A Survey of Technical Literature on Adhesive Applications for Optics

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ABSTRACT

A general overview of adhesive bonding for optical elements addresses all the relevant parameters and properties. An extensive listing of references is associated with many of the critical topics. Technical literature addressing optical bonding has been difficult to find. This paper has conducted a search to aid engineers trying to solve these bonding problems. The user must first look at his/her options for fastening the optical element. Next, he/she must consider all the parameters that influence its cure, performance and survival. If an adhesive represents a good solution, the type of adhesive must be selected. Throughout this selection process, it is important to maintain priorities on critical parameters. Compromises must always be made and assigning priority levels will aid in making these decisions. Future work will establish a selection matrix weighing relevant factors in making the adhesive selection more logical.

Keywords: Adhesives, Bonding, Optics, Optical Bonding

1. INTRODUCTION

Not too many years ago, the electro-optical engineer had a limited selection of adhesives for anticipated success. Most users gravitated towards one or two candidates with which they had gained experience, often modified through either additives or process controls. This selection process has always relied on a balance of priority versus compromise to meet performance criteria. Compounding the user's difficulties has been the very limited amount of published literature on this subject. Notable exceptions include K.H. Spring's 1958 detailed bonding solution paper [1], which concluded that improved adhesives could simplify the process and S. F. Pellicori's 1970 paper [2], "Optical Bonding Agents for Severe Environments," which outlined his search for a compliant and space-qualified adhesive.

Today, engineers have many adhesive choices. Sometimes, too many candidates make proper selection difficult. The *perfect adhesive* does not exist and the user must prioritize the adhesive properties during his/her selection process. The telecommunications industry boom near the turn of the century created new adhesive opportunities with the promise of high volume applications. This attracted a number of adhesive suppliers to the industry. They soon recognized the complexity of most applications and responded by developing a very wide range of new formulae with improved properties. This evolution is far from mature, but the following critical issues are being addressed.

a. Cure-on-demand adhesives such as UV-cure continue to grow with improved properties.
b. The use of cleaner more environmentally-friendly materials to eliminate volatile organic compounds (VOCs).
c. Adhesive material refinement to eliminate out-gassing contamination where the volatiles condense on optical surfaces causing obscuration and/or damage.
d. New adhesive formulae and filler additives to reduce shrinkage on cure to levels below 1%.
e. Adhesive modification (normally through filler addition) generally to lower the coefficient of thermal expansion (CTE) for better matches to optical elements.
f. New adhesives with higher glass transition temperatures. For example, Telcordia (formally Belcore) requires the adhesive Tg > 95 °C. (Section 4.4 of GR-1221-CORE).

This paper presents a review of the literature and available adhesive products. The long term objective is to create a comprehensive adhesive selection matrix for the casual electro-optics engineer, which will provide a guideline with some justification for the proper adhesive choice. The intent of this publication is to provide the background and basis for the long term objective.

New Developments in Optomechanics, edited by Alson E. Hatheway,
Proc. of SPIE Vol. 6665, 666507, (2007)
0277-786X/07/$18 · doi: 10.1117/12.735948

The adhesive selection criteria are based on the all the performance parameters for the specific use. It is beneficial for the user to fully understand all these factors, list them in rank order, define their acceptance criteria, and rank order them according to their importance. These parameters include the optical elements properties, the substrate, the environmental factors, the joint design, anticipated performance, process controls, volume, service life, and others. These selection considerations are discussed in greater detail in the following paragraphs.

2. JOINING ALTERNATIVES

The engineer must decide at the design stage which joining technique best suits his/her application. The bonding methods are broadly classified under contact bonding, hydroxide bonding, diffusion bonding, frit bonding, adhesive bonding, and mechanical fastening. The salient features of each of these methods are summarized below

2.1 Optical contacting

Optical contacting is a non adhesive room temperature bonding process. A condition is created where air is completely removed in the interface between the glass surfaces. This allows inter-atomic forces or weak van der Waals molecular forces to hold the surfaces together. It can be used for precision applications where the bonding surfaces have a reasonably good surface figure match. It is sensitive to surface particulate and chemical contamination and other environmental factors, such as humidity. Traditionally, these bonds have been generally unreliable in strength and lack robustness in a wide range of stressing conditions. Typically, optical contacting has a low first-try success rate. In case of failure, de-bonding usually degrades surface quality and thus lowers the success rate in re-bonding [3-9].

