Adhesives Deliver Low Shrink, Low Stress Bonds *and* Fast UV Cure

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ABSTRACT

Lower stress, higher quality assemblies as well as quantum increases in productivity are now possible with "new generation", light curing adhesives. This new technology makes obsolete the industry-accepted assumption that low strain requires slow curing UV adhesives, epoxies and cements. Curing in only seconds and without the need for secondary thermal cure, these new light curing adhesives produce laminates which are essentially strain-free, and edge bonds with shrinkage as low as 0.2%. This paper will compare and contrast these new adhesives with existing bonding technologies in typical applications. Included are comparisons between epoxies, UV curing mercaptoesters, and the new light curing Aerobic Acrylates, as well as the incorporation of adhesives into optical component design.

Keywords: Aerobic Adhesives, Adhesive, UV Cure, Light Cure, Acrylate, Bond, Cure, Dymax, Cement, USP Class VI

1. INTRODUCTION

UV adhesives for optics evolved from polyester based curing chemistry as early as 1940. Mercaptoesters and acrylic modified epoxies began being used for photonics in the late 1970s. These so called "first generation" optical UV adhesives are typically placed for several hours under low intensity UV lights, commonly called "black lights". It is common to accomplish black light cure with overnight or even longer manufacturing exposure cycles. Frequently, many weeks at room temperature or several days heat soak are then required to develop full adhesion and cure.

Now, new Aerobic Acrylic Adhesives (AAA's) have been developed specifically for optical assembly applications. AAA's are available in both industrial and USP Class VI approved grades.

This new technology offers better adhesive strength, lower stress, lower shrinkage, and very fast UV or visible light curing, resulting in reduced cycle times, higher productivity, and improved quality. Curing in only seconds, and without the need for secondary thermal cure, these new light curing adhesives produce laminates that are essentially strain-free. Edge bonds with shrinkage as low as 0.2% are easily available.

LOW SHRINK, LOW STRESS *AND* FAST CURE

- Low to very low shrinkage – 0.2%
- Low modulus = low stress
- Complete cure in 1-10 seconds
- High bond strength to 3,000 psi
- Positioning, bonding, encapsulation

In order to obtain the maximum benefit of this adhesive technology, it must be combined with UV curing lamps of moderate intensity. Low intensity black lights cure effectively, but at significantly lower production speeds.

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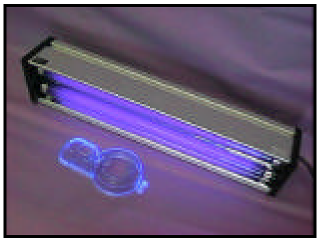
LOW INTENSITY LIGHTS FOR SLOW CURE



Black Light
(minutes to hours)

HHL-400
Low Intensity Spot Lamp
(for visible cure formulations)

HIGHER INTENSITY LIGHTS CURE AAA's COMPLETELY IN SECONDS

Bond Box™ Curing Chamber
(10-30 second wide area cure)

PC-3 Ultra Spot Lamp
(for spot cures in 1-5 seconds)

2. STRESS MANAGEMENT

Conventional wisdom has led to the misunderstanding that only the slow curing of UV or visible light curing adhesives will produce low stress optical bonds. This is because traditional, first generation UV curing formulations can be very slow to cure completely.

Early generation UV adhesives tend to exhibit high (5-15%) shrinkage on cure, leading to strain. Both slow curing techniques and multiple curing techniques have been used in an attempt to minimize stress from shrinkage. Slow curing should allow, theoretically, an internal flow of uncured adhesive to "fill the gaps" caused in shrinkage.

Strain is an inherent property of most adhesives and derives from the curing process itself. Either high modulus or high shrinkage or both can lead to stresses that induce optical defects. Table 1 illustrates that strain is an inherent property of and varies with the adhesive used. However, the modulus of a cured adhesive is not materially effected by the speed of the curing process. Induced stress is a function of its modulus, the chemical constituents of a formulation, and the strain from shrinkage on cure. Strain can be described by Hook´s equation **(1)**:

$$\text{Stress} = Y \times dl/l \qquad \textbf{(1)}$$

Y = Young´s modulus
dl/l = shrinkage

Clearly, lowering either variable lowers stress from strain. Lowering both variable is even more effective. Another method employed to minimize induced stress by the very oldest type of UV adhesives is to use resins that do not exhibit aggressive adhesion to glass. Assembly strength is dependent, to a large extent, upon the "vacuum" that forms between the surfaces as the adhesive cures. Many early UV adhesives that are still used today work by this mechanism, sacrificing permanence, tensile strength, and durability. This is a primary reason why many UV and Anaerobic (not aerobic) Adhesives have an undeserved reputation for lower performance when compared with epoxies.

2.1. AAA's offer alternative, proven strategies for minimizing adhesive bond line strain

New generation AAA's offer rapid fixturing ***and*** full cure within a few seconds. The phenomenon of increasing bond strength on glass over time, (measurable in approximately 30 minutes), is related to AAA's adhesion promoter reacting with hydrated silicon atoms on the surface of glass. It is not an indicator of complete cure. See Appendix II – Light Curing Aerobic Acrylic Adhesives: Composition and Curing.

Table 1 shows that new generation aerobic adhesives can provide new opportunities for increased productivity and lower costs. They offer a unique combination of low shrinkage and high tensile/shear bond strength with low strain and fast cure. See Appendix IV – History of Aerobic Acrylic Adhesives.

