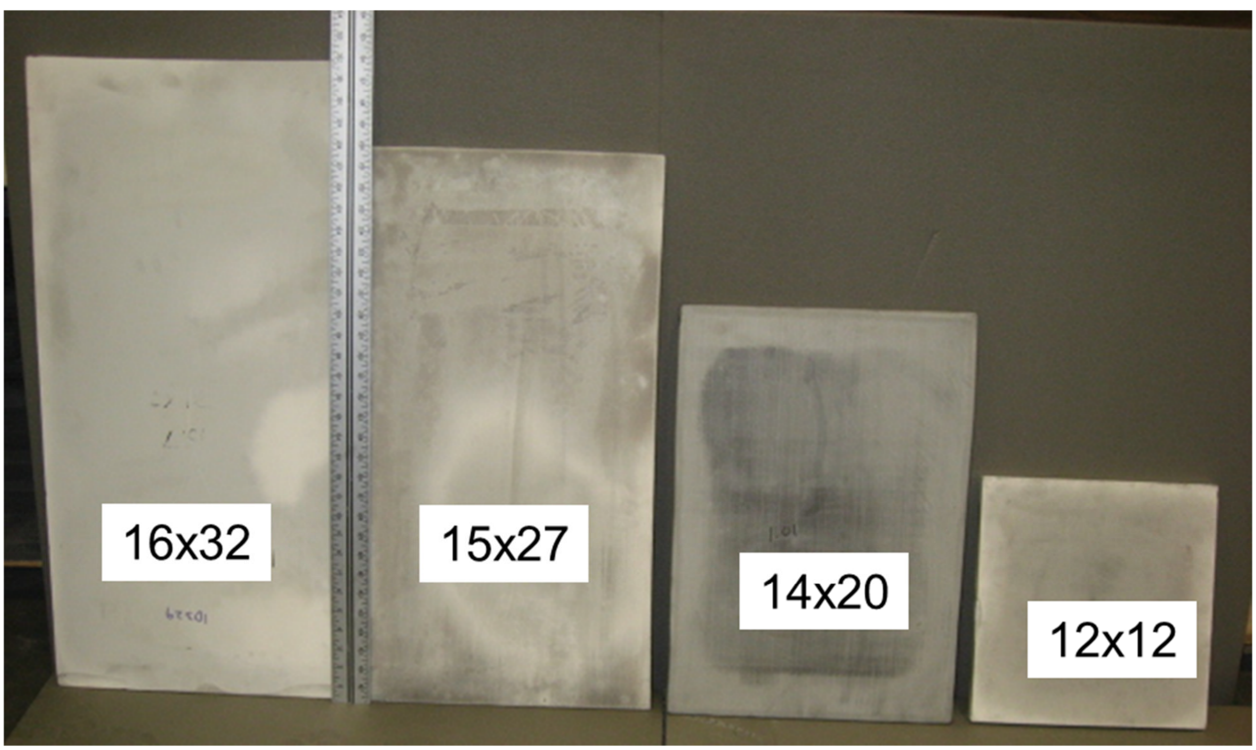


Figure 4: Photograph of blanks of increasing size (Right to left) from 12x12-in to 16x32-in

Surmet is now scaling up under joint funding from DMS&T, Air Force ManTech and Title III to scale up its ALON process to produce 36x36-in sized plates by June 2014. At the present time the largest windows that have been produced are nominally 18x35-in in size, Figure 5.

