OPTOMECHANICAL ANALYSIS AND EXPERIMENTAL VALIDATION OF BONDING BASED PRISM AND MIRROR MOUNTS IN A LASER SYSTEM

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ABSTRACT

OPTOMECHANICAL ANALYSIS AND EXPERIMENTAL VALIDATION OF BONDING BASED PRISM AND MIRROR MOUNTS IN A LASER SYSTEM

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In this thesis, different optomechanical design and adhesive configurations for mounting mirrors and prisms used in a laser system are investigated. Maintaining stability and strength of optical components of a laser device is difficult especially if the system is to be used in military environment.

In order to determine the strength of prism mounts to high acceleration levels, mathematical correlations derived by Yoder are used. By use of these mathematical correlations, safety factor of different prism mounts and adhesive configurations are calculated for an acceleration level of 40g.

So as to decide most stable mirror mount and adhesive configuration, several experiments are conducted. For the experiments, 5 different optomechanical mounts are designed. Then, 25 mirrors are bonded to the designed mounts with 5 different adhesives. These experiments are done to simulate harsh military environmental conditions such as thermal shock, mechanical vibration and mechanical shock.

In the experiments, angular movement of mirrors due to adhesive cure, thermal shock, mechanical vibration and mechanical shock are monitored. Thermal shock is applied between -40ºC and 70ºC with a temperature change of 22ºC/min. On the other hand, mechanical vibration of 14 grms and mechanical shock of 40g for 6 ms is applied in the experiments.

Shortly, this study is done for determination of the most stable mirror and prism mount design and adhesive combination of a laser system subjected to extremely harsh environments.

Keywords: Optomechanical Design, Mounting of Mirrors, Mounting of Lenses, Mounting of Prisms, Thermal Shock, Mechanical Vibration, Mechanical Shock, Bonding, Adhesive, Adhesive Cure

ÖZ

LASER SİSTEMLERİNDE KULLANILAN PRİZMA VE AYNALARIN YAPIŞTIRMA BAZLI OPTOMEKANİK TUTUCULARININ ANALİZİ VE DENEYSEL DOĞRULAMASI

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Bu tez çalışmasında, bir lazer sisteminde kullanılan aynalar ve prizmalar için farklı optomekanik tasarım ve yapıştırıcı konfigürasyonları incelenmiştir. Askeri ortamlarda kullanılmak üzere tasarlanan bir lazer sisteminde, aynaların ve prizmaların kararlılığını ve dayanımını sağlamak zordur.

Prizmaların tutucu ve yapıştırıcı konfigürasyonlarının yüksek ivme değerlerine olan dayanımının belirlenmesinde, Yoder tarafından türetilen matematiksel bağıntılar kullanılmıştır. Bu matematiksel bağıntıların kullanılması ile, 40g ivme seviyesi için, farklı prizmaların tutucu ve yapıştırıcı konfigürasyonlarının güvenlik faktörleri hesaplanmıştır.

En kararlı ayna tutucusu ve yapıştırıcı konfigürasyonunun belirlenmesi için çeşitli deneyler yapılmıştır. Deneyler için, 5 farklı optomekanik tutucu tasarlanmıştır. Tasarlanan optomekanik tutuculara, 5 farklı yapıştırıcı ile 25 adet ayna yapıştırılmıştır. Bu deneyler; ısıl şok, mekanik titreşim ve mekanik şok gibi zorlu askeri çevre koşullarını simüle etmek için yapılmıştır.

Yapılan bu deneylerde; aynaların, yapıştırıcının kuruması, ısıl şok, mekanik titreşim, mekanik şok gibi etkilerden kaynaklanan açısal hareketleri izlenmiştir. Isıl şok, -40ºC

ve 70ºC sıcaklık aralığında 22ºC/min değişiklik olacak şekilde uygulanmıştır. Ayrıca, titreşim seviyesi 14 grms olan bir titreşim profili ile 40g 6 ms'lik bir şok profili de deneylerde uygulanmıştır.

Kısacası, bu çalışma, askeri ortamda kullanılan bir laser sistemindeki en kararlı lens, prizma montajı ve yapıştırıcı konfigürasyonunun belirlenmesi için yapılmıştır.