Table 1. Typical adhesive properties

Adhesive	**Cure Speed**	**Shrinkage on Cure**	**Tensile/Shear**	**Modulus**	**Strain**
UV Aerobic Acrylic Adhesives (AAA's)	Very fast	0.2-4%	2,000 -4,000 psi	500-5,000 psi	Low
Epoxy	Very slow (light) or fast (thermal)	1-6%	2,000 -5,000 psi	100,000 -1,000,000 psi	High to low grades
First Generation UV Adhesives	Fast fixture, then very slow for ultimate properties	5-25%	500-2,000 psi	1,000 -1,000,000 psi	High
UV Curing Anaerobic Adhesives	Fast	2-8%	2,000 -3,000 psi	10,000 -100,000 psi	High

2.2. AAA's – increase bond durability and lower stress

Faster curing UV Aerobic Adhesives are composed of monomers, oligomers and other ingredients that are designed to form low stress, high strength bonds. See Appendix II – Light Curing Aerobic Acrylic Adhesives: Composition and Curing. They are characterized by:

- Polymers with stress absorbing "Elastomeric Domains"
- High tensile strength bonds – 3,000 psi typical
- Low modulus for low stress
- Low shrinkage – as low as 0.2%
- Chemically bonding to glass and metal substrates
- Complete cure in seconds – one to 10 seconds typical

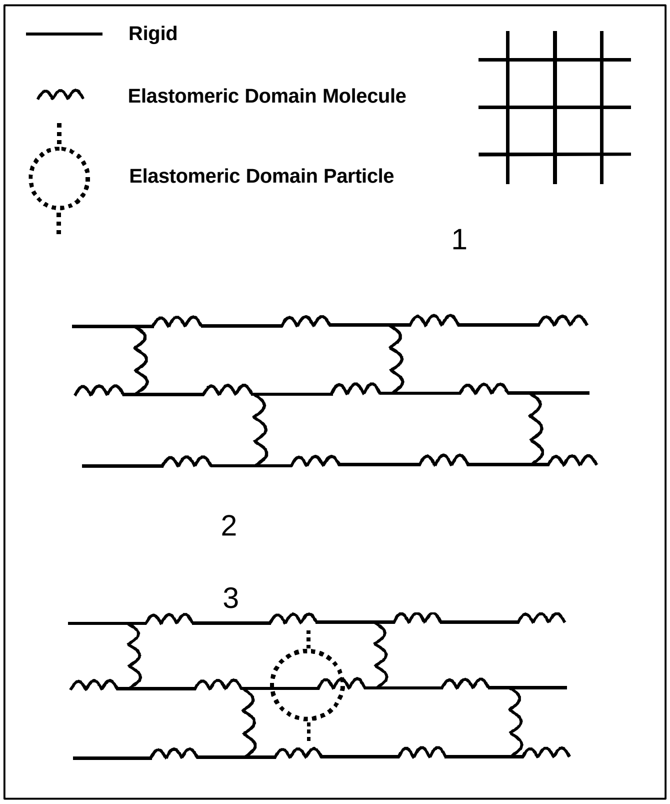
2.3. Elastomeric domains

Appendix II also shows how various proprietary formulation strategies are employed to deliver optimum bond strength. Original composition of matter patents includes U.S. #4,348,503 and U.S. #4,429,088. Originally formulated to deliver the maximum tensile/shear strength on metal, glass and ceramic surfaces when cured with either an activator or UV light[1, 2], Aerobic Acrylic Optical Adhesives combine formulation strategies to produce the characteristic of high bond strength with other unique properties required in optical applications.

Aerobic Acrylic Adhesives incorporate specific formulation strategies to lower modulus, incorporate the feature of elastomeric domains, and various ingredients, both organic and inorganic, that combine to minimize bond line stresses. These adhesives are formulated with a different degree of cross-linking, which minimizes shrinkage.

Figure 1 illustrates different degrees of cross-linking and shows how strain relief mechanisms can be "programmed" into molecules to take up stress from cure by utilizing elastomeric domains. These concepts are illustrated in the schematic illustration below. Properly selected, these domains can also lower Young's Modulus and, thereby, bond line stress. The expressed modulus remains low while still showing high specific adhesion.

Figure 1. Elastomeric domains



#1 represents the high degree of cross-linking and rigid bond lines typical of some early generation UV adhesives, epoxies and Anaerobic Adhesives.
#2 introduces the concept of elastomeric domain molecules.
#3 shows the addition of elastomeric domain fillers, the strategy followed in some Aerobic Adhesives.

2.4. A simple test for detecting stress on cure

A simple test can be performed to identify stress that might develop during cure. First, place two pieces of polarized lenses (such as the lenses from plastic polarized sunglasses) on top of each other at 90° angles. Then view the bonded lens through the polarized "sandwich" under sunlight or a strong white light. Induced stresses in the lens will be clearly visible by its birefringence pattern.

2.5. Thermal induced stress

In many applications, rigid epoxies and older generation UV adhesives often create stress relative to differences in coefficients of thermal expansion. Stress in optical components creates stress birefringence and optical distortion. Birefringence stress creates polarization sensitive changes, which in many cases affects performance. High temperature curing of many epoxies can create stress after cool down to room (and lower) temperatures.

Low modulus adhesives produce less stress on substrates than do high modulus materials and many new AAA's are available with very low modulus. Equation **(2)**[3] describes the shear stress produced by thermal excursions between the substrate and the adhesive bond. Table 2 demonstrates the relative stress inherent in different adhesives.

$$\sigma = (\alpha_{adh} - \alpha_{sub}) * \Delta T * E_{avg} \qquad \textbf{(2)}$$

where,

σ	=	Shear stress due to adhesive bond
α_{adh}	=	Coefficient of Thermal Expansion of Adhesive
α_{sub}	=	Coefficient of Thermal Expansion of Substrate
ΔT	=	Temperature Range
E_{avg}	=	Average Modulus of the adhesive over the temperature range

When choosing a resin system based on the relative shear stress that might be introduced, it is important to evaluate the processing cost and cure speed with the shear stress.

Table 2. Relative shear stress due to thermal expansion from -55/125°C for resins bonding to Aluminum 6061-T6.

