

# Choice of Structural Adhesives

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OPTI 521 Tutorial by Tianquan Su

## **Abstract**

This tutorial focuses on introduction to polymer adhesives. Basic principles are introduced about choice of polymer structural adhesives used in opto-mechanics. The fundamentals of adhesives are addressed. Main classes of polymer adhesives and their properties are described. Basic steps are provided to help make choice during designing.

## **Introduction**

Various adhesives have found welcome places in optical instrument design and manufacture as replacements for screws, rivets, clamps, and other forms of fasteners. When used in structural bonding applications, they always function as integral components in the ensemble rather than as separate entities. Bonded structures are often lighter in weight, lower in cost, and easier to assemble than those made by mechanical methods. They also distribute stresses more uniformly than mechanical fasteners and are more or less flexible. This is a highly desirable feature in some applications involving high mechanical forces or when damping is needed. Among common adhesive material classes, such as polymers, metals (solders), and inorganic glass powders ("frits"), polymers are the most widely used ones. The following discuss will focus within polymers.

## **Adhesive fundamentals**

The basic function of adhesive is to join parts. They offer convenient or cost-effective alternatives to conventional joining methods such as soldering, welding and bolting. Some materials need adhesively bonded joints for optimum or adequate performance, for example: joining of notch sensitive "brittle" materials that are intolerant of bolt holes (e.g., engineering composites, ceramics, and glasses). Some common adhesive material classes are: polymers, metals (solders), and Inorganic glass powders ("frits", solder glasses). Polymer adhesives are the most commonly used bonding agents.

Polymer adhesive technology advances rapidly. So survey current offerings before you pick adhesive for a new application or review an old application. Do not assume "rules" forever hold true, such as "epoxies are brittle." New nano processing technologies, such as polymer chain engineering at the molecular level, are re-writing the rules. The mechanical properties of adhesives have not been fully understood even by experts, so beware when choosing proper adhesives!

## **Chemical fundamentals**

The polymerization chemistry of commercial adhesives is usually complex. An initiator (cross-linking agent and/or a catalyst) is purposely introduced to trigger the polymerization reaction of the "base" material & "cure" the adhesive. There are two popular cure systems:

- “two-part” system: the initiator is mixed into the base just before use.
- “one-part” system: the initiator is water vapor that’s introduced to base by exposure to ambient air.

One-part systems cure by diffusion of initiator thru the bond (years may be needed for a thick bond to fully cure). Two-part systems cure uniformly throughout the bulk and so are preferred for thick section bonds. Both one-part & two-part systems nearly always emit reaction products that may be corrosive (e.g., acetic acid) or flammable (e.g., methanol). One needs to read the data sheet to find out what they are for particular adhesive. If the reaction products are not removed by diffusion, the curing reaction will slow down & possibly reverse itself (depolymerization or “reversion”). Thus ventilation is necessary during curing.

Bulk physical properties (e.g., mechanical properties, thermal properties, etc.) depend on monomer properties & chain structure, so they are not influenced by the chemistry and physics of interfaces.

Interface properties (adhesion) influence the fundamental bond strength between substrate and adhesive. It is controlled by surface chemistry. During cure, full adhesion properties typically develop hours or days after bulk properties. As surface chemistry is notoriously susceptible to trace quantities of molecular compounds, attention is called to purity of cleaning chemicals and solvents; chemical compatibility of storage, mixing and applicator materials. Like any property that depends on surface or interface chemistry and physics, adhesions can possess bewildering complexity. Commercial adhesives often contain small quantities of molecular compounds to promote adhesion.

Some adhesive formulations, when used with certain substrates, require adhesion promoters (primers) - the property data sheet should tell you this. Precisely how adhesion promoters work is rarely understood - formulation of promoters is a quasi-empirical, black art. Their use must be tested in specific applications.

Temperature and humidity generally play important roles in primer activation, and must be monitored & controlled if possible.

Surface cleanliness is critical to adhesion. A consistent surface preparation technique, executed by process procedures, is essential.

### **Mechanics fundamentals**

Strength of certain adhesive is defined here as stress at rupture. Rupture is due to propagation of damage through the bond. When damage accumulates to a critical level, the bond ruptures. Because strength depends on the rupture condition, its fate is tied to the details of damage evolution. The rupture condition for a given material cannot be predicted from the laws of mechanics alone. Experimental data are needed (e.g., toughness – a material property, flaw size – usually a specimen property that can vary significantly).