2.2 Hydroxide bonding

Hydroxide catalysis bonding is a room temperature process employed to bond materials that can be hydrated and dehydrated through hydroxide catalysis. The technique employs an aqueous solution of hydroxides, consisting of hydroxides such as NaOH or KOH, for example, with or without silicate such as SiO_2 as a bonding material. The bonding solution is filtered and dispensed on the surface of one of the bond areas. The second surface is then gently placed in contact and slightly compressed to ensure a uniform bond. This method is used to join precision optical assemblies. The bonding interface is thermally, optically, and electrically thin and resistant to organic solvents, extreme changes in pH and high power laser beam damage [10-13].

2.3 Diffusive bonding

Diffusion bonding is a solid state joining technique in which two surfaces are brought into intimate contact using low pressure at elevated temperatures [14]. In case of bonding glass and metal Anodic bonding (field assisted diffusion bonding) is typically used. Field-assisted diffusion bonding, or anodic bonding, may be applied to joining metal or semiconductor (Al, Cu, Mo, Nb, Si) components to nonmetal components (such as glass and ceramic); this is an electrochemical method which produces the bond through the thermal diffusion of solid phases in an applied electrostatic field [15-19]. The bond is formed by oxidation of the metal surface into the glass by charge transfer due to ion migration. It has been observed that electrostatic attraction is important when parts are not initially brought in intimate contact by an applied pressure [17].

2.4 Frit bonding

Frit bonding is a thermo-compressive process. A mixture of frit materials, consisting of a paste of a low melting point glass powder, organic binders and solvents, is used in the interface between two optical surfaces. The interface created is mechanically strong and chemically resistant in most instances. Prior to bonding, thermal conditioning of the glass paste is done by heating it to a temperature high enough to reduce its viscosity and enable the wetting of the surfaces. Mechanical pressure helps in wetting the surface and promotes complete covering of the bond area. This also aids in reducing the effects of surface roughness and improves sealing. The addition of inorganic fillers is used to influence the CTE of the interfacial layer. This method does not require activation of bonding surfaces. Both hydrophobic and hydrophilic surfaces can be bonded using this process. The bonding strength is observed to be close to that achieved though anodic bonding. The main advantages of this method are that: 1) it can be used to bond rough surfaces; 2) it is reliable; and 3) it provides high bond strength [20-22]. Due to its high temperature requirement, frit bonding requires high temperature rated fixturing for alignment and is, therefore, expensive. Frit bonding is unsuitable if high temperature side effects, such as changes in the physical or chemical properties of the substrates, are problematic.

2.5 Adhesive bonding

Adhesive bonding is the process of uniting optical surface with the aid of an adhesive. The main categories of optical adhesives (based on curing and preparation) are epoxy resins, flexible RTV adhesives, and ultraviolet (UV) curable compositions. Bonding using epoxies is usually a room temperature process and has a good success rate for regular room temperature applications. Epoxies are often two part adhesives which harden when they are mixed together. There are also single-component epoxies which are cured by exposure to heat. Epoxy bonding is typically organic based, making them susceptible to pyrolysis (due to high intensity lasers, for example) and photolysis (due to ultra-violet light) in high power density applications. The strength of the epoxy bond varies with temperature and chemical environment. Epoxy bonding creates a relatively thick interface which makes optical index matching more of a concern in optical applications. An adhesive with a UV light initiated cure is known as a UV curable adhesive. The main advantage of this method is that the bond can be cured instantly on demand by exposure to UV radiation. The mechanical properties such as lapshear, tensile and peel strengths of UV cured adhesive equal that of epoxies. Also, their shrinkage and outgassing are lower compared to epoxy adhesives [23].

2.6 Mechanical fastening

Mechanical retainers or clamps remain provide another joining option. Threaded ring counter-bore designs are still common for larger optical systems, such as camera lens assemblies. Elaborate spring-loaded clamping for odd shaped prisms has been successfully used. In general, mechanical fastening relies on: tight tolerances, multiple components, high stress contact points, and higher costs. Yoder's textbook [24], a handbook for electro-optics design, describes many of these solutions.