Liquid Adhesive Resins	**Relative Shear Stress (psi)**	**Cure Speed**	**CTE Coefficient of Thermal Expansion, (x 10^{-6} in/in/°C)**	**Modulus (psi)**
2 Part Silicone	14	8 hours	340	250
UV Aerobic Acrylic Urethane (OP-30)	**95**	**10 seconds**	**200**	**3,000**
Frozen Filled Epoxy	810	3-4 hours	20	1,500,000
UV Mercaptoester	4,300	10 seconds	200	150,000
2-Part Epoxy Resin	6,345	1-3 hours	70	750,000

Some resins contain high levels of mineral filler in an attempt to lower both the shrinkage and the measured CTE and increase the Glass Transition Temperature (Tg). However, by choosing a low modulus material, the overall stress imparted upon an object will be much less dependent on CTE and Tg. Low shrinkage is not necessarily the prime determinant of stress.

Figure 2 shows that high modulus resins such as epoxies characteristically develop high stress rapidly and with only small physical changes. Stress is much lower and builds more slowly with dimensional changes in flexible resins. Figure 3 shows a bonded doublet assembly.

Figure 2. Stress/strain relationships

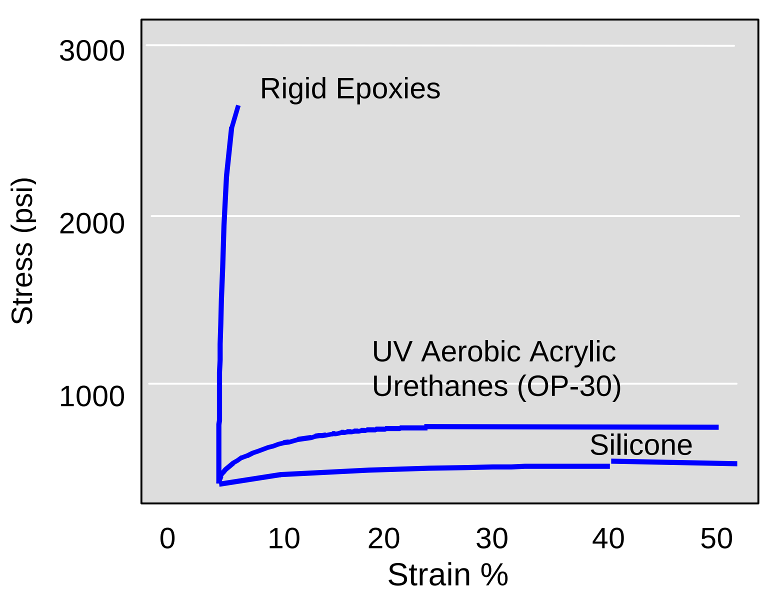
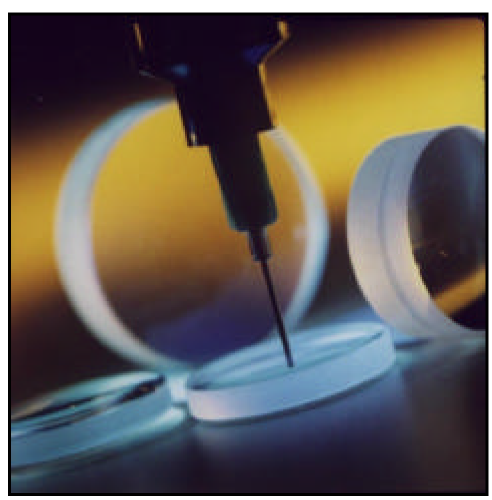


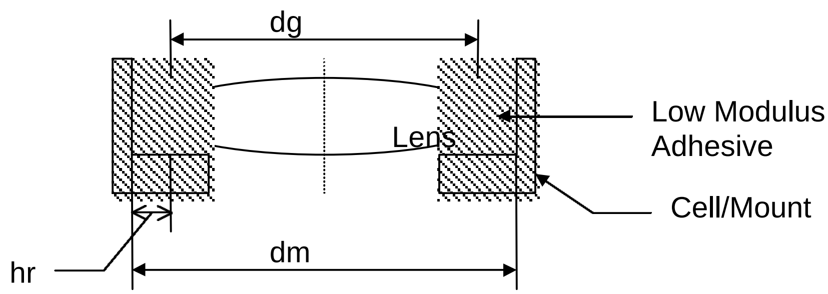
Figure 3. Doublet assembly



2.6. Stress in lens mounting

As lenses get smaller and bonds more delicate, the strategies to overcome the stresses inherent in the materials and between adjacent bonded surfaces, have become more exacting in order to survive the environmental rigors that the device will be exposed to. Choosing a material such as the Dymax OP-29 or OP-30 that is resilient and strong with low shrinkage characteristics may be ideal for an application of this type. Optimization of the adhesive in the bond line can be done with some calculations such as this simple model for calculating adhesive thickness for a lens mount. A preferred bond line might range from 0.002” to 0.005”, but can vary from 0.005” to 0.25” or more, with special applications requiring greater than a 0.25” bond line. Some applications such as pictured on the right utilize an adhesive placed into the mating threads and UV curing to mechanically lock and seal the lens to the housing.

Figure 4. Simple lens potting model[4]



For minimized stress on the lens:

$$hr = \frac{dg(\alpha_m - \alpha_g)}{2(\alpha_r - \alpha_m)}$$

Where: hr - Required Elastomer Thickness
dg - Lens Outer Diameter
α_g - Lens thermal coefficient of expansion
α_m - Cell thermal coefficient of expansion
α_r - Adhesive thermal coefficient of expansion

3. CURING LAMP CONSIDERATIONS

Choosing the right curing lamp for the application can be critical to obtaining maximum productivity and cure properties. Ideally, the light frequency and intensity of the selected lamp should match the curing chemistry of the adhesive. Other factors to consider include determination of desired throughput (whether batch or continuous process), and matching the lamp “footprint” with the area to be bonded. The optimum shape or pattern of light emitted by a lamp for any specific application is called its “footprint”, and depends upon the size and geometry of the bond area and other process recommendations.[5]

UV curing lamps are typically categorized as follows:

- **Spot -** Spot source lamps with light guides are typically used for curing small areas, or areas where light needs to be directed through partially obstructed areas that can not be easily reached.
- **Flood –** Flood sources offer a large cure area but generally lower light intensity. They emit less heat as well, and are usually the product of choice for bonding heat sensitive plastic parts. The large area of flooded light also is useful for curing many parts at once. Floodlights may be fitted over a conveyor or turntable for continuous product assembly.

