# Structural adhesives for bonding optics to metals: a study of opto-mechanical stability

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## ABSTRACT

With so many new adhesives available, characteristics affecting performance are not always well-defined. The user often selects an adhesive based on a single property and later finds his application compromised. This is an effort to study relevant properties of several different structural-type adhesives. The bonding geometry will utilize three types of glass (fused silica, BK-7, and Pyrex) bonded to metal mounts. The mounting geometry will include five different design approaches. These designs will investigate: face bonding, counter-bored mounts, edge bonding, and a flexure mount. The three metals selected (aluminum, titanium, and invar) are not only common to the industry but often used for matching the Coefficient of Expansion to the optical glass. Each optical flat will have its reflective surface used as a reference for angular stability. The adhesives selected will compare more traditional epoxies with one-part Ultraviolet Light (UV) cured products. The obvious advantage of the UV-cured adhesives is the instant cure on-demand. Several adhesives have been selected for differing properties including: viscosity, cure temperature, CTE, modulus of elasticity, out-gassing, and shrinkage upon cure. Discussion will compare each adhesive, its properties, and ease of use. Angular stability will be monitored as a function of: pre vs. post cure, accelerated life testing, thermal exposure, and vibration/shock exposure. Some discussion will be included on the Wavefront Distortion and Stress Birefringence.

Keywords: Adhesives, Bonding, Optics, Optical Stability, Structural Adhesives, Optical Mounts

## 1. INTRODUCTION

In the experience of these authors, very little has been published on the application of adhesives for fastening optical elements. Yoder[1] has briefly addressed this subject in an excellent opto-mechanical text. Optical bonding has been a common practice, but until recently extreme alignment stability requirements have been limited to a small portion of the electro-optical / photonics marketplace. Thousands of adhesives are now available and the selection process is not always clear. Priorities must be assigned to the properties in the determination of a compromised-process. In order to provide continuity and to aid the reader in understanding our adhesive selection evaluation, a short review of the critical adhesive properties is included.

Less than twenty years ago, the majority of all optical bonding utilized a handful of adhesives. In general these were typically 2 part epoxies with good adhesion, high strengths, and some resiliency. For example, 3M's Scotchweld 2216 B/A [2] is still a favorite adhesive candidate. In addition to complying with these common properties, 2216's viscosity made for easy application and its low out-gassing is characterized as NASA space qualified. Some of the principle limitations of these 2-part adhesives included: critical mix ratio dependency; long room temperature cure or high temperature cures; a relatively high CTE (coefficient of thermal expansion); and a high modulus of elasticity. The high CTE and modulus contributed to rigid bonds and high stress levels.

Users today expect much more from adhesives for fastening optical elements. They demand: low costs; excellent adhesion; instant cure; high strength; no stress; precise alignment stability; a wide temperature range; no out-gassing; and long life. Unfortunately, no single adhesive can meet all these requirements. It is the users responsibility to determine where compromises can be made. With thousands of UV-cure polymers available, the appeal of instant on-demand cure merits an evaluation of their properties. We have compared similar bonding geometries utilizing epoxies and UV-cure adhesives.

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Optomechanical Design and Engineering 2001, Alson E. Hatheway, Editor,
Proceedings of SPIE Vol. 4444 (2001) © 2001 SPIE · 0277-786X/01/$15.00

## 1.1 ADHESIVE HISTORY

The older established adhesives were developed for differing applications. Many of the traditional 2-part epoxy favored by optical engineers were originally formulated and marketed for bonding either wood or metal. Adhesion and strength were the principle properties the chemists pursued in these formulations. And in many cases, the adhesion was anticipated to be acceptable under conditions of high temperature cure and high pressure loads. These attributes to the bonding process are not consistent with most optical assembly processes.

Other adhesives for glass-to-glass bonding were independently developed. Early uses of organics for cementing doublets was succeeded by synthetic and more reliable adhesives. Norland [3] developed a complete line of polymer-based adhesives with excellent optical properties that cured with UV (ultraviolet) radiation. This was well-suited to precise alignment / positioning / centering followed by an instant cure-on-demand process by exposure to UV radiation. Attempts to use these adhesives for glass-metal bonding was met with limited success until more specific formulae were developed. Today, Norland, Dymax [4], and many other vendors have UV-cure adhesives that rival the mechanical properties of 2-part epoxies.