Adhesive bond damage includes many different specific mechanisms such as:

- Initiation and growth of quasi-homogeneously distributed damage such as microcracks or microcavities.
- Initiation and growth of a discrete crack.

Damage initiation begins at the atomic level and so is fundamentally governed by quantum physics. When the spatial extent of damage is sufficiently large & homogeneous, classical field equations and the laws of continuum mechanics can be used to characterize damage. Classical fracture mechanics is a special damage case where evolution of a discrete, well-defined crack is described by the laws of continuum mechanics and constitutive laws for sub-critical crack growth (e.g., chemically-assisted crack growth).

Critical damage usually appears first at corner or edge fillets due to localized stress concentrations plus direct exposure to corrosive species in the environment

Fractography (analysis of fracture surfaces) often gives valuable insight into the damage evolution process. (So preserve your test specimens.) Accurate and full interpretation of fracture surfaces is an expert, specialized skill usually practiced by consultants. A few textbooks discuss fractography.

The precise way that critical damage accumulates in a given material varies from specimen to specimen even with specimens of the same geometry under the same loading condition. Hence strength, which depends on the critical damage level, is not a true material constant. The apparent exception of note is the (ultimate) strength of ductile engineering alloys with or without notches. But the constant strength approximation breaks down in extreme cases where a notch is present in a very large specimen.

## Properties of common polymer adhesives

### Epoxies

Epoxies are the most widely used polymeric materials for adhesives. Epoxy resins are versatile thermosetting resins. As a class, they offer unique versatility in application and performance, and are formulated as liquid, paste, tape, film, and powdered resins. Their most desirable properties include high bond strength to a wide variety of different substrates, outstanding gap filling capabilities, excellent electrical insulation, high chemical inertness and outstanding resistance to shock and vibration.

The liquid and paste forms are widely available as one- and two-part types. Two part systems can be cured at either room temperature or elevated temperature. But they have a finite pot life. One part systems



must be cured at elevated temperatures (typically 250 - 300°F). Better thermal and mechanical properties result if they are cured at temperatures up to (typically) 350°F (175°C). One part systems curable by UV light are also available.



Some types contain powdered metals or other fillers to improve their properties for particular uses. For example, silver powder increases electrical conduction, aluminum oxide enhances thermal conduction, and silica powder serves as a thickening agent. Viscosities and cure times can be tailored to meet specific application requirements.

### Acrylics

Chemically, structural acrylics are acrylated polymers of various types. The most common is acrylated urethanes. Available in one- and two-part forms, the urethane (or polyurethane) adhesives form strong, durable bonds to many types of substrates. Some of the most noteworthy properties of polyurethane systems include outstanding flexibility, abrasion resistance, superior physical strengths and gap filling properties. Because of their inherent flexibility, they are especially appropriate for use in bonding non-rigid components or ones with differing CTEs. Environmental resistance is inferior to that of the epoxies. Service operating temperatures range up to 250°F. Certain polyurethane systems have been formulated to adhere well to difficult to bond substrates. Others provide high optical clarity.

Photocatalyzed acrylic adhesives are known as LCMs. One of their advantages is an almost instantaneous cure or fixture. Bonded joints also have high peel strength and toughness. Compared to Cyanoacrylates, they generally have superior properties, particularly in the areas of moisture and heat resistance.

### Cyanoacrylate

Cyanoacrylates are single-component adhesives that cure by exposure to the alkaline moisture and ionic substances found on most surfaces at room temperature. For best adhesion to inert or acidic surfaces, a surface activator (or primer) may be applied to speed polymerization. Since they have low viscosity, they work best on smooth, closely spaced surfaces. These adhesives are fast and easy to use. They do not need any mixing or heat and require only contact pressure to obtain durable high performance bonds. Cure time to fixate is usually very short, typically less than 30 sec under favorable conditions. Some varieties contain elastomers that increase flexibility and gap-filling capability. Additives of this sort tend to increase cure time. Care in application is advisable since the adhesive will quickly bond skin. Full eye protection should be worn during application.

The limitations of such adhesives include a potential for failure at temperature above 71°C (160°F), especially at high humidity. The strength of the bond on glass or ceramics may decrease



with time. Vapor emitted by uncured adhesive and deposit on adjacent surfaces, leaving a white residue. Be aware that this can ruin coatings on optical components.