- **Focused beam** – Similar in configuration to a flood lamp, the focused beam lamp concentrates light energy into a beam, (typically 1” x 6”), generating intensity higher than that of a flood. Focus beam lamps may also be used over a conveyor for continuous processing.

The lamps shown below represent a range of high speed curing equipment suitable for optical assembly applications from the Dymax Corporation.

Bond Box™ Flood Lamp

PC-3D UV Spot Lamp and Dispenser

Compact Cure™ Conveyor

Many applications require only lower intensity curing lamps. Bonding between surfaces, one of which allows light to pass, is one of the applications where resin may be effectively cured with lower intensity, lower cost lamps. Most UV formulations are capable of curing within 1 to 30 seconds through clear glass or plastic parts under lower intensity lamps. Because the inhibiting effect of oxygen is not present, cures are relatively fast. Bond lines are usually fairly thin - 0.001 to 0.125 inches.

Table 3. Typical adhesive and coating cure rates with a range of UV curing lamps

Lamp/Type	Moderate Intensity UV Flood 2000-EC	Higher Intensity UV Flood 5000-EC	High Intensity UV Spot PC-3Ultra	Very High Intensity UV Spot 3010-EC	Conveyorized Beam 2 x 1200-EC High Intensity	Conveyorized Electrodeless Lamps
Spectral Output of Lamps (nanometers)	300-500	200-500	200-500	200-500	200-500	200-500
Nominal Intensity (mW/cm^2)	20-60	175-225	1,000-2,000	1,800-5,000	225-275	1,700 – 2,000
Typical Adhesive Cure Rate						
(UV/Visible Cure Adhesive)						
Between Surface Cures (Glass)	1-4 sec	1-3 sec	<1-2 sec	≤ 1 sec	3-5 feet/min	5-20 feet/min
On Surface Cures*	40-240 sec	10-40 sec	2-10 sec	1-5 sec	1-3 feet/min	3-10 feet/min
(UV Cure Adhesive)						
Between Surface Cures (Glass)	2-6 sec	1-4 sec	1-3 sec	≤ 2 sec	2-4 feet/min	5-15 feet/min
On Surface Cures	30-600 sec	20-50 sec	3-5 sec	1-3 sec	1-2 feet/min	1-10 feet/min

Ranges represent the fastest and slowest cure times of Dymax formulations under the stated lamps.

*Some formulations never achieve a dry surface cure, though most do. The time range stated represents the fastest to the slowest curing products.

Upon selection of an optimal curing system, it is essential that a controlled assembly and curing process be qualified and documented. In order to assure bonding consistency, the process should never be modified from its original implementation without a re-qualification. Deviations from the established process could adversely affect the curing cycle, resulting in bond failures from uncured adhesive.

4. AAA Properties and Design Considerations

Table 4 is a summary chart of the property ranges of the new generation Aerobic Acrylic Adhesives for optical assembly.

Table 4. Typical properties for Dymax AAA's

Property of the Cured Resin	Property Ranges
Normal Cure Depth	1-500 mils
Cure Speed	1 to several seconds cures "typical"
Viscosity	10 - 200,000 cP – non flowing paste
Adhesion to Metals, Plastic & Glass	To 4,000 psi or substrate destruction
Clarity	Water white to transparent light, straw
Shrinkage	Low
Surface Dryness/Slickness	Dry surface cures
Moisture Resistance	Good to excellent
Hardness (Shore A&D)	A30 to D80
Resistance to Thermal Shock Under Load	Good to excellent
Solvent Resistance	Good to excellent

These new adhesives have been designed with the applications and concerns of the optical designer in mind. We will now turn our discussion to these design considerations and associated concerns and how the new adhesives respond to these challenges.

4.1. Other design considerations

Two common areas for use are glass to glass and glass or plastic to metal. In glass to glass bonding such as doublet, prism , or fiber optic assembly, the adhesive transmission and index of refraction are critical. Aerobic Acrylic Adhesives can be developed with excellent lens bonding properties and with a wide range of refractive indices. The instant curing, facilitated through UV or visible light, is well suited to doublet assembly.

Glass to metal or plastic to metal bonding, in applications such as lens, prism, mirror mounting, ferrule bonding, or fiber optic tacking, require other adhesive characteristics. Viscosity, shrinkage, speed of cure, flexibility, and tensile strength can be critical to the success of an application. A wide range of products may be utilized to match every application requirement. Adhesives such as Dymax OP-24 may be utilized for mirror bonding as the multiple cure methods offer many advantages over conventional epoxies. Dymax Multi-Cure® adhesives can cure with UV, visible light, activator (for room temperature cold curing between metal and metalized glass surfaces), or heat for areas not able to receive light for curing.

Some applications require an adhesive that passes the biocompatibility standards established by USP Class VI. Typically involving a medical device, these adhesives must be non-toxic when cured, as they will be coming in contact with human tissue or fluids. Applications may include imaging systems, endoscopic devices or lenses for ophthalmic surgical procedures. The Dymax 140-M series are being used in such applications where optically clear, USP Class VI adhesives are mandated.

4.2. Low shrinkage applications - pinning

Pinning applications, such as vertical-cavity surface-emitting lasers (VCSEL)[6], require an extremely low shrinkage adhesive. As operators align optical components, the adhesive can already be in place. Once the proper alignment has been obtained, a spot curing system can focus a narrow beam of light to the adhesive with subsequent cure in seconds with very little movement upon cure. It is important to cure multiple bond sites simultaneously to avoid uneven shrinkage, even with the low shrinkage values. Adhesives such as the Dymax OP-60 will maintain this position without moving over the life of the part, even at most operating temperatures and through thermal cycling due to the low coefficient of thermal expansion (CTE) value of 58×10^{-6} in/in °C. While for most applications, the correct light source will play a significant role in the shrinkage of the adhesive, these special resins maintain low shrinkage over a wide light intensity range. Figure 5 shows the same approximate linear shrinkage regardless of the energy of the light source. The time of cure is, of course, different for different light intensities. Figure 6 depicts a typical prism mount.