## 1.2 ADHESIVE TYPES

Adhesive types or categories do not follow any common nomenclature. However, most titles are descriptive-enough to avoid confusion. Glass-to-Glass adhesives imply transmissive optical quality but can often work for glass to metal situations. In general, all adhesives are now synthetic. Common categories often utilize these terms: epoxy; polyurethane; acrylic; cyanoacrylate; silicones, etc. Other most application-orientated terms are: 2-part; 1-part; RTV; UV-cure,..etc.

A structural adhesive definition in general has a tensile (or lapshear) strength that exceeds 1000 psi. This arbitrary strength assignment is violated when some flexible RTV adhesives with lapshear strengths near 500 psi are used to secure optics. Many times the exact formulae of an adhesive are treated as proprietary, but the MSDS information can aid in partial identification.

We have studied several 2-part epoxies in this study. Each will be listed with relevant properties as well as the process used in our tests. Several UV-cure polymers will be compared to the performance of these traditional epoxies.

## 1.3 ADHESIVE PROPERTIES

This brief review of relevant properties will aid the reader in understanding their influence on performance and how to evaluate candidates for selection.

Viscosity is defined as the resistance to flow or shear stress. This property is important for uncured adhesives. The viscosity will influence its application and its ability to wet the surface of the substrates. High viscosity adhesives are easy to handle, control bead size and position. However, low viscosity improves the wetting or contact with the substrates. When the viscosity is too low, the adhesive will flow and may corrupt either the bond process or the clear aperture. Viscosity is directly proportional to temperature. Therefore caution is necessary when high temperature curie is employed and a correctly applied adhesive may flow and destroy the process.

Wetting is defined as the ability of the uncured adhesive to make contact with the substrate. This is critical for adhesion. Surface tension is often associated with this property. The adhesive must have a lower surface tension than the substrate for proper wetting to avoid beading. Pressure is also used to improve wetting and therefore adhesion.

After the adhesive has cured, its properties must be understood to determine compatibility with not only the materials but the use and exposure of the assembly. We have focused on the properties that are most relevant to optical alignment sensitive applications: durometer, strength, CTE, modulus, shrinkage on cure, the glass transition temperature, and outgassing.

Durometer is a measure of the hardness where a relative scale of penetration is employed with a dedicated instrument. A common denominator for plastics, this can provide an indication of compliance or hardness of the cured adhesive.

Strength is critical to performance and is typically measured as: tensile; compressive; lapshear; peel; or cleavage. In general, lapshear tests are most common and provide adequate information. However, peel and cleavage can be common modes of failure when these loads are experienced. Because of the high stress concentration in peel and cleavage loads, these strengths are much lower than tensile of lapshear. The bonding design should attempt to achieve loads free from peel or cleavage situations.

The CTE values become important for applications where exposure to wide temperature ranges exist. If possible, the user tries to match the substrate CTE's first, and then use an adhesive with a value close to these. Differential expansion (or contraction) will create optical element movement and also high stresses that can result in fracture of the optical element. The modulus of elasticity plays a similar role in the selection of an adhesive. Tensile moduli are normally available, however bulk and compressive can be determined. A high modulus adhesive that experiences either shrinkage on cure or differential expansion will experience proportionally high stresses.

All adhesives experience some shrinkage during cure. Typical epoxy values are 3 to 5 %. This contributes to movement for critical alignment applications. It also creates high stress levels. Suppliers are working on improved products with lower shrinkage values. We have studied some UV – cured adhesives with shrinkage on cure levels of less than 0.2%

Polymer chains have limited mobility at temperatures below their Glass Transition Temperature. Above the Tg, whole chains are mobile and visco-elastic behavior results in diminished mechanical properties. The glass transition temperature should be factored into the selection of any adhesive. The mechanical properties of strength, modulus, and CTE are temperature dependent. Most suppliers will quote the CTE value for two temperature ranges: below Tg and above Tg. It is the degradation in these parameters that is important and not the Tg, so the user must evaluate accordingly.