Anahtar Kelimeler: Optomekanik Tasarım, Ayna Montajı, Mercek Montajı, Prizma Montajı, Isıl Şok, Mekanik Titreşim, Mekanik Şok, Yapıştırma, Yapıştırıcı, Yapıştırıcının Kuruması

To My Family…

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CHAPTER 1

INTRODUCTION

1.1 Laser Definition and Working Principle of Lasers

Laser is acronym for “Light Amplification of Stimulated Emission of Radiation.” In laser, light is emitted through a process of optical amplification based on the stimulated emission of photons. In this acronym, light denotes not only visible light but also elctromagnetic radiation of any frequency [1].

A laser is considered to consist of mainly three elements:

- An Active Material; a material with properties that allow it to amplify light by stimulated emission [1]. According to the physical state of the active material laser types may be considered as solid-state lasers, liquid lasers and gas lasers [2].
- A Pumping Scheme; is the process of supplying the energy required for the amplification of light [1]. Pumping process may be accomplished mainly by optically pumping, electrically pumping and chemically pumping [2]. Optical pumping, application of light sources for pumping lasers, is managed mostly by using flashlamps, cw arc lamps and laser diodes [42]. Electrical pumping is accomplished by means of a sufficiently intense electrical discharge [2].
- A Resonator; in which the laser radiation can circulate for feedback and sustain the amplification process [3]. The most widely used laser resonators have either plane or spherical mirrors of rectangular or circular shape, seperated by some distance L. A resonator is mainly composed of mirrors as stated before however prisms, polarizers, wave plates and q-switching prisms

may also be main components of a laser depending on the application and the laser resonator architecture.

Shortly, for generation of laser beam it is necessary to have three elements named as active material, pumping scheme and a resonator (Figure 1.1). A portion of the light is resonated between the mirrors of the resonator and escapes as a laser beam from a partially reflective mirror [4].

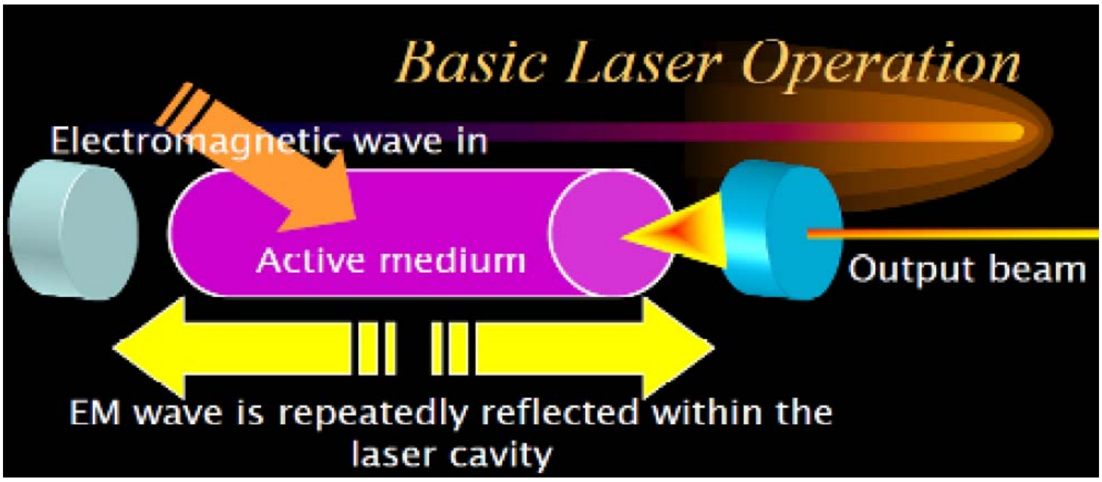


FIGURE 1.1 Basic Laser Source Unit [4]

In the present study; mechanical interfaces of a solid-state optically pumped laser resonator will be investigated.

1.2 Areas of Usage of Lasers and Laser Target Designators

Laser source is a light source as sun, light bulb and candle. However, it has some distinctive properties such as [5];

- Monochromaticity (Figure 1.2); light coming from sun, light bulb and candle contains light in the form of different wavelengths however laser light has specific wavelength depending on the laser type.