Figure 5. % shrinkage vs. energy for OP-60

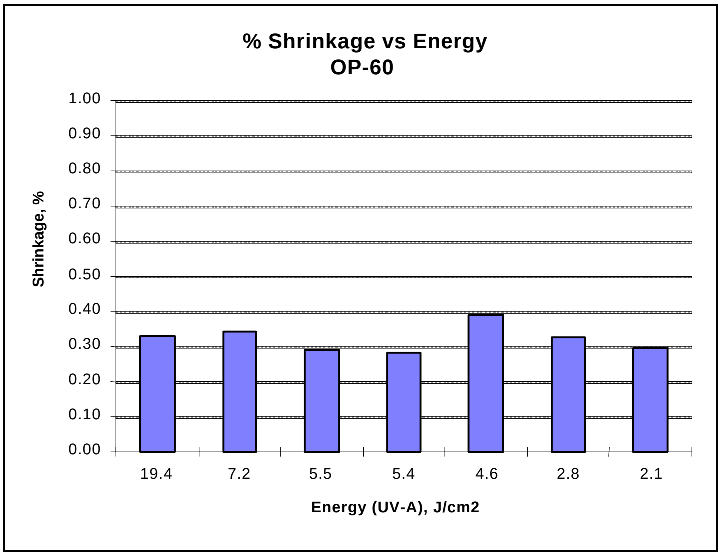


Figure 6. Typical prism mount

5. PHOTOCURING LIMITATIONS

As with any technology, there are applications that stretch certain abilities to impracticality. Photocuring adhesives requires light transmission to the bond area to effect cure. Therefore one of the surfaces must be transparent or translucent to permit light transmission. However, bonding techniques such as “bridge bonding”, have been successfully implemented that circumvent many seemingly impossible photocuring adhesive opportunities. (Bridge bonding is a technique whereby the adhesive is dispensed in a bead over a joint between two or more substrates, creating a surface bond when cured.) In addition, technological advances continue to enhance the sensitivity of light curing adhesives to visible light, which has the ability to penetrate through substrates that are nearly opaque. Another alternative is to incorporate a light-curing adhesive containing a secondary heat cure mechanism, such as the Dymax Multi-Cure® series. The majority of curing is still accomplished with UV and visible light. Remaining uncured adhesive shadowed by opaque surfaces can be cured with heat. Only through an evaluation of each new application can a fair assessment be made for the practicality of implementing a light curing bonding process.

SUMMARY

Understanding the functional differences between old and new generation UV or visible light curing adhesives permit the optical engineer to utilize the latest technology in developing manufacturing processes which offer increased productivity, reduced cost, and improved product quality. This paper has discussed the unique benefits of the new Aerobic Acrylic Adhesives for optical assembly, including their ability to produce low strain assemblies while curing in only seconds. This new generation adhesive technology can be implemented in existing adhesive bonding applications with only a minimum process modification. While curing rapidly under lower cost black lights, the highest productivity gains occur when AAA’s are coupled with higher intensity light sources.

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6. “VCSELs”, *Photonics Spectra*, September 2000, Pg. 155.

APPENDIX I - ADHESIVES AVAILABLE TO THE OPTICAL ENGINEER

Optical Engineers often consider adhesives to be the only reasonable method of mounting components. Adhesive use is a reliable approach that is cost effective and process-controlled. As with any assembly process, problems do arise. These problems include, but are not limited to material handling (shelf life/proper mix ratio/pot life); long cure times often at high temperature; application (tooling/training); and environmental concerns. Single component, light curing Aerobic Acrylic Adhesives reduce the occurrences of these types of problems, and are more suitable for continuous production processes. With improved performance these new generation adhesives are replacing many traditional adhesives. Table A provides a quick comparison of typical adhesives used in the optics industry.

Table A. Adhesives for optical applications

Adhesive	Aerobic Acrylic Adhesive	UV Mercaptoester	Epoxy	RTV Silicone	Cyanoacrylate
Cure Mechanism	UV or visible light	UV light	2-part mix or frozen	Moisture	Moisture
Typical Properties	Resilient - hard to very flexible	Resilient – hard to very flexible	Very hard and brittle	Very flexible and soft	Hard and brittle
Time To Full Cure	Tack in seconds Full cure in minutes	Pre-cure in seconds Post cure for minutes Post bake	Minutes to hours	Hours	Seconds
Odor	Low	Pungent	Low	Low	Pungent
Storage	1 year, room temperature	4-6 months refrigerated	Various	1 Year	4-6 months refrigerated

Light curing Aerobic Acrylic Adhesives - offering a wide range of options

A tough, resilient urethane polymer backbone gives Aerobic Acrylic Adhesives high strength, toughness, and resiliency as well as a range of properties from rigid to flexible, from very hard to very soft, depending on the formulation. Formulations can come in a range of viscosities, from thin wicking grades to thixotropic gels. These adhesives cure “on demand”, allowing the operator to position the lens before affecting cure. UV curable resins can be cured with UV light only. Light curing Aerobic Acrylics, some termed “Ultra Fast™, cure with UV or visible light and offer the benefit of being able to cure even through UV blocked plastic, such as polycarbonate, polystyrene, and polymethylmethacrylate (acrylic). Multi-Cure® formulations offer the ability to cure with heat as a secondary cure method, permitting cure in a shadowed area.

Light curing Aerobic Acrylate Adhesives cure by a free radical polymerization as depicted in Figure A below. Cure is generally complete within a few seconds though optimum glass adhesion may take longer due to the slower reaction rate of adhesion promoting additives.