### UV-curable adhesive

UV-curable adhesives include polyurethanes, epoxies, polyesters and acrylics. They vary in thicknesses, hardness, chemical resistance, strength, clarity, etc. When exposed to a suitable UV light source, UV curable compounds usually cure in a matter of seconds. Upon cure they exhibit minimal shrinkage. They have a long shelf life when stored at ambient temperatures in the absence of UV light. They have excellent bond strength to metals, ceramics, many plastics and most rubbers. Additionally, they offer superior temperature and chemical resistance. If required, special formulations can be developed to best meet specific product application and performance needs.



### Silicones

Silicones are elastomeric systems with the unique combination of flexibility and high temperature resistance. Silicone systems are either one or two part. One part systems cure by moisture in the air. Two part systems are cured by the polymerization reaction that occurs when a curing agent is added. Generally, the two part systems can cure in thicker sections than the one part systems.



Aside from temperature resistance and inherent high flexibility, other noteworthy properties of silicones include excellent resistance to water, superb electrical insulation properties and sealing/adhesive properties particularly to glass, plastics, metals and rubber

(including silicone rubber itself). Their inherent flexibility allows for "repairability" when this property is needed.

Table 1: Properties of Structural Adhesives. (from machindesign.com)

<b>PROPERTIES OF STRUCTURAL ADHESIVES</b>					
Material family	Epoxy (two part)	Silicone (one part)	Cyanoacrylate	Acrylic (LCM)	Acrylic
Cure method	Reaction (two-part mix or one-part heat)	Moisture	Moisture	UV or visible light	Activator or heat
Time to attain handling strength	15 min to 2 hr	30 min	10 to 30 sec	0.5 to 5 sec	(Heat) 30 to 90 sec (20 to 30 min)
Time to attain full strength	12 hr	24 hr or more	24 hr	30 sec	24 hr (20 to 40 min)
Tensile-shear strength,* (psi)	5,000	<500	3,500	2,500 to 4,000	2,500 to 3,000
Useful temperature range, °F	-65 to 450	—	-75 to 300	-85 to 400	-85 to 350
Suitable substrate materials	Plastics, glass, metals	Glass, rubber, most plastics	Glass, rubber, most metals, thermoset plastics	Glass, most plastics (including plasticized PVC), most structural metals, ceramics, ferrites	Ferrites, metal, glass, ceramics, filled plastics
Properties of bonded joints	Good toughness and impact strength, excellent environmental resistance, good hardness, excellent gap filling (depth of cure almost unlimited), exothermic cure process (can damage some plastics)	Heat and weather resistance, low bond strength, excellent gap filling (depth of cure almost unlimited)	Excellent strength (with some materials, bond can exceed strength of substrate), poor impact strength, film "bloom," poor gap filling (depth of cure <0.010 in.), poor flexibility, properties degrade at high temperatures and humidity, can cause stress cracking in thermoplastics	High peel and tensile shear strength, excellent toughness and impact strength, good gap filling (depth of cure up to 0.5 in.), selectable hardness and viscosity based on formulation	Same as for LCM except that gaps are limited to 0.020 in. and they cure only between surfaces unless they are a multicure grade which means that they are also photocatalized so that exposed surface can be cured with light.

\*Conventional tensile strengths have little relevance to adhesive bonds; strength is measured as "tensile shear" where bonded, overlapped surfaces are pulled in opposite directions, or as "peel" strength where one bonded surface is curled back over the other surface.

Values represent averages or ranges of those within polymer families.

Table 2: Properties of representative structural adhesive (from Vudabratovich)

ADHESIVES PROPERTIES							
ADHESIVE	Joint Strength	Temperature Range	Thermal Coefficient of Expansion	Cured Flexibility	Outgassing		Use
Parameter			$\alpha$		Percent Total Mass Loss	Condensable Volatiles	
Units	Pa	°C	m/m-K		%TML	%CVCM	
3M EC 2216 B/A	1.70E+07	-55 to +90	1.02E-04	Moderate	1.01	0.05	General purpose, widely used for lens-to-mount bonding
Abelfilm 506	9.60E-06	-55 to +150	3.15E-04	Good	0.9	0.32	Prism bonding
Dow Corning 732	2.20E+06	-55 to +200	3.10E-04	Excellent	NA	NA	RTV, high outgassing
Dow Corning 93-500	6.89E+05	-55 to +155	3.00E-04	Excellent	0.25	0.05	Space qualified RTV
Epo-tek 302-3M	8.90E+06	-55 to +125	6.00E-05	Moderate	0.7	0.01	Clear epoxy for optical bonding, space qualified
Epo-tek 353ND	1.38E+07	-55 to +225	5.40E-05	Moderate	1.14	0.01	Fiber optic applications
General Electric RTV142	3.78E+06	-60 to +204	2.70E-04	Good	0.17	0	White RTV, low outgassing
General Electric RTV88	5.90E+06	-54 to 260	2.10E-04	Excellent	NA	NA	Red RTV, high outgassing
Norland 61	1.93E+07	-60 to +125	2.40E-04		2.36	0	UV cure, optical adhesive meets military standards
Summers Milbond	1.45E+07	-60 to +100	7.20E-05	Moderate	0.98	0.03	Glass-to-metal prism bonding