Further, the bonding type can be of precision and non precision types. There is no clear-cut demarcation between precision and non precision bonding, but they are additionally categorized as: (1) precision bonding using bonding materials that do not interfere with interface thickness; (2) non precision bonding using bonding materials that do not interfere with interface thickness (e.g., when precision is affected by contaminants); and (3) non precision bonding using bonding materials that interfere with interface thickness.

3. SELECTION CONSIDERATIONS FOR JOINING TECHNOLOGY

Selection considerations for joining technology are provided in the following sections.

3.1 System stability:

Various factors influence the stability of an optical assembly. Joint design problems such as asymmetric design or asymmetric execution, non uniform stress distribution over bond area, or over constraining causing distortion can render the optical system unstable. Internal material stresses, residual stresses, CTE mismatch between the substrates and mounting material are some causes for instability. Adhesive issues such as incomplete cure, irreversible dimensional changes over temperature cycling, hygroscopic expansion, acid or alkali degradation, changes caused by light source, and differential properties due to entrapped gases are other sources [25, 26]. It is seen that for precision application a high viscosity adhesive is good to hold the bond in position during cure. In some cases higher modulus adhesive material bonds show angular instability. This may be caused due to anisotropy in materials crossed with bond spot thickness, location, shape and CTE difference between elements. Bond thickness is reported to play a significant role in the stability of the system. Thicker bonds generally do not contribute to strength. More stable bonds result from thin bond lines and uniformity of the bond layer is shown to play an important role [25, 27, 28].

3.2 Stress levels

There are various sources that induce stresses in an optical assembly. Mechanical loads acting on the optical assembly during operation can generate stress or uniform temperature changes can induce mechanical stress in an optical assembly due to mismatch in CTE between the bonded elements and mounting materials. It is also seen that pressure, inertia, and vibratory loads, internal distortion of the adhesive during cure, and residual stresses due to manufacturing and fabrication processes can develop stress in an optical system. Stress and strain can be examined with Hooke's Law and knowledge of the elastic modulus. This can create movement or in extreme cases fracture. Stress can also change the index of refraction of the optical material and generates *stress birefringence* which creates wave-front error and polarization changes in light propagation though the optical system. Thus, for polarization sensitive applications it is essential to account for the effects of mechanical stress for a successful design. A good way to avoid stress birefringence is by reducing the CTE mismatch between the substrates and the mounting material [29, 52]. Also, birefringence of the optical adhesive can be decreased with annealing temperature. Refractive index is shown to be increased by annealing as a result of volume relaxation, which makes the adhesive more isotropic [30, 31]. Increase in stress in the bonding interface can exceed the material strength and cause delaminations or cracking [28]. Stresses are also generated during curing due to adhesive shrinkage (changes in molecular packing). These stresses are higher when joints have a higher ratio of total bonded surface area to total unbonded surface area. There is therefore higher shrinkage stresses in the case of thinner substrates because there is less scope for strain- relief at the unbonded surfaces [26].

3.3 Outgassing:

Many adhesives are formulated with solvents that evaporate during cure and produce high levels of contaminants. The user can often smell these by-products. These volatile ingredients are emitted during curing or when the bonded assembly is exposed to vacuum or elevated temperatures. These emitted ingredients may then condense as contaminating films on nearby surfaces, such as optics or opto-mechanical assemblies [23, 32]. This causes dimensional instability and changes in material properties, such as micro roughness. This subsequently changes the absorption and scattering characteristics. It is seen that the problem is further aggravated by other factors such as UV exposure, thermal cycling, and exposure to atomic oxygen atmosphere (ATOX) [49, 50]. Also, the deposited contaminants, when illuminated with high power optical beams, give rise to local heating due to optical absorption. The heating can deform the optical figure or induce a thermal-lensing effect from the coupling of thermal dependence of the refractive index to temperature gradients in the affected optics [51]. Total mass loss (TML) and collected volatile condensable material (CVCM) are two measures of outgassing [23]. NASA has done extensive work in characterizing material outgassing [33]. This is an excellent source of information. They have associated the term “space-qualified” with materials that exhibit TML < 1.0% and CVCM < 0.1%. This is an excellent source of information. Many military electro-optics device suppliers have found higher sensitivities to outgassing contamination and have adopted specific material screening tests as described by Hovis [34]. Capping material may be used to encapsulate the exposed periphery of bonding material. Capping material may emit an acceptable level of outgassing species that does not severely degrade the optical performance of the optical assembly. Conformal coating materials have been used in this manner.