Out-gassing is the release of volatile solvents. This occurs during cure but also throughout the life of any material. NASA has tested thousands of materials and publishes a website with this information. The two measures of performance are the TML ( Total Mass Loss, in %) and CVCM (Collected Volatile Condensable Material, in %). NASA[5] has determined that Space-Qualified materials should have a TML < 1.0% and a CVCM < 0.1%. We have found these guidelines to be valid and in application of high fluence laser exposure additional testing may be conducted. Laser induced optical damage from the CVCM can be further evaluated by out-gassing and subsequent laser exposure tests[5].

## 2. METHODOLOGY

The adhesives selected were representative of traditional epoxies with proven performance. In addition, several new UV-cure adhesives were selected for comparison in similar applications. Each candidate adhesive is listed below with it properties as well as the supplier source.

For simplicity, only one optical element geometry was tested. One inch diameter optical flats with a 0.25 inch thickness were used for most tests. Some thinner samples were available. The optical materials included BK-7, Pyrex, and fused silica. This is representative of common materials with a wide range of mechanical properties.

The metal substrates were defined in five geometries: (1) a flat plate; (2) three raised in-plane pads; (3) a counter-bored recessed cell with a through hole; (4) a counter-bored opening with a through hole and side holes for injected edge bonding; (5) and a flexure designed mount. Three materials have been used for each geometry: black anodized aluminum (6061-T6); titanium (6AL-4AV) ; and gold-plated invar (invar-36). Figure 2.1 – 2.3 show these fixtures. These solid metal fixtures were designed to accommodate 4 optical test pieces independently (except the injection hole design with its three-optic geometry). In addition, at the center of each fixture the metal was machined with a ½ inch raised surface which was diamond-polished to a mirror surface. This surface was the integral reference mirror from which angular movement of the test optics could be compared. This design eliminated any dependency of the reference mirror stability.