## Choice guidelines

“Golden rules” for design with adhesive:

- Never conceptualize a design that requires a critical adhesive bond without addressing the bond problem early on.
- Always use pedigreed engineering adhesive.
- Do not use adhesive if very-high, quantifiable bond reliability is required for a long time (>10 years) unless hard data or past experience prove that the specific adhesive meets the requirements under all conditions.

There are some preparations you need to achieve before you make your decision:

- Detailed stress analysis.
  - Analyze the exact bond geometry in detail, especially stresses near corners and fillets. Critical damage will nearly always initiate in the region of highest stress.
  - Analysis must include all driving forces such as: residual stresses caused by bulk expansion/contraction of adhesive during curing and differential thermal stresses.
- Operating environment details.
  - Temperature, humidity, chemical species present.
  - Extreme environmental conditions and the time spent at those conditions.
- Substrate particulars:
  - Standard metallic alloys: specify alloy designation (AISI, SAE), heat treatment condition & other form/physical conditions.
  - Glasses & ceramics: specify chemistry, physical properties, anneal condition.
  - Polymers: specify chemistry & physical properties.

Some points cannot be ignored during adhesive application. Opto-mechanic designers who have no idea about these will probably make bad choices. So one should keep these in mind when choosing adhesives.

- Close attention is needed to the operational temperature range. Polymers become brittle and show remarkably different properties when taken below their glass transition temperature ( $T_g$ ).
- Polymers creep at widely different rates. If bond dimensional stability is important, be aware of creep. Creep rate usually increases exponentially with temperature and sometimes applied stress. Creep rate also increases with humidity level for most adhesives.

- Bond longevity: What is the reliability requirement? What is the average lifetime requirement?

When you are clear what performance you want, you can start the data collection. You are supposed to compare all of the forgoing requirements to published adhesive property data. Does the adhesive meet all requirements under all operating conditions? What vital adhesive property information is missing? If the known property database does not address all requirements, you have a potentially serious problem. It's time to get help & put on the lab coat, or find a different adhesive that's better characterized.

Table 3: Manufacturer Catalog Sample

## MASTER BOND TWO COMPONENT SERIES APPLICATION SELECTOR GUIDE

Selected Two Component Epoxy Adhesives, Sealants, Coatings, Encapsulants & Potting Compounds  
 Partial Listing Only — Other Grades Available

