Recent Advances in ALON™ Optical Ceramic

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ABSTRACT

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

The technology for producing transparent ALON was developed at Raytheon and has been transferred to Surmet Corporation where it is currently in production. Surmet is currently selling ALON into a number of military (e.g., windows and domes) and commercial (e.g., supermarket scanner windows) applications.

The capability to manufacture large ALON windows for both sensor window and armor applications is in place. ALON windows up to 20x30 inches have been fabricated. In addition, the capability to shape and polish these large and curved windows is being developed and demonstrated at Surmet. Complex shapes, both hyper-hemispherical and conformal, are also under development and will be described.

Key Words: Aluminum Oxynitride, ALON, MWIR windows, domes, ballistic armor

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1. INTRODUCTION

Advanced EO systems are increasingly moving toward common aperture systems with requirements from the visible through the MWIR as well as RF transparency. Some new systems also require large apertures and consequently larger windows/domes. In addition to the very demanding optical requirements, these large transparencies must also be durable and affordable.

For many of these applications sapphire has been the material of choice for windows and domes where transparency from the visible to mid-wavelength infrared (MWIR) spectrum is required and where demanding optical, physical and environmental conditions exist. The high cost of sapphire can be prohibitive, and its an-isotropic mechanical properties make it difficult to fabricate. Furthermore, some applications require windows that are too large or shapes that are too complicated to be made from single crystal sapphire.

Aluminum Oxynitride (ALON™ Optical Ceramic) and Magnesium aluminate spinel are materials which have similar optical and mechanical properties to sapphire. Their crystal structure is cubic, so they are transparent in polycrystalline form. Consequently, they can be made by conventional powder processing techniques into near net shaped blanks as well as larger sizes and more complicated shapes than can be achieved with sapphire. Furthermore, their isotropic mechanical properties mean that they can be optically fabricated at a fraction of the cost of sapphire. Surmet's capabilities in fabricating spinel are described elsewhere in these proceedings by T. Mroz, et al.[2]

2. ALON™ OPTICAL CERAMIC

ALON was developed by scientists at Raytheon in the 1980's for use as windows and domes in infrared missiles. The goal was to produce a material with optical and mechanical properties similar to those of sapphire, but which could be produced at lower costs using conventional powder processing techniques. Even for small missile domes, sapphire is often considered to be too expensive for many systems. Prototype missile domes and launch tube windows have been manufactured, Figure 1.

ALON did not find its way into wide spread use, in part because of a lack of investment and marketing, and in part because of the reluctance of other defense companies to rely on Raytheon as a materials supplier. In 2002, Surmet Corp acquired the intellectual property, related equipment, and key personnel associated with the ALON process from Raytheon. Since acquiring the ALON technology, Surmet has addressed these issues by becoming a commercial supplier of this important material and by making substantial investments in production capabilities necessary for producing large quantities of ALON at affordable prices. Surmet has put in place a vertically integrated manufacturing capability for manufacturing ALON optical ceramic from powder to fabrication and polishing of complex shapes and large geometries.

Figure 1. Prototype ALON missile launch tube windows and domes, at various steps of manufacture. Powder→ Injection molded components→ Heat treated components → Finished window and dome

The addition of a small amount of nitrogen converts the rhombohedral crystal structure of alumina into the cubic spinel structure of ALON. It is the cubic structure which provides ALON with its' isotropic optical properties. Importantly, this means that ALON is transparent in polycrystalline form, can be produced by conventional powder processing techniques into more complicated shapes, larger sizes and at lower costs than are possible with single crystal sapphire. Furthermore, its' isotropic mechanical properties mean that it can be ground and polished with a fraction of the effort and cost required for sapphire.[3]

ALON is made by conventional powder processing techniques. These processes begin with the synthesis of the ALON starting powder from precursor materials. The powder is then formed into a green part, using one of a number of forming techniques which includes: cold isostatic pressing, slip-casting and injection molding. The green part is then heat treated to full optical density, and finally cut, ground, and polished into a final component. A schematic of this process is shown in Figure 2.

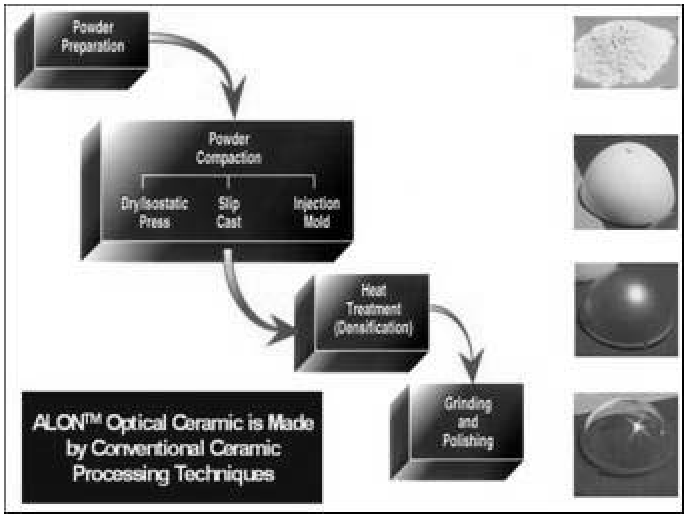


Figure 2. Schematic of process for producing optical ceramics

2.1 Composition and Properties

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. The most current measurements and data under development are presented elsewhere in this proceeding by C. Warner, et al.[4]

ALON has excellent transparency (>80% transmittance) from the near ultraviolet through the mid-wave infrared (MWIR) region of the spectrum, as is shown in Figure 3. The refractive index varies between 1.81 and 1.66 over the range of wavelengths 0.2 to 5.0 µm.