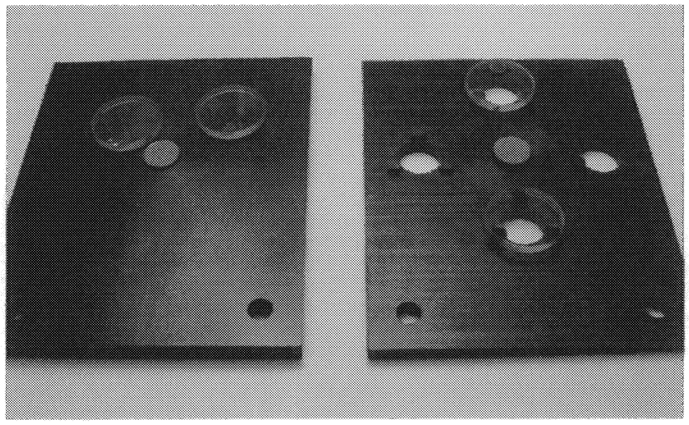

Figure 2.1 Test fixtures # 1 & 2: Flat Plates

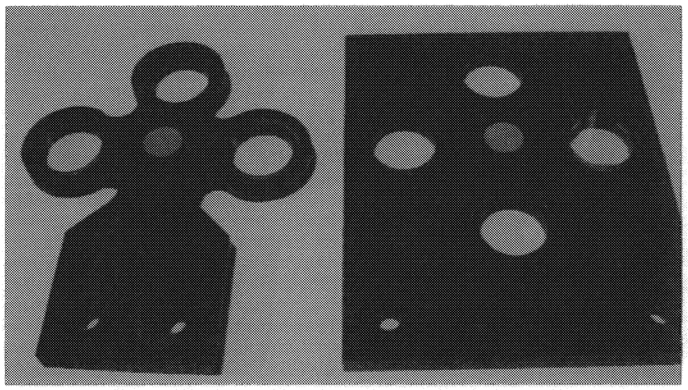

Figure 2.2 Test Fixtures # 3 & 4; Counterbore recessed

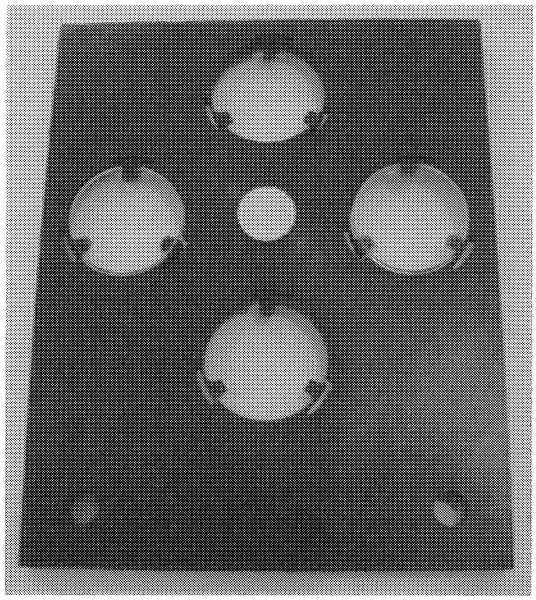

Figure 2.3 Test Fixture # 5 : Flexure Mount

## 2.1 ANGULAR STABILITY TESTING

In many cases, the test optic was aligned and cured with its angular alignment measured post-cure. Further temperature exposure allowed alignment stability to be monitored at high and low temperature as well as after ambient equilibrium. The long term angular stability was monitored. The angular alignment was measured as the parallelism of the test optics surface to the reference mirror surface on the test fixture. For these tests we used a Nikon 6D Autocollimator[7]. The projected reticle provided a comparison of the reflected returns with a resolution of better than 20 microradians. Newer instruments with CCD arrays and computer interface are available but our work was limited to the older traditional autocollimator method. In cases of severe distortion and optical element bowing, the image blur would limit resolution and these conditions were noted in our data. It is not possible to quantify the surface deformation from this information, but a subjective assessment was possible.

Data was collected in two formats. The optical element's first surface angular alignment was recorded with-respect-to the diamond polished reference mirror. The stability or retention of this initial alignment was measured under ambient conditions: after bonding, after thermal testing, and after storage times. Thermal testing involved active monitoring of the alignment during temperature changes and at each stabilized temperature extreme. Typical data started at ambient, followed by a measurement at +55°C. Cold exposure at –30°C was recorded unless distortion limited resolution. In that case, data was collected at 0 °C.

## 3. DATA

| Adhesive | 2216 B/A gray | 724-14C | OP-61 |
|---|---|---|---|
| Supplier | 3M | Ablestik | Dymax |
| Type | 2-part epoxy | 2-part urethane | 1-part |
| Comments | High strength epoxy and low out-gassing | Flexible high strength | Multi-purpose glass to metal bonding<br>Low shrinkage and low out-gassing |
| Cure | Room temp | Room temp | UV light |
| Viscosity | 100,000 cps | High | 160,000 cps |
| Work Life | 90 minutes | 30 minutes | n/a |
| Durometer | D 60 | A 92 | D 85 |
| Shrinkage upon cure | 3% (est.) | 3% (est.) | 0.3 % |
| Lapshear Strength Al-Al @ 25°C | 2500 psi | 1900 psi | 2800 psi |
| Peel strength | 25 piw | N/a | n/a |
| Glass Transition Temperature | 40 ° C | N/a | 70 ° C |
| CTE<br>Below Tg<br>Above Tg | 102 x $10^{-6}$/°C<br>134 x $10^{-6}$/°C | N/a | 43x $10^{-6}$/°C<br>59 x $10^{-6}$/°C |
| Modulus |  |  | 2,400,000 psi |
| TML | 1.01 | 1.11 | 1.22 |
| CVCM | 0.05 | 0.12 | 0.02 |
| Temperature Range | -55°C to +100°C | -55°C to +125°C | -45°C to +170°C |