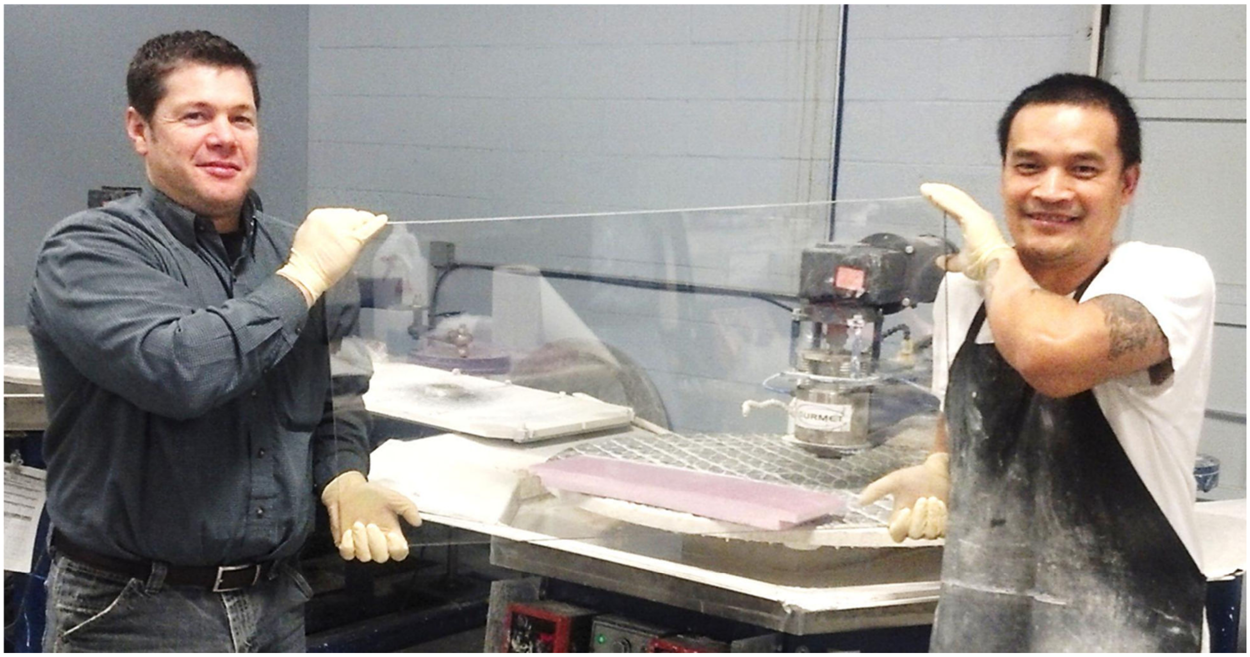


Figure 5: Photograph of 18x35-in ALON® Window

Recce windows

Sensor windows typically require $<\lambda/10$ 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. Large window blanks in other similar sizes have also been produced (e.g., 16x32, 18x24 and 19x25-in).

The ability to produce such large, crack-free window blanks itself is difficult. Even in opaque ceramics it is difficult to produce crack free 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 which can then 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 couple of years 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 3 showing a photograph of 11-15x27-in plates, repeated three times to reflect the 3x increase in capacity

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 6a. 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 6b.

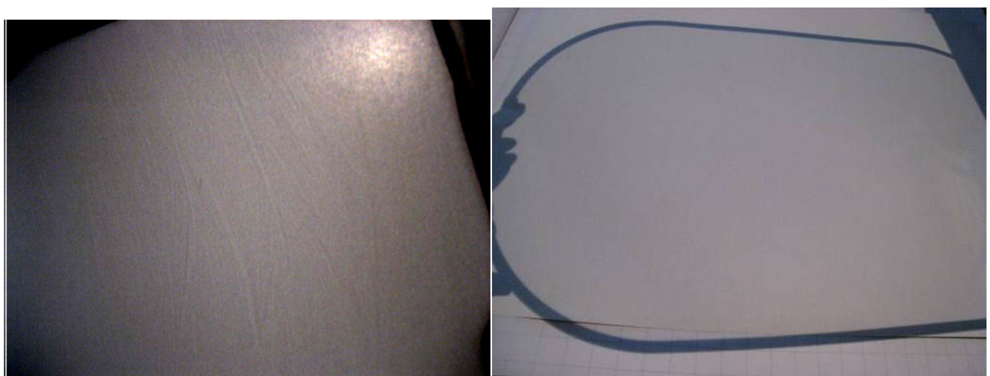


Figure 6a and 6b: Shadowgraphs of old (left) and new (right) ALON® window blanks

The striae that was seen 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 (now United Technology Corporation, UTC) 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 7.