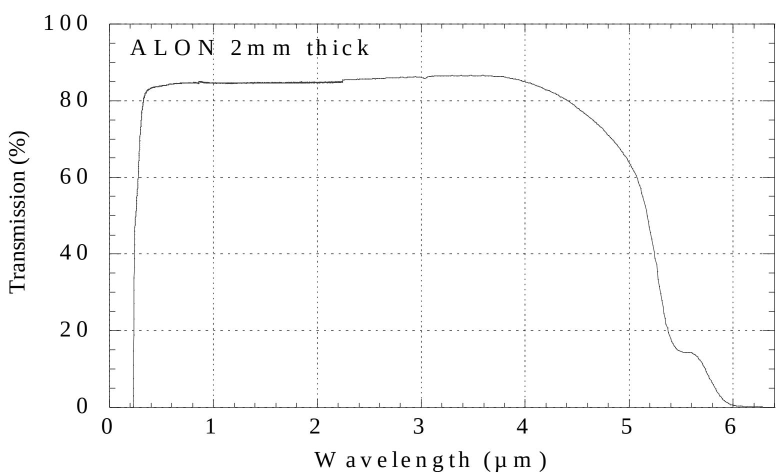


Figure 3. Optical transmission spectrum of ALON optical ceramic.

Table 1. Typical Properties of ALON Optical Ceramic

Physical Properties			
Density (g/cc)	3.688	Crystal Structure and Stoichiometry	Cubic Spinel: $Al_{(64+x)/3}O_{32-x}N_x$ ($2.75 \leq x \leq 5$)
Grain Size	250 µm	Lattice Constant	7.946 Å
Elastic Properties[5]		**Mechanical Properties**	
Young's Modulus	321.05 GPa	Flexural Strength[5]	700 MPa
Shear Modulus	127.35 GPa	Compressive Strength	2677 MPa
Poisson's Ratio	0.26	Fracture Toughness[6]	2.0 – 2.4 MPa-m½
Optical and Dielectric Properties			
Index of Refraction[7] (n @ λ) Accuracy ± 0.0012	1.792 @ 0.6328 µm, 1.778 @ 1.064 µm 1.726 @ 3.39 µm, 1.655 @ 5 µm	Dielectric Constant and Loss Factor Frequency =1GHz	k = 9.19 $\tan\delta = 31 \times 10^{-5}$
Transmission Range	0.2 to 6.0		

Thermal Properties[8]			
Temperature °C	Specific Heat J/g-°C	Thermal Conductivity W/m-°C	Mean CTE 10^{-6} /°C
-50	0.600	17.36	4.070
23	0.781	12.30	--
100	0.916	10.48	5.230
500	1.165	6.89	6.758
800	1.235	5.13	7.432

3. APPLICATIONS OF ALON™

Because of its excellent optical transparency, strength and hardness, ALON™ optical ceramic has emerged as the material of choice for a number of military and commercial applications. These applications include:

- Windows and domes (UV, Visible, IR , and millimeter Wavelengths)
- Transparent armor
- Point of Sale (POS) Scanner Windows
- Ceramic for semiconductor processing equipment
- Low cost alternative to sapphire
- Transparent alternative to alumina
- Etch resistant alternative to quartz

3.1 IR Windows and Domes

Surmet is now producing windows, domes, and lenses for many major defense companies. ALON optical components are now being used in such diverse applications as laser windows for underwater towed arrays, lenses, missile domes and FLIR windows/domes. Examples of these components can be seen in Figure 4. Several ALON prototype domes have been produced.

A significant cost component of finished domes is in the fabrication process. Minimizing the rough dome blank size (waste) is not always the lowest cost path. The blank yields must be taken into consideration. Thin shells can be more difficult to produce and reproduce accurately. This not only considers furnace drop out during heat treatments, but dimensional tolerance considerations. Material can be removed rapidly and effectively during the generation stages. Fixturing considerations also play a part in set up time for thin domes. Detailed cost savings have been demonstrated for the fabrication of ALON domes versus sapphire domes.[3]