Figure A. Free Radical Polymerization

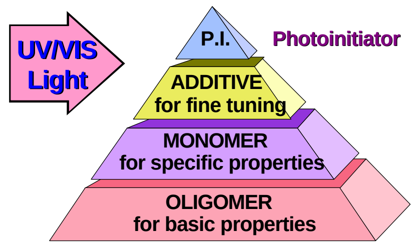
>C=C< + R• → R-C-C•	Free Radical Initiation
R-C-C• + >C=C< → R-C-C-C-C•	Chain Extension
R-(-C-C-)$_n$-C=C< or R-(-C-C-)$_n$-C-C-R	Termination

Discussion of other adhesive options used in optical applications can be found in Appendix II – Light Curing Aerobic Acrylic Adhesives: Composition and Curing.

APPENDIX II – LIGHT CURING AEROBIC ACRYLIC ADHESIVES: COMPOSITION AND CURING

UV curable acrylates are comprised of oligomers, monomers, additives, and photoinitiators. These formulations can be tailored to provide optically clear resins with specific refractive indexes, adhesion, weatherability, resistance to UV light, etc. Oligomers are medium length polymer chains that contribute to tensile strength, modulus, and elongation. Monomers provide adhesion to different substrates. Additives can provide a wide range of viscosities to allow for easier dispensing, or can be incorporated as fillers for extremely low shrinkage.

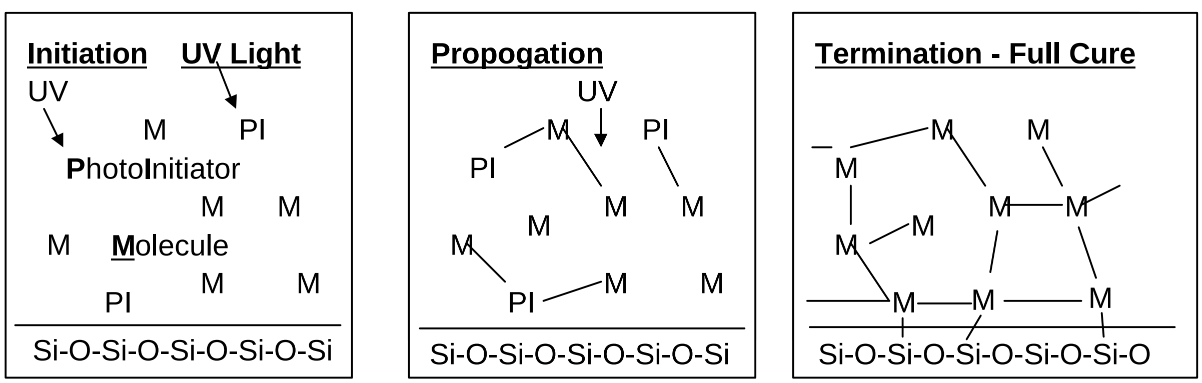
Figure A. Typical light curing Acrylate Adhesive



The UV adhesives cure upon exposure to UV light in the 300-400 nm range of the electromagnetic spectrum. (Figure C). UV/visible light curing adhesives cure in the 300-500 nm range, which allows for curing to deep sections, faster cures, or cure through UV blocked substrates. Using a visible light curing adhesive also allows for faster cures using a lower intensity, low power light source, an advantage when considering the cost of light sources.

All light curing formulations include, in addition to the basic resin chemical constituents, oligomers, monomers, thickeners, adhesion promoters, etc. Photoinitiators that react when exposed to light of the correct wavelengths cause polymerization of the resins. These photoinitiators are organic molecules that can absorb light and produce radical species upon splitting. It is these radicals that initiate the polymerization of the monomers and meth(acrylate) oligomers. The final adhesion to glass and metal is developed by secondary reactions with adhesion promoters directly to the silicone atoms in the glass within 1-60 minutes to gain a 10-200% increase in compression strength. (Figure B).

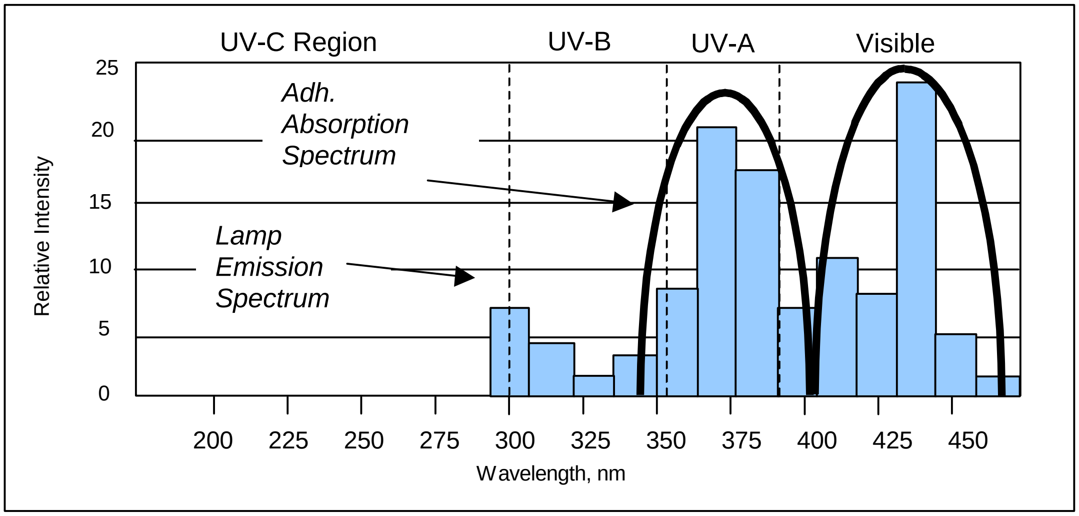
Figure B. Free radical initiation, propagation, and termination/adhesion to glass surface



Aerobic Acrylic Adhesives are designed to be sensitive to those areas of the electromagnetic spectrum which allow the optimum combination of speed and depth of cure for assembly applications. Formulations that cure only with UV light are primarily triggered by longwave UVA spectrum. Formulations for bonding through UV inhibited surfaces, combine catalysts from both the UV and visible regions and generally produce faster and deeper cures.