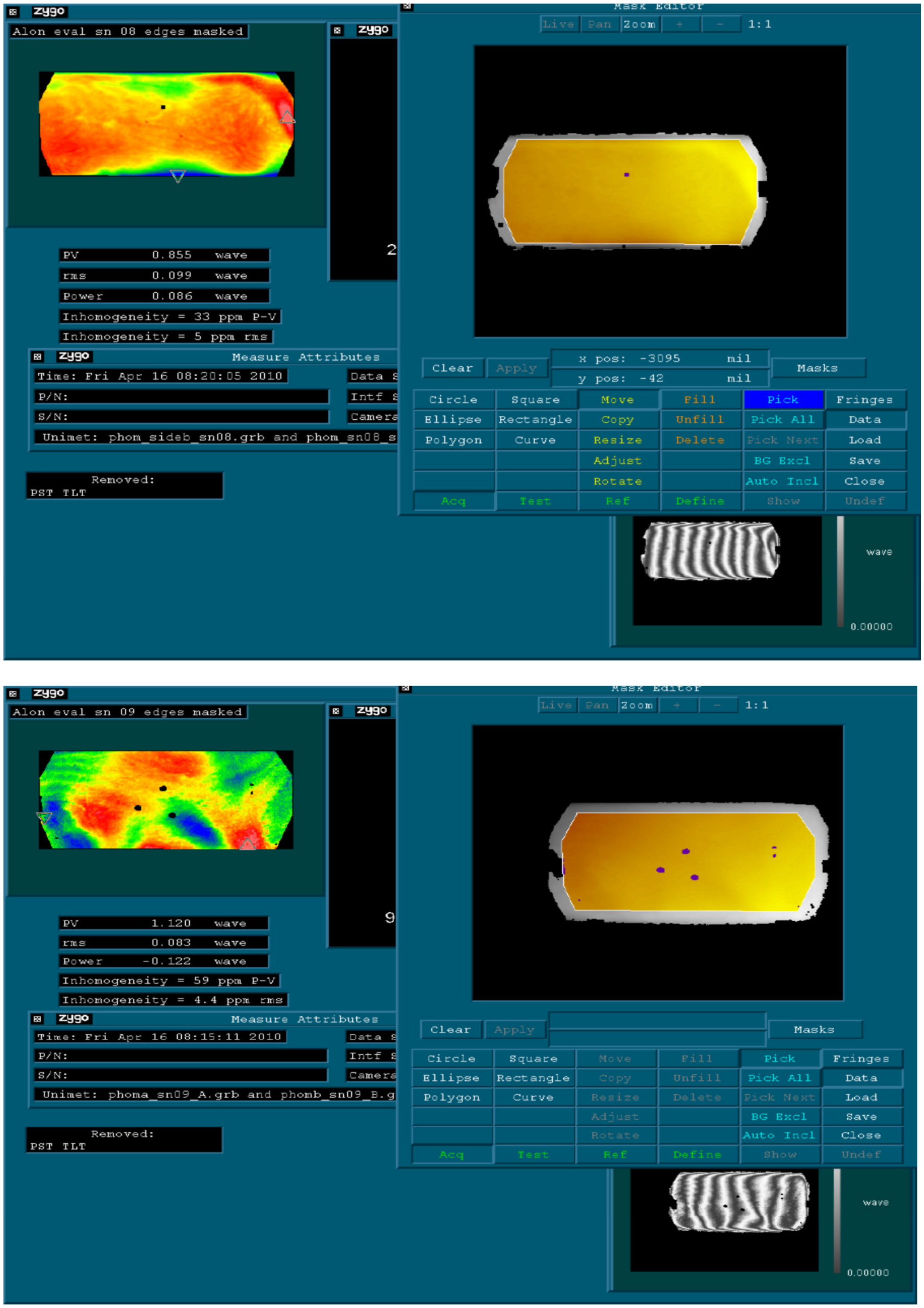


Figure 7: Inhomogeneity measurements of ALON® Windows S/N 08 and 09 made using Goodrich's Zygo interferometer with a 24-in aperture. The inhomogeneity of these windows was measured to be only 5 and 4.4 ppm respectively over the entire aperture

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 8 shows in-process results of this effort in which residual stresses were substantially reduced.