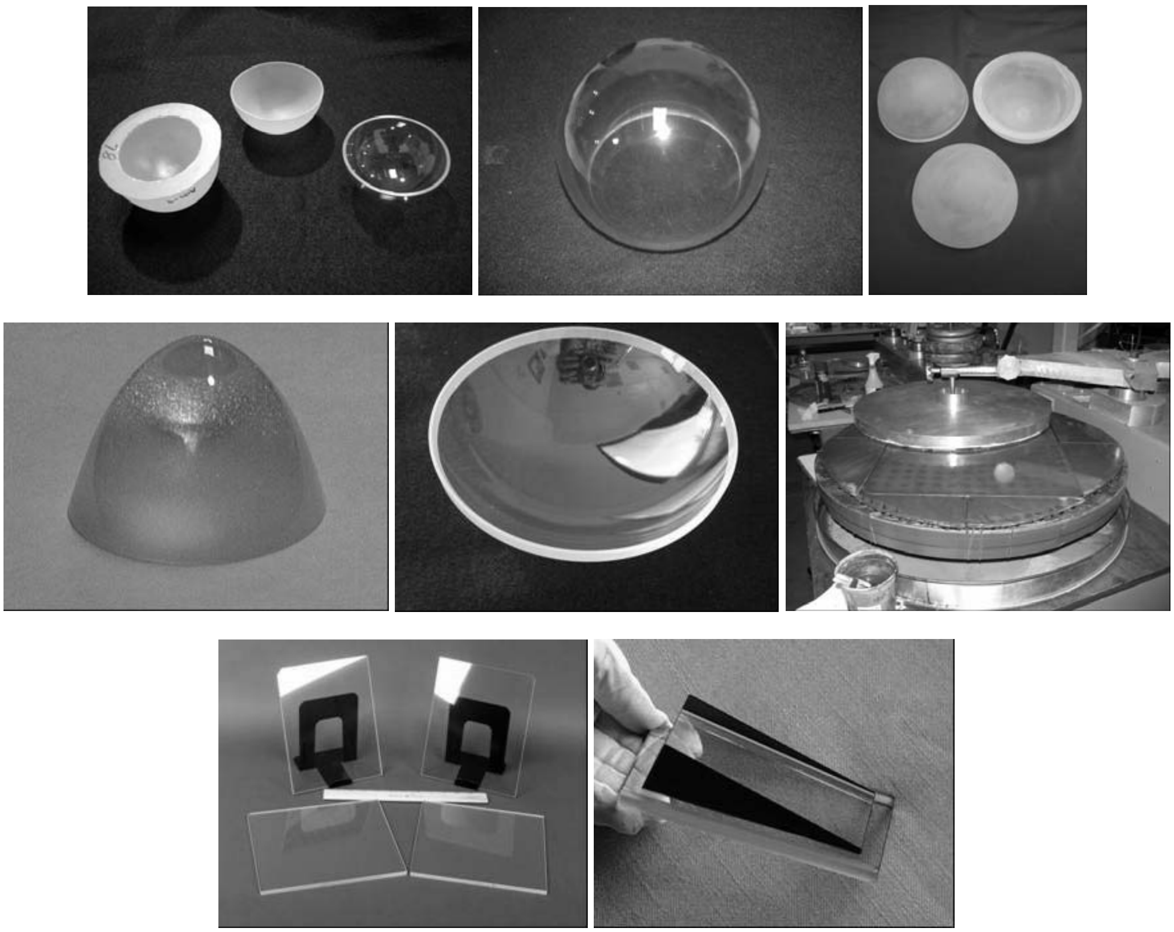


Figure 4. Examples of ALON optical components produced by Surmet.

The largest challenge facing polycrystalline optical ceramics is the ability to produce large components of high optical quality and uniformity. The powder process in principle is only limited by the size of the available equipment. That is not to say there are not challenges in making large powder processed transparent optical ceramics. Large optical quality windows have been produced by CVD techniques in both ZnS and ZnSe. There have not been any reported powder or melt processed monolithic large aperture optical ceramic windows of either single crystal or polycrystalline materials over 15 inches. These large sizes create problems in powder processing ranging from survival of the high shrinkage associated with consolidation to temperature uniformity in the furnace and its affect on the optical property uniformity. Surmet has produced optical windows with diagonal measurements in excess of 30 inches. An example of a large optical window during polishing is shown in Figure 4, middle right.

3.2 Transparent Armor

In terms of volume, the largest potential market for ALON is transparent armor. These include applications on land vehicles as well as aircraft and water craft. Figure 5 shows ALON plates, both flat and curved, which have been produced for transparent armor testing and demonstration.

