# CONTROLLING STRESS IN BONDED OPTICS

Andrew Bachmann, Dr. John Arnold and Nicole Langer
DYMAX Corporation, Torrington, Connecticut
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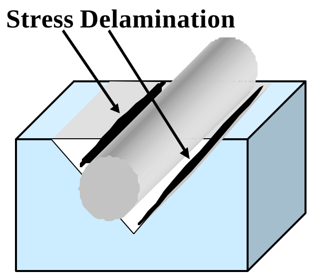
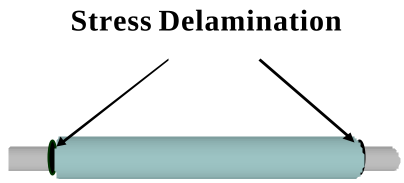
## INTRODUCTION

Stress from adhesives can be an important factor affecting the quality and durability of bonded joints. High stress from adhesives can delaminate fiber optics or cause birefringence. Divergent coefficients of thermal expansion (CTE) can lead to relative movement between bonded parts. New DYMAX Light Curing Adhesives technology provides more durable, lower stress, low movement bonds, improving in the quality of finished optics.




Stress in a V-groove connector




Stress in a sleeve-type connector

Stress birefringence in a lens

**Figure 1.** Adhesive induced stress, either from shrinkage on cure, aging, or thermal excursions can cause birefringence or delamination failures. Overly rigid materials may not relieve the stress from divergent coefficients of thermal expansion (CTE) which can manifest themselves in substrate delamination or in substrate distortion.

Stresses induced by an adhesive are minimized by using adhesives that:

- Minimize the shrinkage on cure
- Lower the modulus of the cured adhesive polymer
- Utilize polymers with a small $T_g$ effect.
- Use polymers with a small overall CTE, independent of the $T_g$.

## I. STRESS FROM SHRINKAGE ON CURE

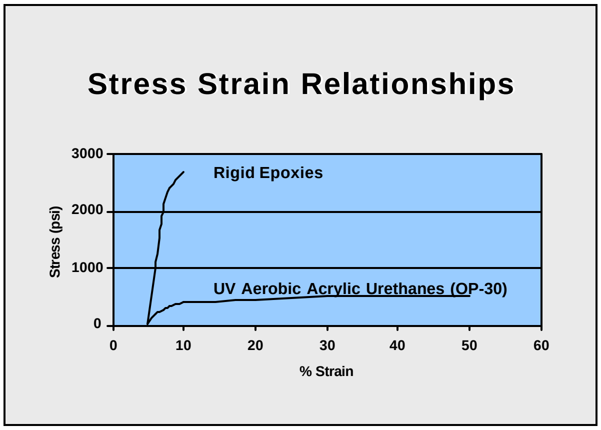
All adhesives experience some shrinkage during cure (polymerization). Shrinkage on cure from most epoxies and "early generation" UV adhesives typically range from 2 to 5 %. This shrinkage may move some optics out of alignment. Glass can break when adhesive-induced stress exceeds the tensile strength of glass. New DYMAX Light Curing Adhesives ( LCA) are available with shrinkage on cure levels of less than 0.2% and an induced stress of less than 100 psi., thus facilitating fine optics assembly with tight tolerances.

**Table 1.** Tensile strength of common optical substrates

| | |
|---|---|
| BK 7 | 1,000 psi. (6.9 Mpa) |
| Pyrex | 3,000 psi. (20.7 Mpa) |
| Fused Silica | 7500 psi (51.7 (Mpa) |

Stress from shrinkage is an inherent property of the chemicals making up adhesives. Chemical bond changes and molecular distance contribute to shrinkage. Bonds from the relatively distant molecules in a liquid adhesive polymerize to form the shorter bonds of the cured adhesive (polymer). Also, the molecular bonds of a polymer are shorter that those in a monomer. Molecular bond length changes are independent of either fast or slow cure curing processes. Degree of cure gives the effect or changing *apparent* shrinkage and may change on aging the optic.