3.4 Settling time/curing time

The settling/curing time is the time elapsed before the materials become attached and impossible to move without mechanical destruction of the bond. Typically, a longer settling time is required for fine alignment of the surfaces in precision applications [10]. The cure rate is often temperature sensitive [35]. In some bonding methods, the settling time can be reduced by subjecting the bond to an elevated temperature or UV rays. However, the size and number of voids tend to grow as the isothermal temperature increase, which, in turn, detrimentally affects the long term reliability of the system. Thus, proper curing is essential to reduce void formation and increase adhesive strength. It has been reported that a step cure can minimize void nucleation as compared to isothermal curing [36, 37]. In some cases optical gels, which cure only at elevated temperature, are used. Rapid filling of uncured adhesive is done at room temperate and then the bond is snap cured by subjecting it to high temperature [35]. Many users de-gas their adhesive during the mix process. Commercial devices are now available to degas during mixing, such as Adaptive Energy’s mixers [38].

3.5 Optical performance

Optical performance issues include wavefront distortion, index of refraction, polarization characteristics, and optical losses, to name a few. The ratio of optical power arriving at an optical interface to the optical power reflected back is called the optical return loss. It is desirable to minimize this reflection of light. Use of adhesives to fill the gap between the bonded substrates having a refractive index close to that of the materials to be joined leads to reduction in reflection occurring at the bond junction. In the case of some UV curable adhesives, refractive index is lowered by introducing fluorine into the system [29, 30, 31]. Index of refraction of the adhesive for joining dissimilar materials with different refractive indices that gives minimum reflection loss is usually equal to that of the geometric mean index [35]. Bonding methods can induce stresses in the assembly and lead to optical coupling losses which affect the optical performance of the system. The thickness of the bond is shown to have an influence on the optical losses. Also, uneven distribution of the adhesive over the bond layer can cause angular misalignments which may result in heavy coupling losses [28]. Thicker bonds cause problems of interface reflection losses. However, in the case of dissimilar substrates, the joint can be very stiff and have stresses if the interface bond is too thin [39].

3.6 Environmental factors

These factors include temperature, humidity, pressure, and pH and have been reported to exert a major influence on the optical assembly behavior.

a. Temperature

The knowledge of the range of temperature over which the bond has the required strength is critical. The mechanical properties of the bond, such as strength, modulus, viscosity and CTE change, are typically temperature dependent [23]. Also, refractive indices of various optical adhesives are often temperature dependent. As the temperature increases, the adhesive refractive index decreases due to a volumetric increase and density reduction [30]. This change in refractive index causes optical losses due to Fresnel reflection. [35].

b. Humidity

Humidity is shown to affect the refractive index of adhesives. An irreversible change in the chemical makeup of adhesives can be observed due to moisture absorption [30]. A hygroscopic expansion in the adhesive causes deformation resulting in alteration of its optical properties and stress. Possible solutions would be a reduction in the amount of optical adhesive and the use of adhesives with lower coefficient of moisture expansion (CME) and higher adhesion strength [40].

c. Pressure (vacuum)

When an optically bonded joint is subjected to vacuum, outgassing generally takes place [41].

d. pH

Changes in pH can cause degradation of the optical bond. Acid or alkali environment can affect the chemical stability of the system [26].

3.7 Durometer

Durometer is the hardness or compliance of the adhesive on curing [23] and is a common parameter for elastomeric materials. Its use for adhesives provides a measure of the cured hardness and implied flexibility. It can be a useful relative assessment in adhesive comparison during selection. Low durometer is useful in applications where significant physical deformation is required during the bond service life. However, high hardness is seen to provide better dimensional stability in an encapsulation volume or as a pre-molded standalone part [35].