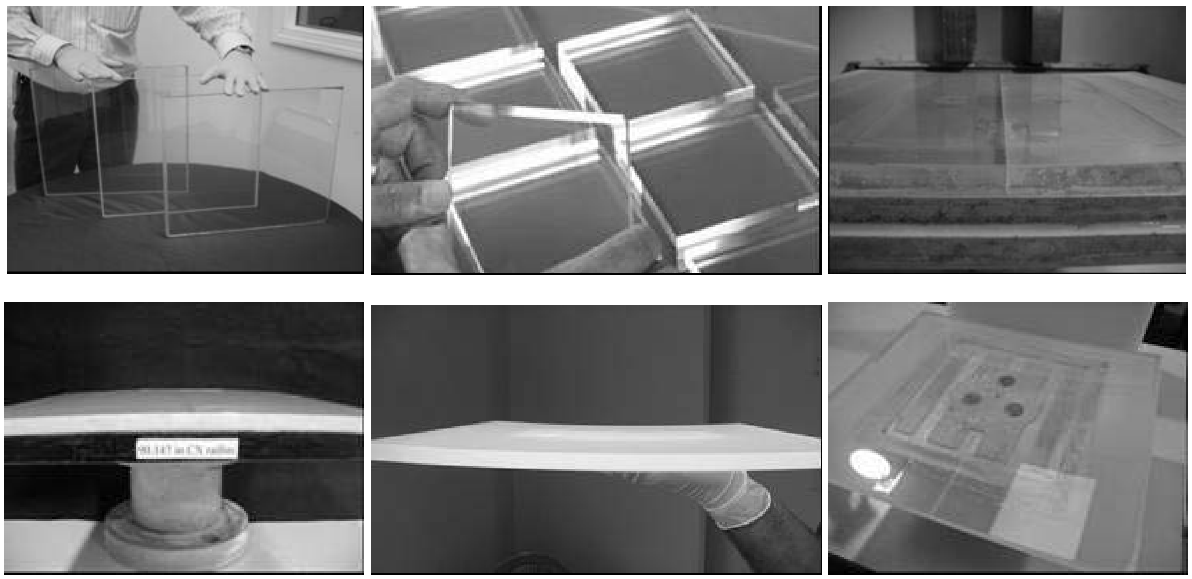
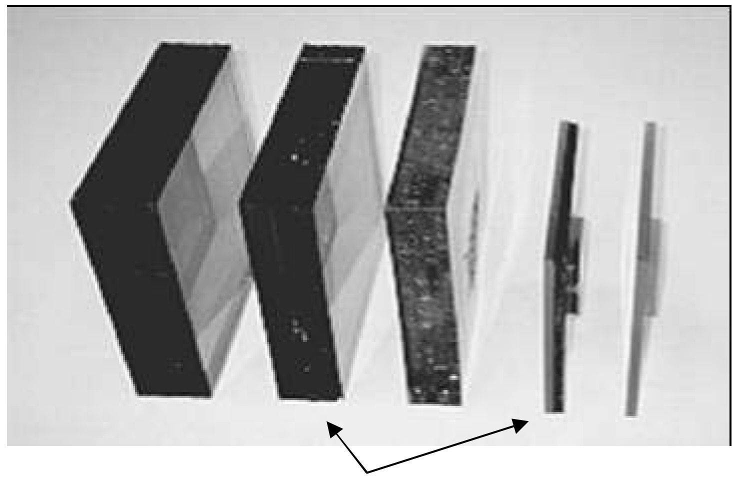


Figure 5. Photographs of ALON Plates, both flat and curved, that have been produced for Transparent Armor Testing.

When compared to conventional glass/plastic laminates used against armor piercing rounds, ALON™ transparent armor provides equivalent protection at half the weight and thickness. Some comparative ballistic results between conventional glass laminates and ALON laminates are shown in Figure 6. These results indicate a potential for hundreds of pounds of weight savings per vehicle (based on HMMWV window set replacement). Furthermore, ALON transparent armor has demonstrated superior multi-hit performance against armor piercing threats. A demonstration of the effectiveness of ALON was performed at the Team Patriot exercises at Fort Drum in 2004. ALON test laminates were demonstrated in the field to stop both .30 and .50 caliber armor piercing threats. Figure 7 shows the ALON laminate following the defeat of a .50 cal armor piercing round.

There are currently needs for large armor transparencies for land, air, and sea based vehicles. Surmet is currently developing this technology internally and through government R&D contracts. Initial process development was conducted to manufacture flat windows out of which the curved window was fabricated. To save costs the forming and processing of curved window blanks is also under development. This will save on material by reducing waste material usage. It will also decrease generation time and costs. Green blanks weighing 45 and 70 kilograms have been produced. The largest green blanks are approximately 46 x 24 x 1.25 inches. Figure 8 shows a large, 75 kg curved blanks for the vehicle window application under development. Surmet has successfully processed the 45 kg blanks to transparency. These blanks are currently being finished at Surmet Precision Optics. We are outfitting a vehicle with front and rear side lites and rear windows. The size of some of the vehicle windows dictate that the ALON armored version be fabricated in two pieces. All of these windows have a single cylindrical curvature. Surmet is developing fabrication methods and techniques for both blank manufacture as well as finishing techniques for large curved monoliths and segmented windows. Figure 5 (upper right) shows a segmented curved window in the process of polishing.