Table 3.1 Adhesive Property Matrix

| Material | Aluminum | Titanium | Invar |
|---|---|---|---|
| Alloy | 6061-T6 | 6AL-4V | Invar-36 |
| Surface finish | Black anodized<br>Mil-A-8625<br>Type II, class 2 | Not plated | Base: electroless Nickel Gold per Mil-std-45204B<br>Type 2, class 00<br>(.00005 min) |
| Density | 0.098 $\text{lb/in}^3$ | 0.161 $\text{lb/in}^3$ | 0.291 $\text{lb/in}^3$ |
| CTE | $23.9 \times 10^{-6}$ / °C | $8.46 \times 10^{-6}$ / °C | $0.9 \times 10^{-6}$ / °C |
| Young's Modulus | 10,000,000 psi | 16,500,000 psi | 21,500,000 psi |
| Tensile Yield Strength | 31,000 psi | 130,000 psi | 70,000 psi |

Table 3.2 Metal Substrate Mechanical Property Matrix

| Material | Pyrex | BK-7 | Fused Silica |
|---|---|---|---|
| Comments | Inexpensive high temperature glass | Borosilicate glass with excellent optical quality | Synthetically fused quartz for critical optical requirements |
| Density | 2.23 $\text{g/cc}^3$ | 2.53 $\text{g/cc}^3$ | 2.2 $\text{g/cc}^3$ |
| CTE | $3.6 \times 10^{-6}$ / °C | $7.1 \times 10^{-6}$ / °C | $0.56 \times 10^{-6}$ / °C |
| Young's Modulus | N/a | 11,700,000 psi | 10,600,000 psi |
| Tensile Yield Strength | 3,000 psi | 1,000 psi | 7500 psi |
| Index of refraction, $n_d$ | 1.473 | 1.5168 | 1.459 |
| Optical transmission | 325 nm to 2500 nm | 325nm to 2500 nm | 190 nm to 4400 nm |

Table 3.3 Optical Element Property Matrix

## 4. RESULTS

As summarized in our conclusions, the data presented in this paper represent only preliminary results. The following table shows initial trends from configuration changes in bonding a one-inch diameter flat optical element in an aluminum mount.

In each case, 3 adhesive bond points were used. This common practice accomplishes the following: definition of a plane; controlled and consistent adhesive application; minimum use of adhesive; and adequate bond area for strength. The only mount material tested has been aluminum. This black anodized surface was cleaned with acetone prior to bonding.

The three glass materials represent not only common materials, but a wide range of CTE values. Ratios of CTE for glass-to-Aluminum are: fused silica (42.7), Pyrex (6.6), and BK-7 (3.4). All adhesives were cured at room temperature. Therefore the CTE difference will manifest itself during thermal testing. The high temperature test at + 55°C was less severe than the – 30 °C test since the temperature deltas were: 28 vs. 57 ° C.

The adhesive used in these preliminary tests are defined above. Our objective to evaluate these newer instant cure UV adhesives with respect to the traditional epoxies can be assessed from the data summarized below. We found the performance of OP61 to match the epoxies. Since the mechanical properties of the UV-cured adhesive equal the conventional epoxies, their use can be recommended. Early tests with another UV-cure adhesive Dymax OP30 have started since the very low modulus offers low stress applications.