3.8 Alignment accuracy

Shrinkage during cure and uneven bond layer contributes to movement of the assembly and, in turn, influences alignment accuracies [23, 28]. Low shrinkage adhesives are more suitable for precision application and are shown to maintain excellent alignment during and post cure without complicated fixturing [36]. UV curable adhesives can bond within seconds at room temperature and are suitable for applications where alignment is critical [29, 42]. Also, an adhesive must be in fluid form with low viscosity so that it wets the substrates completely, leaving no voids in case of rough surfaces [43]. Viscosity can be reduced by using active diluents with the adhesives [44].

3.9 Light source

Considerations include laser power and spectral characteristics. Optical assemblies subjected to continuous wave (CW) UV lasers must consider photo-reactive degradation. The adhesive absorbs the UV spectra and gets photolyzed and produces dark spots causing reduction in transmission. There are ways to determine the optical losses due to the material absorption if the thickness of the bond and thermal diffusivity are known [36, 45, 46]. Shorter wavelengths (UV) have higher photon energies that can exceed chemical bond strengths and, therefore, can pose a threat to the final product's adhesive bond survival.

3.10 Shock and vibration

Optical assemblies are sometimes subjected to mechanical shocks and vibrations. These can cause fracture or delaminations. Also, these mechanical changes degrade the optical performance in terms of decreased light output, reduced sensitivity, increased back reflection, or even electronic failure. Optical bonding methods that offer strain relief can reduce detrimental effects. Optical gels can be used in this case because their compliance can respond to stress preventing build up of stresses in adjacent optical parts. However, they cannot assure high dimensional stability [35].

3.11 Bond strength

Bond strength is critical to the system performance [23]. For a system where weight support is not required, low adhesive strength is permissible [47]. Pressure and curing time is shown to influence the strength of the bond [43].

3.12 Substrate materials

The properties of the materials be bonded are very important in determining the bonding method. The method employed will vary for glass/glass and glass/metal bonding.

3.13 Thermal expansion of substrates

If the CTE of the substrates don't match and the assembly is subjected to temperature change, an adhesive forming a flexible bond must be employed to ensure stability of the system [27].

3.14 Surface finish and figure of substrates

For substrates with poor surface finish, low viscosity adhesive with high wet-ability aid in improving the surface contact. An adhesive with lower surface tension and pressure usually has good wet-ability [23].

3.15 Joint type

Joint design is essential in reducing the stresses induced in the optical assembly and also to control the alignment. An adequate design can help in controlling curing induced misalignments [28]. The joint can be of lap, butt, 'T', and other types and can be tensile, compressive, lapshear, peel, or cleavage. Most designers try to achieve designs with lapshear loads because pure tensile or compression loads are nearly impossible to maintain. High stress concentration in peel and cleavage loads should be avoided since these strengths are lower than tensile or lapshear strengths. Designs should avoid peel and cleavage situation when possible [23].

3.16 Number of assemblies to be joined

For high speed production lines, ease of application of the adhesive is important. Viscosity dominates other properties in this case because it determines the ability of the adhesive to wick into tight spaces. Higher viscosity adhesives require higher pressure to move a given volume of material though an orifice per unit time. If the viscosity is too low, the adhesive may wick too easily and be difficult to contain in the device within the designated area or long enough to complete cure. This can also pose a constraint in high speed production line [35]. Viscosity can be controlled by means of diluents. This results in reducing the stickiness and spreading of the adhesive, thus facilitating the bonding process [29]. Also, the cure rate and temperature can be manipulated to overcome viscosity related assembling problems.

3.17 Disassembly

Debonding means to separate the joint surfaces. Rigid or elastic/plastic damage (or decohesion) is brought out by dissipative, irreversible normal gap increase and tension decrease at the bonding interface. The factors influencing debonding are: substrate material, adhesive type, curing temperature, and time [48].

3.18 Size of assembly

To improve assembly accuracy, it is generally preferred that curing time be minimized (provided the assembly alignment can still be achieved). Larger assemblies, with larger surface areas, tend toward longer curing times. UV curable adhesives are often beneficial in these instances [43].

3.19 Post-joining manufacturing or assembly steps

In some instances, grinding or machining of the assembly must be completed after a bonding step. In this case, the bond strength must be sufficient to withstand the processing forces.

3.20 Cost.

In general, adhesives are much more cost-effective than mechanical fastening. This is attributed to simplified designs with reduced parts count and relaxed tolerances. Material costs are not significant, since the volume used is typical very small. Touch labor costs have been a factor with long cure times impacting production rates. However, recent improvements in "cure-on-demand" adhesives have resolved this issue.