Provide Similar Ballistic Protection

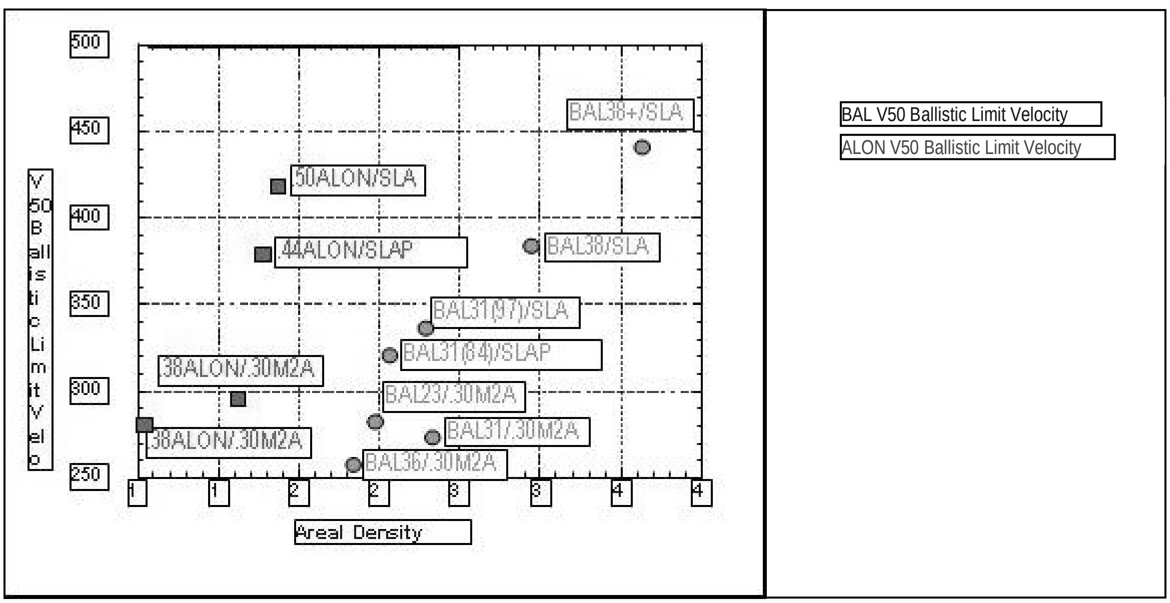


Figure 6. Comparison of Glass and ALON ballistic laminates and their performance against armor piercing threats.

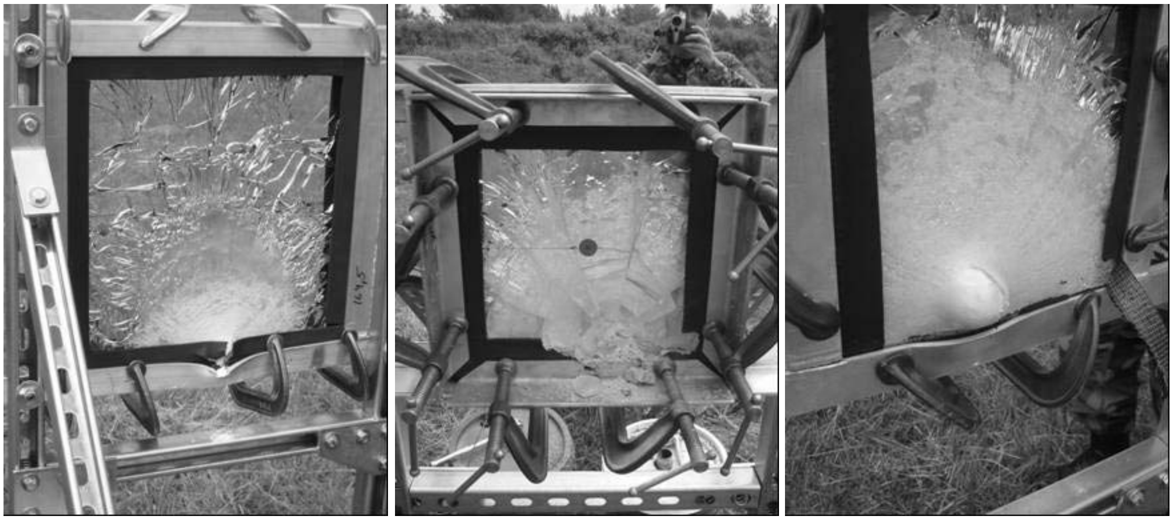


Figure 7. Team Patriot exercise demonstration of .50 caliber AP defeat by ALON ballistic laminate. Left: Backside complete penetration of glass laminate. Note penetration of backside ¼ inch frame also. Center: Front side of ALON laminate post defeat. Note penetrator fragment on frame. Right: Backside of ALON laminate post defeat.