| Glass Type | Adhesive | Long term ambient stability | Angular movement from –30°C to+55°C | Comments |
|---|---|---|---|---|
| Aluminum Flat Plate | | | | |
| Fused Silica | 3M 2216 B/A | < 15 μrad | For 0°C to +55°C<br>< 60 μrad<br>no data @ –30°C | Large CTE mismatch caused distortion at –30°C. |
| Fused Silica | AbleBond 724-14C | < 10 μrad | < 200 μrad | This more flexible adhesive reduced distortion but lacked stability. |
| BK-7 | 3M 2216 B/A | < 45 μrad | < 80 μrad | Closer CTE match improved performance. |
| 3 Raised Pads on Aluminum | | | | |
| Pyrex | AbleBond 724-14C | < 150 μrad | < 85 μrad | Well defined geometry provides improvement relative to flat plate. |
| Pyrex | OP 61 | < 100 μrad | < 20 μrad | |
| Counterbore Recess in Aluminum | | | | |
| Pyrex | 3M 2216 B/A | < 50 μrad | < 100 μrad | Similar performance. Most movement from more flexible 724-14C adhesive. |
| Pyrex | AbleBond 724-14C | < 50 μrad | < 200 μrad | |
| Pyrex | OP 61 | < 70 μrad | < 80 μrad | |
| BK-7 | 3M 2216 B/A | < 30 μrad | < 50 μrad | Improvement from better CTE match for BK-7 vs. Pyrex. |
| BK-7 | AbleBond 724-14C | < 50 μrad | < 200 μrad | |
| BK-7 | OP 61 | < 70 μrad | < 90 μrad | |
| Injection Side Holes in Counterbore Recess in Aluminum | | | | |
| BK-7 | 3M 2216 B/A | < 15 μrad | < 80 μrad | Results similar to counterbore but much easier to bond and to control adhesive on edges only. |
| BK-7 | AbleBond 724-14C | < 50 μrad | < 90 μrad | |
| BK-7 | OP 61 | < 45 μrad | < 100 μrad | |
| 3 Pad Flexure Mount in Aluminum | | | | |
| BK-7 | 3M 2216 B/A | < 80 μrad | < 45 μrad | All adhesives result in very stable performance during temperature exposure. |
| BK-7 | AbleBond 724-14C | < 60 μrad | < 60 μrad | |
| Fused Silica | AbleBond 724-14C | < 100 μrad | < 50 μrad | |
| Fused Silica | OP-61 | < 30 μrad | < 30 μrad | |
| Pyrex | OP61 | < 80 μrad | < 60 μrad | |

Table 4.1 Test Data and Results Summary

With strengths similar to epoxies, the alignment retention stability shows similar results justifying their consideration for potential use. Adhesive shrinkage upon cure will also influence the alignment stability. High shrinkage will create optical element movement during cure as well as high stress.

## 5. CONCLUSIONS

As this paper deadline approached, we continued to record data. Definition and setup for these tests coupled with some time constraints relegated this paper to preliminary test results. However, this paper successfully defines our objectives and test methodology. We will continue to record data and refine our tests until a full range of results for each optical element and metal substrate is compared for epoxies and UV-cured adhesives. We also have scheduled tests with new experimental UV cure adhesives that have combinations of low CTE, low shrinkage on cure, high Tg, and high strengths.

The authors will present updated results at the SPIE annual meeting later next month. As well, the authors remain available for subsequent questions concerning these tests and our results.

From the preliminary results, the following statements can be made.

1) These new UV adhesives have similar lapshear, tensile, and peel strengths to epoxies.
2) Several UV adhesives have much lower shrinkage on cure values.
3) Several UV adhesives have lower CTE values.
4) Many UV adhesives have low out-gassing and are NASA space-qualified.
5) Our tests show that the optical element alignment retention for these UV adhesives is comparable to the traditional epoxies.

From these preliminary results, the high strengths of OP-61 and its instant cure make is a realistic candidate to replace epoxies for optical mounting where alignment stability is required. Other UV-cured products with similar properties are expected to perform well and our continued tests will address this subject.

The Flexure mount tested is similar to the work of Bacich[8]. The results for these tests clearly show that this design is extremely stable over thermal exposure. Similar angular stability was recorded for all three varying CTE value optical materials. This type of mount was easily fabricated with a final step of EDM (electrical discharge machining) and can be successfully employed where stable mirror alignment is required over a wide temperature range.

## ACKNOWLEDGEMENTS

The authors must acknowledge the Dymax Corp, Torrington, CT. for funding for this effort. They requested an independent evaluation of their UV-cured adhesive products as substitutes for epoxies in opto-mechanical applications. In addition to funding and adhesive samples, Dymax also provided valuable technical support. Northrup Grumman Laser Systems, Apopka, FL provided access to their optical assembly equipment and environment test equipment. Intellitec, a division of APD, Deland, FL. also supported this effort by providing access to their optical and environmental test equipment.

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