**Figure 2**. A comparison of stress and strain relationships. High modulus polymers such as epoxies tend to have a higher ratio of stress to strain[3].




Shrinkage and modulus are major components of stress on cure. Table 2 illustrates how induced stress may exceed the strengths of the substrates. The result can be delamination or movement between bonded parts. Equation 1 below is a first approximation to estimate stress on cure. Table 2 illustrate calculations.

**Table 2.** Shrinkage on cure, as well as the modulus of an adhesive polymer affect induced stress

| Polymer | Shrinkage on Cure (unfilled) | Modulus (psi) | Shrinkage on Cure (filled) | Calculated Stress |
|---|---|---|---|---|
| Commercial Optical Epoxy | 2-3% | 550,000 | - | 10,000 psi.* |
| Filled Commercial Epoxy | - | 1,250,000 | 1% | 12,255 psi.* |
| OP-29 Lens Bonding LCA | 2-3% | 35,000 | - | 980 psi. |
| OP-60-LS Positioning LCA | - | 1,000,000 | 0.05-0.1% | 750 psi. |
| OP-4-20641 Fiber LCA | 0.5% | 3,000 | - | 15 psi |

* Exceeds tensile strengths of most optical substrates and adhesives implying substrate and/or adhesive deformation to relieve the stress.

**Table 3.** A first approximation of stress that commonly leads to failure in precision optics

**s shrinkage** **= (Shrinkage) x Modulus** **(Equation 1)**

$\sigma_{shrinkage/epoxy}$ = 0.01 X 750,000 = 7,500 psi (Equation 2)

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$\sigma_{shrinkage/OP\ 29}$ = 0.02 X 35,000 = 980 psi (Equation 3)

$\sigma_{shrinkage/OP\text{-}60\text{-}LS}$ = 0.0075 X 1,000,000 =750 psi (Equation 4)

## II. Stress Induced on Thermal Excursion

In addition to shrinkage, bonded optics can fail due to thermal stress. Thermal stress can be quite large even during mild thermal excursions. Assembly failures can happen when thermal stress is excessive. For example, when the stress exceeds the bond strength the adhesive, the adhesive delaminates; when stress exceeds the yield strength of the bonded optic or the adhesive, then the optical alignment suffers; and when the stress exceeds the ultimate strength of the optic or adhesive, then the optic shatters or the adhesive shatters or tears and the device falls apart.

When choosing an adhesive one typically tries to match the Coefficient of Thermal Expansion (CTE) of an adhesive to the CTEs of different substrates. If not closely matched, the resulting differential expansions create both stress and relative movement between bonded parts. Designers often use models to determine and minimize stress. If the model is well understood, then such calculations can be very accurate, predictive and able to handle very complex bonding configurations.

Complex stress models are beyond the scope of this paper. However, a simple model can provide us with a foundation for discussing stress and adhesive properties. The simplest model is that of an adhesive bound to one substrate as illustrated in Figure 3 below.

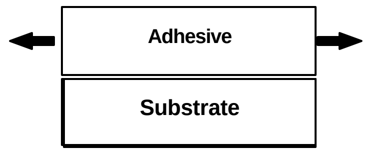


**Figure 3.** Simple model for Stress Calculation

For this system the thermal stress due to the adhesive, $\sigma_T$, can be described by a few simple material properties: $\alpha$, the coefficient of thermal expansion of the substrate and the adhesive; E, the modulus of elasticity (of the substrate and the adhesive) and $\upsilon_{adh}$ Poisson's ratio of the adhesive. $T_2$ & $T_1$ refer to the upper and lower temperatures.[1]

**(Equation 2)**

$$\sigma_T = \int_{T_1}^{T_2} \frac{\alpha_{adh}(T) - \alpha_{sub}(T)}{\left[\dfrac{1}{E_{sub}(T)} + \dfrac{1}{E_{adh}(T)}\right] \left(1 - \upsilon_{adh}\right)} dT$$

Even without performing the integration, the equation suggests the well-known result that the stress equals zero if the substrate and the adhesive have the same CTE at all temperatures.