Shown in Figure C is the lamp's spectral output matched to an adhesive's spectral absorbency, indicating a synergy between the curing lamp and the intensity and wavelength that the adhesive needs to cure.

Figure C. Matching the lamp's spectral output with the absorption spectrum of the adhesive



APPENDIX III - COMPARISON OF AEROBIC ACRYLIC ADHESIVES WITH OTHER ADHESIVES USED IN OPTICAL ASSEMBLY

UV curing mercaptoester

Long a “standard” in optical assembly, thiol-ene polymer (a.k.a. mercaptoesters) systems can yield sealants or adhesives that range from hard to soft. Some formulations contain solvents and may be flammable. Initiated by UV light, thiol-enes cure by an addition mechanism as shown in Figure A. Most commercial literature indicates that a significant amount of time is required for cured properties to fully develop. Post cures of at least one week at 50ºC (122ºF) are frequently required according to conventional literature.

Figure A. Mercaptoester polymerization

$>C=S< \quad + \quad R+ \rightarrow R-C-S+$ Addition Reaction Initiation

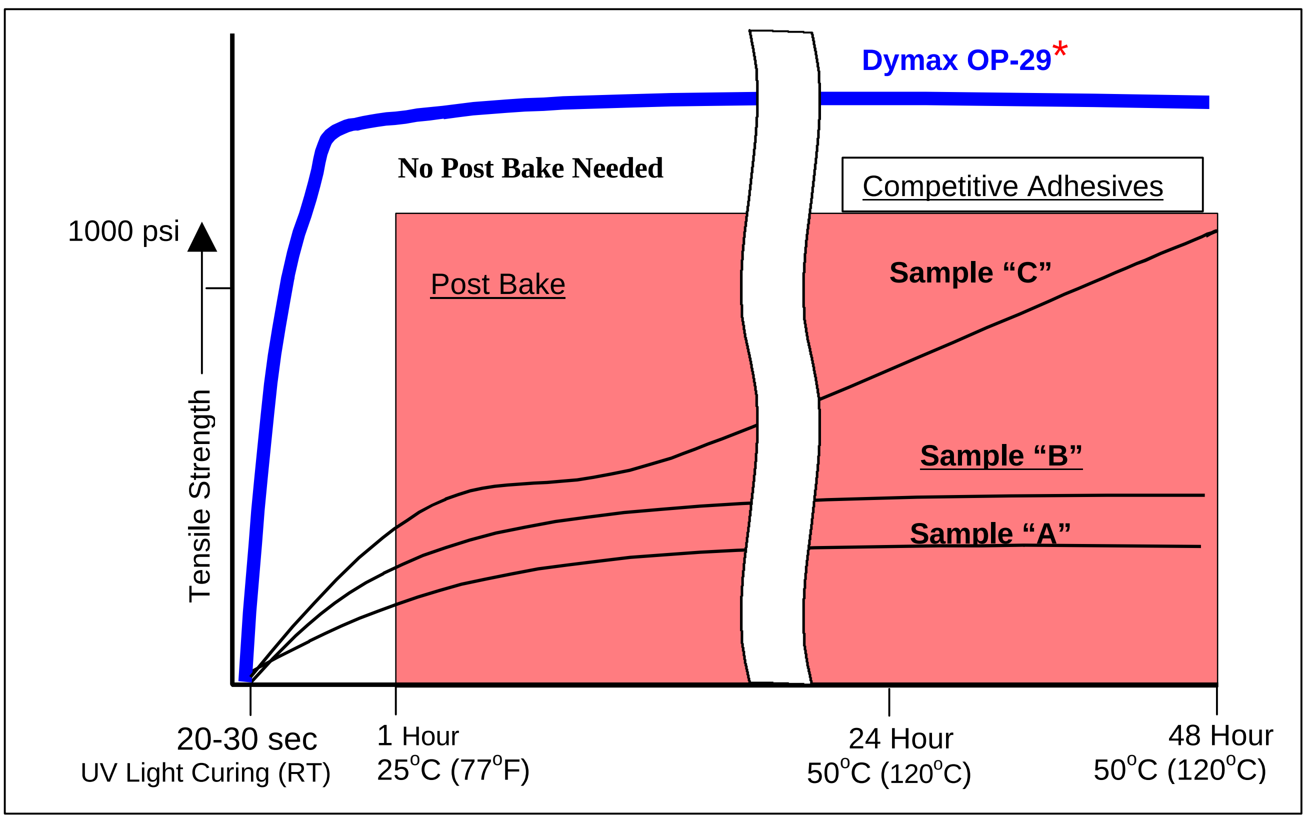
$R-C-S+ \quad + \quad >C=S< \quad \rightarrow \quad R-C-S-C-S+$ Chain Extension

$R-(-C-S-)_n-C=S<$ or $R-(-C-S-)_n-C-S-R$ Termination

Both the Anaerobic Acrylic Adhesives and the mercaptoesters cure upon exposure to UV light though the cure chemistries are different. Does this difference in composition then, result in a difference in performance? Laboratory testing of these two types of UV curing products in conjunction with a review of published literature has shown some significant distinguishing features.

Figure B below shows a significant increase in both the speed of cure and strength of the Aerobic Acrylic Adhesives compared with the mercaptoester based adhesives.

Figure B. Compression strength versus time following UV cure



During UV cure, adhesion promoters become part of the polymer matrix, which after cure, can react with the glass surface to show a 10-200% increase in compressive strength. This increase is due to a secondary cure mechanism that forms strong covalent bonds directly to the silicone atoms in the glass. See Figure 6 for more information.