3.21 Electrical (& magnetic) properties/requirements

These properties are normally available from the supplier's data. Electrical conductivity (resistivity or dielectric constant) can be critical to many applications. Additives are commonly added to improve these properties. Magnetic properties are more difficult to find, however, inquiries to the supplier normally are successful.

3.22 Glass transition temperature

T_g is now commonly quoted for most adhesives. The mechanical properties transition from a glassy-rigid state below T_g to a more flexible rubbery state above T_g. This is attributed to the long-chain polymers becoming more mobile at higher temperatures. RTV's typically have T_g values of - 90 °C and therefore are used below the Tg so that they remain flexible. Telcordia requirements have specified stable mechanical property performance for materials as limiting their use to temperatures below their T_g. In the past few years, many suppliers have responded and provided excellent adhesives with T_g values above 100 °C.

4. IS AN ADHESIVE BOND APPROPRIATE?

The most difficult step in selecting a bonding solution is the prioritization of critical properties. The user must define which parameters are mandatory and what is the minimum acceptance level for each. Many may not be negotiable. Temperature range, bond strength, and alignment accuracy can not be violated in many applications. The cure process can be down selected; however, high volume production is not compatible with lengthy high temperature cures, for example. Outgassing that creates condensed volatiles (contaminants) on optical surfaces may be catastrophic in devices such as high energy laser systems.

With the expansion in the optical adhesives market, many improvements have created products that overcome some of the traditional disadvantages often associated with a particular adhesive type. However, major limitations persist. The following list highlights generic disadvantages of adhesives and must be carefully factored into their selection for a mechanical fastening solution.

1. Limited temperature range is necessary.
2. Surface preparation is critical.
3. Critical process controls are required.
4. Cure times may be long.
5. Shrinkage on cure can impact performance.
6. CTE mismatch can be a concern.
7. Limited ability to remove and replace (R/R) may exist.
8. Environmental exposure can be a concern.
9. Out-gassing contamination can be a concern.
10. Limited service life may be a consideration.

Adhesive do possess many unique properties that make them superior solutions to fastening applications. The following list highlights these properties that can be used by the engineer to improve his/her product.

1. Adhesive bonds result in a more uniform distribution of stress.
2. Adhesives adapt well to odd shapes.
3. High strengths and low weight result in excellent strength to weight ratio.
4. The compliance of adhesives provides shock and vibration dampening.
5. Designs with adhesives can support minimal parts count and loose tolerances.
6. Adhesives can also function as seals.
7. In general they are not expensive.
8. In production, process controls can evolve without significant design changes.

5. ADHESIVE TYPES

Categories for adhesives do not follow any set format. A wide variety of descriptive terminology has been adopted by different communities. The following is a consensus commonly encountered by the engineer trying to solve and optical bonding problem. The term structural is often used which simply implies high strength.

One common differentiation is between thermoset adhesives that employ a non-reversible polymerization or chemical change and thermoplastic adhesives that are reversible with temperature. Many plastics such as ABS or Teflon are thermoplastic. Nearly all reasonable optical bonding solutions employ thermoset technology. Two other principle categories are often included: rubbers (such as silicones) and natural adhesives or glues.

Epoxies are the most common industrial adhesive. They are thermoset resins, generally two-part that cure with high tensile strengths. For example, 3-M's 2216 is a structural epoxy with excellent adhesion, high strength, and low outgassing, which has led to its selection in many military optical applications.

Polyurethane (or, urethane) adhesives are attractive options for lower temperature applications. They also are more flexible then traditional epoxies which often become brittle. Earlier products suffered from moisture sensitivity, but recent progress has eliminated much of this concern.

Acrylic adhesives come in a variety of types. In general, they cure quickly and offer high strength, excellent moisture resistance, and low toxicity. Many acrylic adhesives have excellent optical properties well-suited to uses in the optical light path. Norland's UV cure product line (Norland Products Inc., Cranbury, NJ), for example, is based on acrylics.