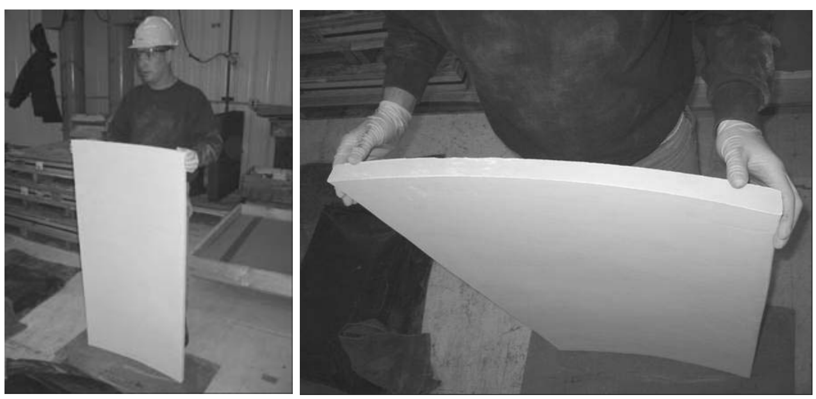


Figure 8. 70 kg curved green ALON transparent armor blank, nominally 46x24x1.25 inch.

3.3 Commercial Applications

ALON™ products are being manufactured for use and evaluation in a number of commercial applications. The high hardness and durability of ALON make it suitable for use as POS (Point of Sale) scanner windows seen in everyday use at supermarkets and other retail stores. Here, scratch and impact resistance, as well as optical clarity and low cost, are essential. ALON continues to find new applications in semiconductor manufacturing equipment because of its outstanding chemical resistance and its ability to be manufactured in complex shapes and in the large sizes required for these components. Examples of components include; plasma delivery tubes, wafer carriers, shower heads, and process enclosures (envelops and windows). ALON has demonstrated excellent durability when exposed to many of the corrosive chemical processes used in the electronics industry. ALON is not only a low cost alternative to sapphire, it is also an etch resistant alternative to quartz for many applications. This means that while the acquisition cost of ALON may be higher than quartz, it may have an overall lower cost of ownership due to its substantially longer lifetime in corrosive environments.

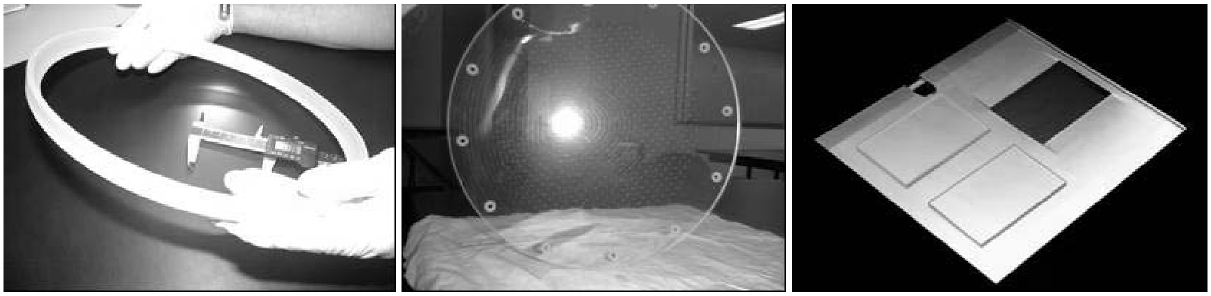


Figure 9. Examples of Commercial ALON applications. Point-of-sale (POS) windows, and semiconductor parts made of ALON optical ceramic are in increasing demand for evaluation and use.

3. FABRICATION DEVELOPMENT

A very thorough review of fabrication options for ALON, Sapphire and Spinel, all crystalline materials, was undertaken by Surmet during the past several years with the intent of identifying not only the most appropriate sequencing of fabrication steps but also the most suitable equipment for fabricating these very hard, ceramic materials.

Configuration of the optical component, curved or plano, were considered in this evaluation process. Many conventional processing options are viable for fabrication of plano configurations of these hard materials. There are, however, significant differences in this process from those required for other, less dense/softer materials typically used in IR/Near-IR applications. When considering a curved configuration such as a dome, conventional fabrication processes were deemed ineffective due to long processing times and difficulty in holding tight mechanical tolerances, such as true-position between the convex and concave surfaces, and optical requirements such as surface and wave front accuracy.

When considering ‘curved’ optics comprised of ceramic materials such as ALON and Sapphire, a multitude of fabrication options were explored. Among these were conventional ‘lap’ polishing, Magnetorhelogical (MRF) ‘zone’ finishing, diamond turning and grinding, and, our final selection, synchronous fabrication, Figure 10.