Epoxies

Typically used when induced stress or speed of cure are not important, epoxies can provide durable, rigid structures for high temperature applications. There are a wide variety of systems. Typically, epoxies fall into one of three categories; two-component systems, one-component heat cure systems, and one-component frozen systems. However, all present processing problems, ranging from limited pot life and slow cure to special storage. Two-part epoxies typically require 24 hours for full cure. Heat curing types, whether premixed, frozen or a true single component grade, usually requires exposure to 120º - 150ºC heat.

UV curing epoxies

While similar in properties to heat curing epoxies, UV curing epoxies are typically lower in adhesive strength, especially to glass and metal. Older types of UV epoxies bond parts together by efficiently forming a vacuum between closely matched surfaces. Their greatest advantage is low shrinkage and good thermal stability. UV curing epoxies cure as fast or faster than other UV curing adhesives in very thin layers. However, their depth of cure is very limited and that coupled with lower adhesion has tended to limit their use in many assembly applications.   Lower durability is frequently observed.

Figure C. Epoxy and UV epoxy polymerization

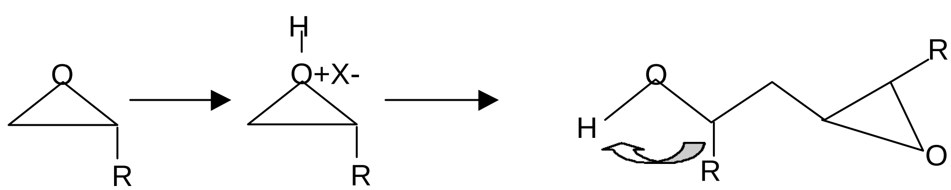


Table A. Cure time comparisons of Aerobic Acrylic Adhesives and epoxy systems

	UV Aerobic Acrylic adhesives	**Conventional UV Epoxy**	**2-Part Epoxy**	**1-Part Thermal Cure Epoxy**	**Frozen 1-Part Epoxy**
Speed of Cure to 0.125”	15-30 seconds	120 minutes or longer	10-50 minutes	15 min - 2 hours @ 100 -150^{o}C.	3 hour thaw; 10-50 minutes
Time to Reach Full Strength	20 minutes	24 hours	24 hours	24 hours	24 hours
Pot Life	Unlimited	Unlimited	5-60 minutes	Days @ room temperature	10-50 minutes @ RT

Silicones

Silicones have a highly flexible polymer backbone and are usually used in gasketing and sealing applications. Two-part mix silicones cure in a few minutes while one part “RTV” types need controlled humidity and many hours to many days to cure fully.   There are a few types of UV curing silicones. Most are used as release agents. Other types on the market are simply mixtures of UV curing acrylics and RTV silicones. As with other RTV types, full cures require long exposures to humidity.   Most RTV silicones give off other chemicals on cure (outgassing) which may fog or even damage precision optical components.

Cyanoacrylates (CA’s)

Rigid and brittle CA’s (superglues) cure in seconds upon contact with the moisture that is naturally absorbed on almost all surfaces. Some plastics require priming. Many CA’s effloresce on cure, resulting in a “frosting” effect that can effect both appearance and the clarity of optical components. Though depending on it for cure, CA bond lines are quite sensitive to and degrade with exposure to too much moisture. Most CA bonds are not shock resistant.

APPENDIX IV – HISTORY OF AEROBIC ACRYLIC ADHESIVES

UV curing is almost as old as civilization itself. Certain dyes used to preserve Egyptian mummies had to be dried (cured) in sunlight. UV curing resins found their first commercial use during World War II to protect acrylic windows, nose cones and firing “bubbles” for military aircraft. The late 1970’s saw large-scale acceptance and use of UV curing acrylic resins by the ink industry as an alternative to solvent-based inks. In the early 1980’s UV curing Aerobic Acrylic Adhesives (were introduced to the assembly industry. Aerobic Acrylic Adhesives have the ability to cure between two surfaces regardless of the presence or absence of air. The absence of hydrocarbon-based solvents makes the choice of these adhesives much more environmentally safe than conventional adhesives. Recent improvements in Aerobic Acrylic Adhesives have yielded performance properties that equal or exceed epoxies as shown in Table A below.

Table A. Adhesion of various UV resins

		UV Aerobic Acrylics	UV Aerobic Epoxies
Tensile Strength	Steel	>3,000 psi	>500 psi
per ASTM D1002,	Glass	>2,000 psi	>1,500 psi
DSTM 250, DSTM 251	Plastic	Generally exceeds material strength	>100 psi
Speed of Cure:	1 mil	~ 2 seconds	~ 2 seconds
	20 mil	< 5 seconds	< 5 seconds
Surface Finish:		Some may have oxygen inhibition	Dry

The principal advantage of Aerobic Acrylic Adhesives include:

- Lower costs
- Faster cure times
- Simpler application
- Environmentally safe
- Long shelf life
- Room temperature cures
- Less material waste
- Higher production yields
- Elimination of complex jigs and fixtures
- Overall reduction in production times

For all of these reasons and the strength and durability of the bonds formed, Aerobic Acrylic Adhesives began replacing heat curing and two-part epoxies, urethanes and silicones in most applications where light could reach them to effect cure. Since the early 1980’s, use and acceptance of these products has cut across the industrial spectrum to include uses in automotive motor and lighting assembly, aerospace, optical, military and industrial electronic assembly, appliance, medical disposable device assembly and electrical and architectural applications, to name a few. In addition, Aerobic Acrylic Adhesives are able to operate over a wide temperature range, from –60°C to 200°C, depending on the adhesive. Table B lists some typical applications for which these adhesives have been used. Figure A pictures a bonded headlamp assembly.

Table B. Typical applications

Typical Applications for Aerobic Acrylics
Glass and plastic headlamp assembly
Electrical sealing and tacking
Optical component assembly
Microelectronic assembly
Dome coatings
Conformal coatings
Medical disposable device assembly
Coil terminating
Tamper proofing
Fingernail coating
Formed-in-place gaskets

Figure A. Headlamp lens assembly