RTVs and silicones have been popular due to reasonable tensile strength with high peel strength, good adhesion, a wide temperature range, and excellent flexibility. Recent development of refined silicone RTVs with the exclusion of low molecular weight contaminants and solvents has produced a low outgassing product line compatible with space-qualified applications.

Optical gels are RTV-type adhesives that commonly employ thixotropic properties to secure optical elements in a flexible, optically clear medium. Another classification of optical gels is the two-part materials that cure. In general, they have a wide operating temperature range and available index of refractions from 1.46 to 1.62.

UV cured adhesives have become the most popular new candidate. The instant cure-on-demand type is well suited to precise alignment criteria and high volume applications. Recent modifications have included: visible light (longer wavelength) cures; two step cures where heat can be used to complete the curing process; and cationic UV cure products where the cure process continues in the absence of UV radiation.

6. SELECTION OF ADHESIVE TYPE

The user must first select which type of adhesive meets his/her application, then he/she must choose an appropriate product. A matrix listing all the selection considerations as shown in Section 3 is a good starting point. Each parameter must be characterized with acceptable limits. Categories ascribing criticality must be included and may be labeled as: required, negotiable, or not important, for example.

Other factors to consider include experience and approved products within the user's facility. A new adhesive will require justification that may include internal testing and an explanation for why a previously applied adhesive does not meet a specific property. Use of a new adhesive in a product with long service life may be considered risky. The engineer must understand that it is his/her responsibility to confirm not only critical performance, but to include adequate margin in the application. For example, the lapshear strength criteria must examine worst case conditions. For example, an advertised strength of 2000 psi at ambient conditions may degrade to 300 psi with significant temperature change. The margin must be applied after all worst case predictions have been completed. A minimum margin of 10x is typical.

Finally, the best tool for the engineer is to test his design. Fabricate and assemble several units and test them under the most severe conditions for all required parameters. Outgassing concerns can be addressed by noting the TML and CVCM values. Additional outgassing concerns often require specific tests, such as the laser exposure survival described by Hovis [34].

7. COMMERCIAL ADHESIVES USED BY OPTICAL ENGINEERS

In this section a representative list of adhesives that have been previously used in optical applications in various facilities is presented. This is not an endorsement of a specific product, but a statement that it has been used in prior applications.

I. Structural epoxies for military/aerospace electro-optic devices

Three candidates that have been used since the late 1970's have similar properties, but have become independent favorites of several competing military electro-optics device manufacturers. They are all two-part epoxies with lapshear strengths near 2500 psi, wide temperature range (-55 °C to 100 °C), low outgassing (TML < 1.0% and CVCM < 0.1%), and long service life (> 20 years). Two of these candidates were developed as furniture (wood) glue: 3-M's 2216 and Armstrong's A-12. The third was developed for this specific application by Summers Optical (EMS, Hatfield, PA) as Mil-Bond. High strength and low outgassing were the most important properties in their selection.

II. Replacements for epoxies where more flexibility is required

The wide temperature exposure for military/aerospace products has been a source of stress leading to severe birefringence, movement, or fracture. Users looked for similar strength adhesives with low outgassing. Several of the polyurethane adhesives, such as Ablebond 724-14C (Ablestik Labs, Gardena, CA) have been successfully used. In applications where low CTE glass is mated to high CTE substrates, such as aluminum, more flexibility is required. The RTV class of adhesives can be used with adequate lapshear strength, excellent peel strength, a wide temperature range, and proven service life. However, all traditional products suffered from excessive outgassing levels. Pellicori in 1970 suggested the low outgassing Dow 93-500 RTV's use as a structural adhesive. Similar products such as Dow 3145 and GE RTV 566 A/B meet similar criteria and are used extensively.

III. Cure-on-demand solutions

With technology changes, the telecommunication industry required that proof of design opto-mechanical assemblies be constructed using small components with critical alignment and stability requirements, as well as the ability to withstand severe environmental exposure. Epoxies were normally used. Concerns with respect to shrinkage on cure or long cure times causing misalignment threatened high volume production. The UV cured adhesives presented an obvious solution. However, most initially available candidates exhibited high shrinkage and excessive outgassing. Newer products continue to resolve these issues and acceptable production processes have been realized. Many applications use UV cure to bond critical alignment components. This is followed by a flexible adhesive potting step to provide a mechanically stable package.

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