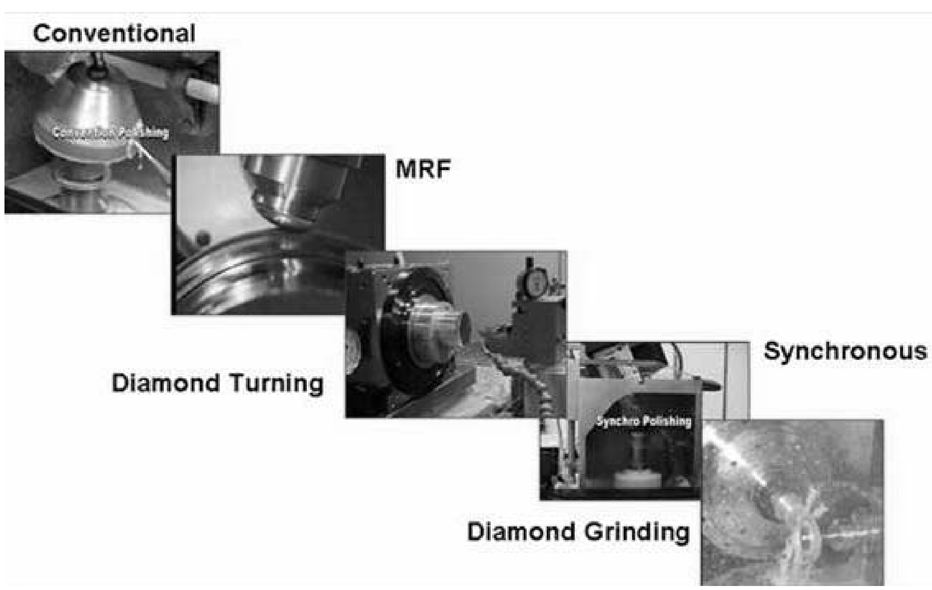


Figure 10. Various fabrication methods for the manufacture of curved ceramic components.

As previously mentioned, although conventional processing techniques can be employed in the manufacture of ceramic curved optics, these techniques are very slow and therefore costly. Diamond turning was deemed ineffective in processing hard ceramics due the nearly instantaneously dulling of the single-point diamond 'tip'. Diamond grinding techniques were found to be capable of successfully removing material from the ceramic dome, but left a significant 'annular' surface on the optic which degraded the surface figure. Synchronous processing was found to be very effective for processing ceramic materials. A subjective chart was developed as an aid in selecting an appropriate fabrication process for hard ceramic materials, Figure 11.

Process/ Equipment	Useful on Oxide Materials ?	Mature Process for Oxides ?	Relative Equipment Cost	Effectiveness on Oxides	Ability to Process Domes	Over-all rating (1 low 10 high)
Synchro-Speed	**Yes**	**Moderate**	**High**	**Potentially High**	**Yes**	**8**
Conven-tional	**Yes**	**Yes**	**Low**	**Effective, extremely slow**	**Yes**	**4**
MRF	**Limited**	**Moderate**	**Extremely High**	**Minimal, slow probably only final finishing**	**CX, not CC on steep domes such as AIM9X or JCM**	**3**
Diamond Turn	**No**	**No**	**High**	**N/A**	**Yes, not oxides**	**0**
Diamond Grind	**Yes**	**No**	**High**	**Moderate due to 'single' contact point process**	**Yes**	**3**

Figure 11. Subjective chart to aid in selecting an appropriate fabrication process for hard ceramic material.

The roughing or curve generation step for dome fabrication is not unlike a conventional process in that a diamond impregnated tool is used to remove excess material into the desired configuration, convex or concave. Synchro does, however, typically employ significantly more sophistication in the generation equipment when compared to a typical conventional generator. The typical conventional generator has no feed-back loop to the control system thereby requiring the operator to 'hit-and-miss' to get to the final curve. Most synchro generators are now CNC controlled allowing for a control 'feed-back loop'. An operator inputs the variables into a user friendly control system and then makes an initial cut. The part is then measured and the error is fed into the control system which makes the necessary displacement adjustment or head angle changes in order to correct the surface to the required curvature.

The 'fining' process entails removing enough material from the surface of the dome post-generate in order to minimize and eliminate sub-surface damage. A significant difference between the conventional and synchro process is this intermediate material removal step. Conventional processing techniques typically employ a loose abrasive for this step whereas synchro processing uses a fixed abrasive tooling concept. Diamond impregnated pellets are used to remove material from the surface of the dome. Surmet has found that the differences between loose and fixed abrasive processing to be significant. While both processes can be used very successfully, fixed abrasive fining will nearly always yield faster removal rates with similar or better surface roughness.