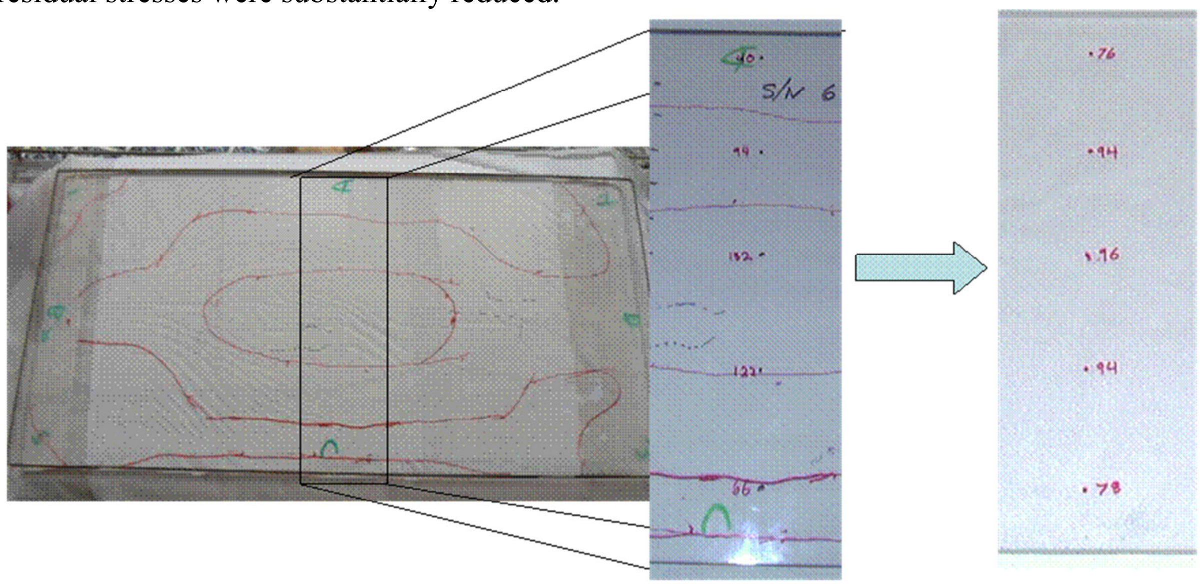


Figure 8: Comparison of stresses within large ALON® plate produced by old (left) and new (right) processes. Section shown is a 2-in wide strip across the ~15-in width of 15x27-in ALON® plates. Measured values from a Babinet Compensator are written on the face of the windows. The new window shows substantially 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 stress birefringence result for these windows is shown below in Figure 9.

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

The 18x35-in windows that we have produced are currently being characterized for stress birefringence.

ALON® Transparent Armor

Transparent ceramic materials such as ALON® Optical Ceramic, Magnesia Spinel, and Sapphire offer >2x improvement 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 Magnesia 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 2), 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.

Comparison of ALON® to Sapphire for Transparent Armor

While ALON is made by conventional powder processing techniques (Figure 2), 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 where 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 weight-efficient 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 will require much slower crystal growth rates.

Figure 10 below shows a photograph of a monolithic ALON® window that is ~1.3-in thick.

Figure 10. Photograph of 1.3-in thick ALON® window from the front and side

Recent Ballistic Testing

Recently Surmet has concentrated on developing ALON® transparent armor solutions for multi-hit scenarios against armor piercing threats. One of the most commonly specified threats is the 30 caliber M2AP round. This round has a hard steel core covered with a copper jacket. ALON® Transparent Armor has demonstrated the ability to stop this round at areal densities as low as 10 psf. However, as the number of impacts increases and the spacing between impacts decreases, the areal density required to stop this round (against multiple hits) increases.

Current testing protocols specify shot spacing as low as 2-in between shots. Such a small shot spacing is significant because the second shot will fall on top of a region that has already been damaged by the previous shot. Consequently, the armor laminate must be substantially heavier to stop shot on a region that is damaged. Figure 9 below shows the first and second shot on a 6-in ALON tile, with the second impact overlapping the region damaged by the first shot. The areal density of this laminate is ~23psf.

Figure 11: Photographs of 6x6-ALON® Armor laminate prior to shooting (left) after first shot (center) and after 2nd shot (right)

As the number of shots increases, the damage to the armor laminate is accumulates, even for shots with relatively large separations. The shot sequence shown below in figure 10 is for the same threat on a 12x12-in ALON armor laminate. This laminate successfully stopped 9 shots in the following sequence: 4 shots on the corners of an 8-in square, 5th shot in the center the square, 4 additional shots on the midpoints of the squares edges. Not only did the laminate successfully stop all 9 rounds, but it also maintained a fair amount of transparent region through much of the testing.

Figure 12: Shot sequence on12x12-in ALON Armor Laminate, after 2, 3 4 and 5 shots. 4 additional shots were also successfully stopped by this laminate

In order to achieve this level of ballistic performance with a conventional glass laminate an areal density of approximately 50 psf would be required (vs. 23 psf for this ALON laminate).