Equation 2 is often approximated with the following expression[1]

$$\sigma_T = (\alpha_{adh} - \alpha_{sub}) * \Delta T * E_{avg}$$

**(Equation 3)**

where,

| | | |
|---|---|---|
| $\Delta T$ | = | Temperature Range, ºC |
| $E_{avg}$ | = | Average Modulus of the adhesive over the temperature range, psi |

This approximation is useful for some practical calculations. Equation 3 suggests that matching the CTE will zero the stress. However, controlling the stress by CTE matching is difficult and often impractical, as this method requires using a different adhesive for each substrate. It is also not presently possible to exactly match the CTE of glass with an organic based adhesive. Furthermore, the CTE of substrates and adhesives are both not consistent over a range of temperatures and differ from one another over a range of temperatures.

However, Equation 3 also implies that a low modulus adhesive will generate less stress than a high modulus adhesive having the same CTE. Since the modulus of commercial adhesives can vary from 10 psi to 10,000,000 psi, contributions to stress due to the modulus term in equation 6 should not be ignored. Clearly, a high modulus adhesive that experiences either shrinkage on cure or differential expansion will experience proportionally high stresses that can result in the fracture of the optical element. This contribution to stress can be even greater than with divergent CTEs.

(1) J.A. Emerson "Robust Encapsulation of Hybrid Devices" in Proceedings of 40th Electronic Components and Technology Conference 1990, IEEE, vol. 1, pgs. 600-605.

Most adhesives do not have the favorable combination of a low modulus and low CTE. Most adhesives fall somewhere along the line of having a low CTE and high modulus or a high CTE and low modulus. Table 3 compares the thermal stress of a commercial optical epoxy to that of two UV curable adhesives.

**Table 3:** Comparing the stress of thermal change

| Property | Commercial Optical Epoxy | No Shrink™ OP-61-LS UV Acrylic | No Shrink™ OP-30 Lens Bonding UV Acrylic |
|---|---|---|---|
| $\alpha_{adh}$ | 80 x $10^{-6}$ in/in/$^oC$ | 200 x $10^{-6}$ in/in/$^oC$ | 200 x $10^{-6}$ in/in/$^oC$ |
| $a_{sub}$ | 2.8 x $10^{-6}$ in/in/$^oC$ | same | Same |
| $\Delta T$ | -40 to 125$^oC$ | same | Same |
| $E_{avg}$ | 550,000 | 35,000 | 3,000 |
| $\sigma_{T\ calc.}$ | 7,000 psi | 1,100 psi | 100 psi |

## THE EFFECT OF GLASS TRANSITION TEMPERATURE

Some polymers have larger dimensional changes at the Glass Transition Temperature ($T_g$). than do urethane/acrylic polymers as used in DYMAX LCA's . (2) A resilient adhesive can exhibit both low stress and low TOTAL MOVEMENT. Table 4 compares published data from a leading optical epoxy supplier compared to selected DYMAX LCA's. DSC techniques tend to report the highest $T_g$ . However, since the most important property of interest to designers is movement and not heat absorption, TMA is the favored test method for optical design. Looking at the final column, the CTE from -45ºC to +200ºC is a measure of the TOTAL MOVEMENT, regardless of $T_g$ over the operating temperature range. The smaller the number, the smaller the movement between parts.