Master Bond Grade	Mix Ratio (by weight)	Color Code	Mixed Mixes/RT occ	Set Up Time (Minutes)	Set Up Time (Hours)	Cure Schedule (Temp/Time, F)	Service Temp Range, F	Applications
E221	10:2:0	W: grey E: tan	5: 100-50,000	30-60		24-48 hrs @ RT 2 hrs @ 200F	-60 to +250F	High performance general purpose adhesive sealant and coating. Can also mix ratio by user for business and health.
E221AC	10:2:0	W: grey E: white	light paste	45-60		24-48 hrs @ RT 2-3 hrs @ 200F	-60 to +250F	Thermally conductive version of E221. Used primarily for bonding and sealing.
E221AC.V	10:2:0	W: grey E: white	4: 100-50,000	75-90		24-48 hrs @ RT 2-3 hrs @ 200F	-60 to +250F	Lower viscosity version of E221AC. Easy to use, the only conductive potting material/sealant.
E221AN	10:2:0	W: grey E: white	light paste	30-60		24-48 hrs @ RT 2-3 hrs @ 200F	-60 to +250F	Highest thermal conductivity version of E221AC. Thermal conductivity at 75F: >22 E.T.U./in <sup>2</sup> in <sup>2</sup> in <sup>2</sup> in <sup>2</sup> .
E221AR	10:2:50	W: clear E: amber	1: 100-15,000	30-35		24-48 hrs @ RT 2-3 hrs @ 200F	-60 to +275F	Superb resistance to many organic and inorganic acids. For bonding sealants and coatings.
E221BAS	10:2:0	W: off white E: off white	> 175,000	30-60		45-60 hrs @ RT 2-3 hrs @ 200F	-60 to +250F	Flexible viscous adhesive sealant/coating for medical and medical electronic applications.
E221FL	10:2:5	W: amber E: amber	3: 100-4,000	120-150		24-48 hrs @ RT 2-3 hrs @ 200F	-60 to +250F	Flexible version of E221. Superior thermal stability, shock and thermal stresses. Excellent adhesive/sealant.
E221FRLVSP	10:2:0	W: red E: white	25: 100-50,000	30-60		24-48 hrs @ RT 2 hrs @ 200F	-60 to +250F	Flame retardant, UL94V-0 certified system. For potting and bonding.
E221HT	10:2:0	W: clear E: amber	5: 100-50,000	50-70		24-48 hrs @ RT 2 hrs @ 200F	-60 to +400F	High temperature resistant version of E221 with excellent chemical resistant properties. Converter handling.
E221LSL	10:2:60	W: clear E: clear	1: 100-1,500	30-35		24 hrs @ RT 1-2 hr @ 200F	-65 to +250F	Low solvent non-yellowing version of E221 for bonding sealant and coating. For optical and display applications.
E221LV	10:2:0	W: clear E: amber	5: 100-8,000	30-60		24-48 hrs @ RT 1-2 hrs @ 200F	-60 to +250F	Lower viscosity than E221. Food grade & USP Class V certified. For bonding, sealing, coating & encapsulation.
E221MD	10:2:0	W: grey E: tan	paste	45-60		24-48 hrs @ RT 2 hrs @ 200F	-60 to +250F	Non chip version of E221. Suitable for medical applications. Excellent adhesive/sealant.
E221RCL	10:2:0	W: grey E: lighter	moderate paste	30-120		24-48 hrs @ RT	-60 to +250F	Durable, tough, two shot flooring with high chemical resistance.

When looking up data sheets, be care of some design pitfalls.

- Do not assume that the strength factor-of-safety (FOS) design strategy applies to adhesive. FOS was developed and proven for ductile engineering alloys in static, non-corrosive, non-creep conditions. A static (time-independent) FOS cannot be applied unless the adhesive is below its damage threshold. Some materials just have no damage threshold, such: superalloys used at high temperature and silicate glass (controversial subject)
- Nearly all polymers (including elastomers) behave as brittle materials, and so linear elastic fracture mechanics can be used to estimate strength. This implies that a constant toughness serves to characterize energy dissipation in the fracture process zone. (Note this implicitly assumes that the fracture process zone is small compared to specimen dimensions.)
- In bonds, the substrate constrains the free-development of damage compared to bulk. Interface mechanics become important.
- Fracture mechanics estimates of bond strength based on cracks in bulk material are still useful for benchmark comparisons.
- The implicit assumption that materials exist which meet every imagined requirement is poor design practice.

Keep the design envelope within easy reach of existing materials. Use your mechanical ingenuity to overcome material limitations.

Lifetime is another fundamental design metric. No bond lasts forever. Adhesive lifetime depends on strain level and environment (temperature, humidity, chemical species present, etc.) Probabilistic lifetime is the most useful design parameter but is rarely ever addressed explicitly. There are no specific rules, formulas or procedures to predict adhesive bond lifetime. Barring quality lifetime data from the lab, field data are the best source of information. Determination of accurate bond lifetime predictor equations requires extensive experimental testing & fitting to theoretical or empirical models. Such data is rarely available to the design engineer.

A typical designer would probably use conventional statistical strength (e.g., 99% CI on strength) or FOS design based on data in the manufacturer's product data sheet or in-house data collected at one testing speed. Beware that the product data sheet doesn't mention a strength-speed or strength-time dependence.

The bond also creeps under load & the creep rate depends on humidity. There is no mention of creep either in the product data sheet.

## Reference

- 1 Paul R. Yoder, Jr. *“Opto-Mechanical Systems Design”* Third Edition
- 2 Daniel Vukobratovich and Suzanne M. Vukobratovich *“Introduction to Opto-mechanical design”*
- 3 Blain Olbert *“Adhesive Selection & Characterization – What You Don’t Know Can Kill You”* (presentation)
- 4 Master Bond Inc. <http://www.masterbond.com/prodtype.html#pepoxy>
- 5 Nicole Langer *“Where adhesives beat mechanical fasteners”* Dymax Corp.