Night Vision Goggle Performance

In addition to providing superior ballistic performance, ALON® Transparent Armor also offers significant improvements in transparency for Night Vision Goggles (NVGs) over conventional glass laminates. The higher levels of transparency are due in part to the higher levels of transparency of ALON® Optical Ceramic compared to glass, and in part to the relative thicknesses of the laminates required to defeat particular threats.

The figure below compares ALON® Transparent Armor to ballistically equivalent conventional glass laminate.

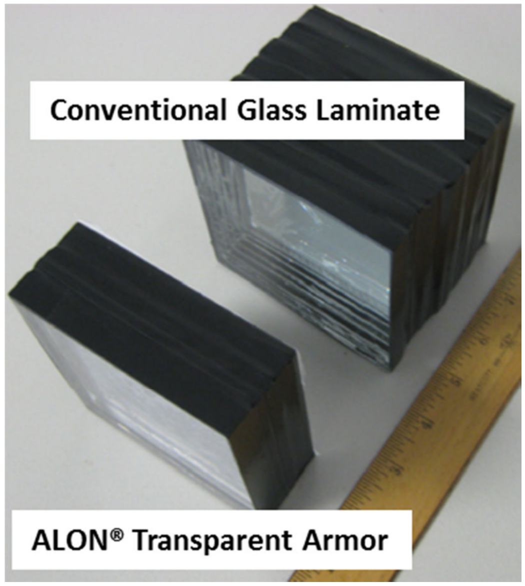
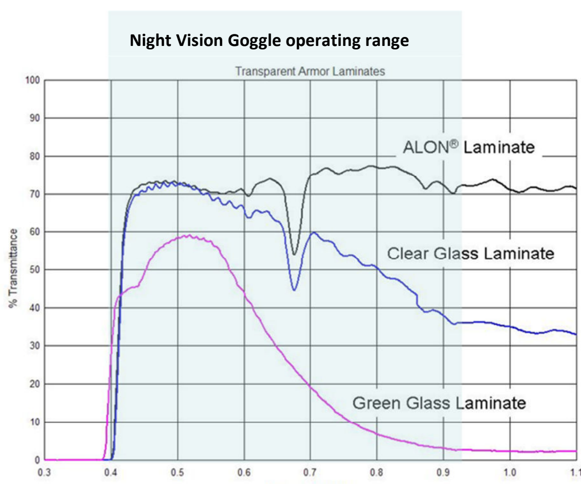


Figure 13: Photograph of ALON® Transparent Armor Sample and Ballistically Equivalent Conventional Glass Laminate.

The photograph shows a glass laminate made from water clear glass. It should be noted that many glass laminates are actually made using less expensive green glass which is less expensive, than clear glass and roughly ballistically equivalent, but which has poor NVG transparency. The figure below compares the transmission of ALON® Transparent Armor to that of conventional glass laminates made of clear (low iron) glass and green glass. The calculated NVG Transmittance for ALON laminate is 45 percent higher than for the clear glass laminate, which will provide a remarkable improvement in low light situational awareness for the warfighter.



Transmittance Measured for Ballistically Equivalent Laminates

	Luminous Transmittance	Weighted NVG Transmittance
ALON® Laminate	70.95%	73.74%
Low Iron Glass Laminate	67.64%	52.44%

Figure 14: Plot of transmission vs. wavelength for ALON® Transparent Armor and ballistically equivalent clear and green glass laminates. The table compares the luminous and weighted NVG transmittance for ALON® and clear glass laminate.

Summary

Surmet continues to develop and improve our capability for producing large ALON® Windows. We are now able to routinely produce windows as large as 15x27-in in large quantities and with high yields. Surmet is scaling up to much larger sizes under its ongoing Title III program. The largest windows that have been produced to date are 18x35-in in size and the goal is to produce 36x36-in windows by June of 2014.

The 15x27-in in blanks have been shown to be of sufficient high optical quality for reconnaissance applications. Blanks of this size have been characterized for homogeneity of index of refraction and shown to be uniform to 5ppm over the entire clear aperture of the blanks. Furthermore, these blanks have been measured to have acceptably low stress birefringence for recce applications as well.

In addition to superior performance against armor piercing rounds, ALON® Transparent armor also offers superior transparency for Night Vision Goggles. New ALON® Transparent Armor designs have been developed and tested against multi-hit armor piercing threats, at less than half the weight of conventional glass laminates.

Acknowledgements

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