**Table 4**. Data comparison of leading optical epoxy supplier vs. selected No Shrink™ UV curing adhesives

| | Glass Transition ($T_g$) | | CTE ($X10^{-6}$ (by TMA) | CTE ($X10^{-6}$) (by TMA) | TOTAL MOVEMENT ($X10^{-6}$) (by TMA) ** |
|---|---|---|---|---|---|
| **Optical Adhesives** | **(by DSC)** | **(by TMA)** | **Alpha 1** | **Alpha 2** | **-45 to 200** |
| High $T_g$ positioning "Red" Epoxy (heat cure at 150ºC) | 120ºC* | 90ºC** | 56.0 | 139.0 | 87.0** |
| Commercial UV Curing Epoxy | 116ºC* | 57ºC* | 58.0 | 156.0 | 110 (est.) |
| OP-61-LS Positioning Adhesive | Over 120$^oC$ | 65ºC | 27.0 | 121.0 | 74.0 |
| OP-66-LS Positioning Adhesive | None detected | 125ºC | 27.0 | 66.0 | 50.0 |
| OP-4-20632 In Light Path Adhesive | NM | 100ºC | 45.0 | 105.0 | 90 |

NM = Not measured * Published values ** Tested value

(2) A more complete discussion of Tg, CTE and Total Movement can be found in "Movement between Bonded Optics", Nicole Langer and Dr. John Arnold, September 13, 2001, DYMAX Corporation.

## III. STRESS BIREFRINGENCE

Stress, whether from shrinkage on cure or from thermal excursions has the same result. In addition to fracture and delamination, birefringence can lead to optical failure. Figure 4, below shows a photograph of birefringence caused by the adhesive at three stress points. The birefringence radiates out from the stress points from a positioning adhesive as seen through a polarizer . Figure 5 shows adhesive-caused stress in a doublet boned over the entire lens surface.

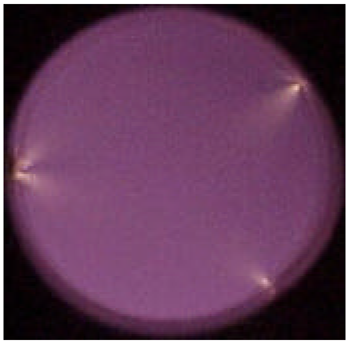

**Figure 4**. Birefringence as seen through a polariscope at each of a 3-point bond for a 1 inch diameter optic

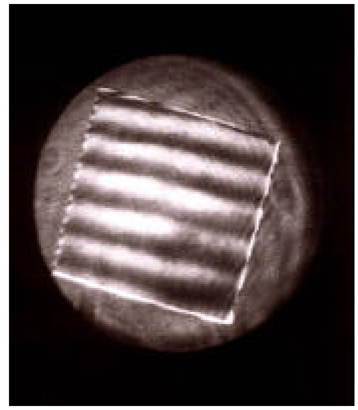

**Figure 5.** Lens, as seen through a polarized film

Birefringence (or double refraction) is a property of an anisotropic material where two differing indices of refraction exist for orthogonal planes of incident polarization. If polarization is not critical in your optical system, birefringence may not be catastrophic.. However, a lens can suffer transmission loss if bonded with a stress-causing adhesive. Such birefringence may not be apparent on bonding, but develop as slower curing adhesives develop full properties over time or the optics experience thermal cycles. Lasers and other devices are often polarization-coupled or have polarization dependent gain. In these cases, induced birefringence can be devastating.

Most optical elements are isotropic and have no natural birefringence. However, even isotropic materials can become anisotropic by the application of stress. Thus, stress can make an isotropic material birefringent, creating a pattern from which double refraction occurs. The pattern is best seen under polarized light and derives from the two differing indices of refraction that exist for orthogonal planes of incident polarization.

**SUMMARY**

This paper discusses the effect that stress can play in the quality of bonded optics. The effect of stress can be delayed for days, weeks or even months as some epoxies and “first generation” UV adhesives complete their cure cycles. New technology DYMAX Optical Adhesives that are designed to minimize stress while producing durable bond lines. Complete cures in seconds can enhance productivity and allow “on-line” quality control inspection.

DYMAX Corporation
51 Greenwoods Road
Torrington, CT. 06759
Phone: (860) 482-1010
Fax: (860) 496-0608
E-mail: info@dymax.com

DYMAX Europe GmbH
Trakehner Strasse 3, D-60487
Frankfurt am Main Germany
Phone: (49) 69-7165-3568
Fax; (49) 69-7165-3880
E-mail: info@dymax.de