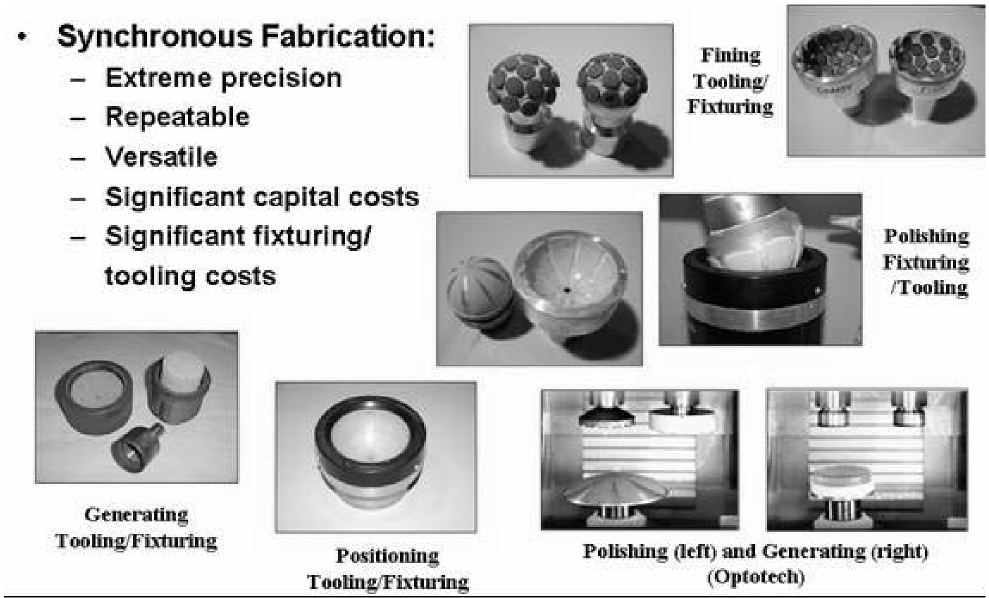


Figure 12. Synchronous process curved part tooling.

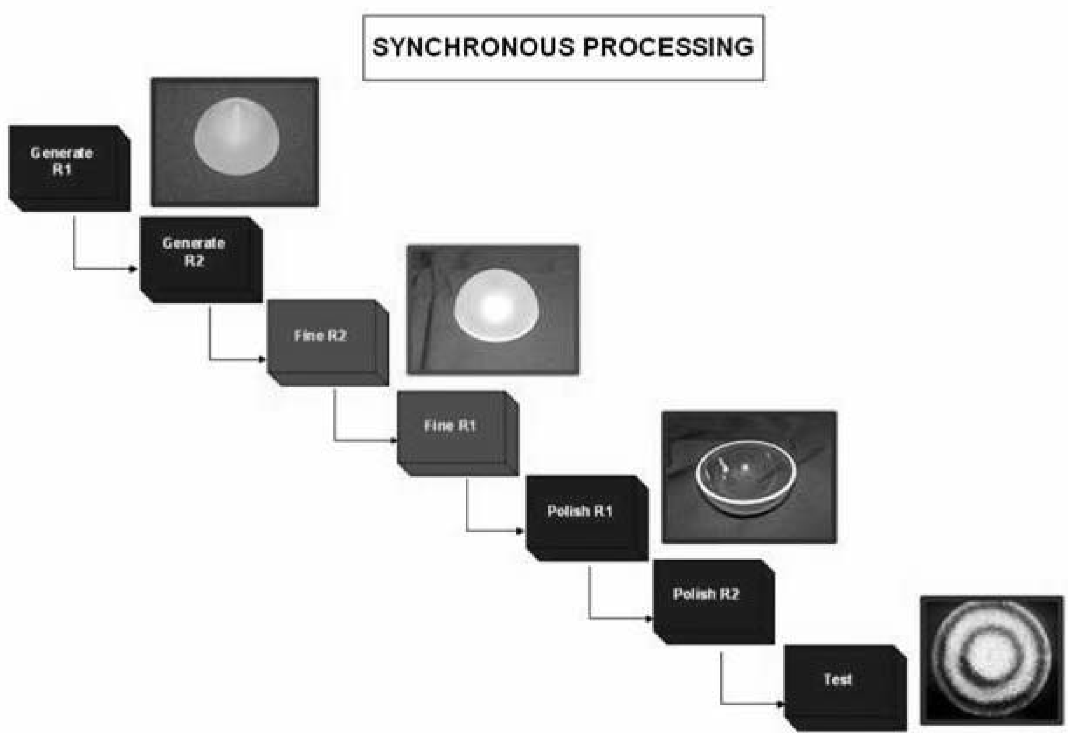


Figure 13. ‘Synchronous’ process employs a three stepped approach in the fabrication of an optic.

The polishing step in a 'synchro' process uses a fixturing and tooling concept in which a rotating air-accentuated holder is pressured into a rotating tool which is, typically, covered with a polyurethane pad. Both upper and lower spindles are driven. A conventional process typically employs the use of a pitch covered tool and a weighted over-arm with only the lower spindle driven. Additionally, conventional processing techniques typically 'hard-mount' the optic on the opposite the side from that being worked. When the part is 'de-blocked', there is a high potential for 'springing', meaning that the surface form changes when release from the mount. Synchro processing does not 'hard-mount' the optic but rather uses a second polyurethane pad covered tool in conjunction with the pressure mechanism to press the optic into contact with the polyurethane polishing pad. Surmet believes, and has shown, that these differences between conventional and synchro processing makes synchro the clear choice for the fabrication of ceramic curved optics.

5. CONCLUSIONS

Surmet has acquired the ALON technology from Raytheon and has brought this important material to the commercial market place. Its powder processed manufacturing method and polycrystalline structure make ALON producible in large and complex shapes not available in other high performance optical ceramics. ALON is currently being produced in large quantities, for a variety of applications, both military and commercial. Surmet has put in place a vertically integrated manufacturing capability for manufacturing ALON optical ceramic from powder to fabrication and polishing of complex shapes and large geometries.

6. ACKNOWLEDGEMENTS

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