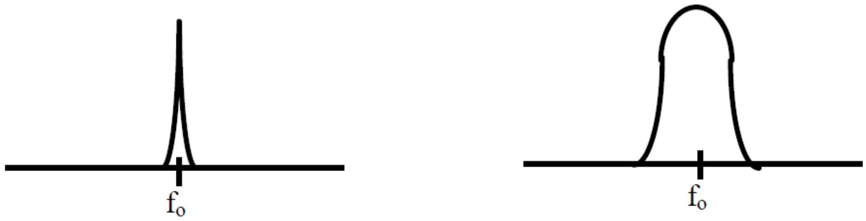


FIGURE 1.2 Monochromaticity of Laser Light [5]

- Coherent (Figure 1.3); laser light is composed of light particles (photons) having the same phase. However; sun light, light bulb and candle light contains light particles having different phases.

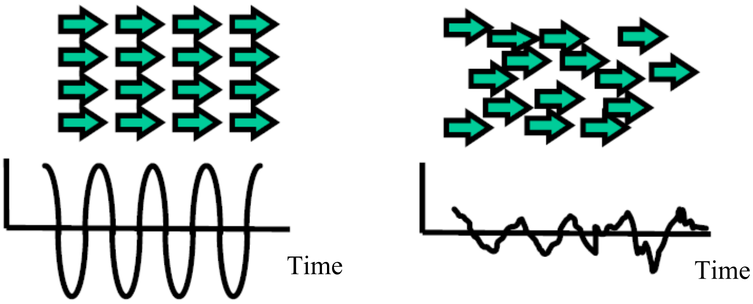


FIGURE 1.3 Coherence of Laser Light [5]

- Small Divergence; divergence of a beam is a measure for how fast the beam expands. Laser beam has very small divergence when compared with sun light, light bulb and candle light. In Figure 1.4, the difference between the divergence of a laser beam and sun light, light bulb and candle light is seen. In other words, 1 m laser beam becomes 1.1 m at 1 km distance whereas 1 m sun light, ligth bulb and candle light becomes 20 m at 1 km distance.

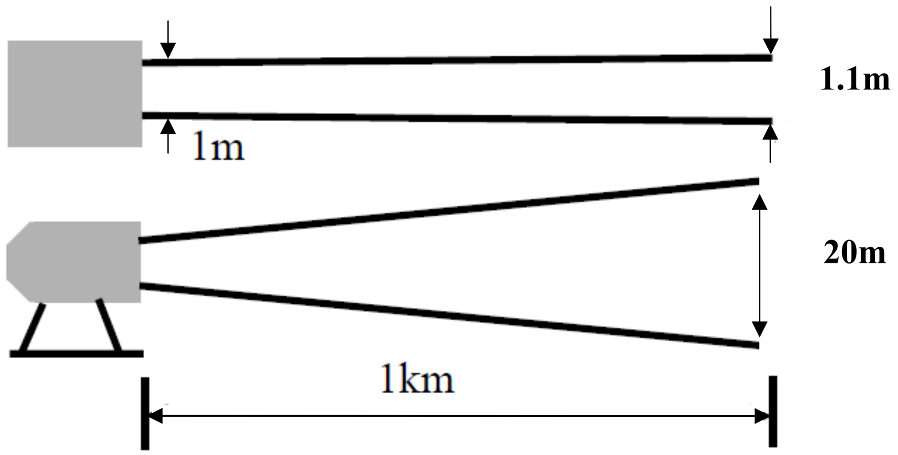


FIGURE 1.4 Divergence of Laser Light [5]

The properties that are stated above makes the laser beam special. So, it has so many different areas of usage such as;

- INDUSTRY; in industry lasers are used for material cutting processes, welding applications for different materials, 3D modelling of parts, temperature measurement.
- MEDICINE; is one of areas that lasers are widely used. Lasers are used for bloodless surgery, kidney stone treatment, eye treatment and dentistry.
- RESEARCH; for sensitive measurements, for measurements of the small movements of the earth and chemical analysis of materials are some research areas in which laser technology is used.
- COMMUNICATION; by using lasers, communication on Earth in Fiber-Optic systems and storage of data is provided.
- MILITARY; laser technolgy is most widely used in military systems. Some uses of lasers in military systems are target designation, range finding, alternative radar (LIDAR-Light Detection and Ranging) and so on [6].

In the present study, lasers used in military environment will be investigated. Main concentration will be on mechanical components of a laser system that is used for target designation and range finding. In range finding applications, laser beam is used for determination of the distance to an object and is accomplished by the time of flight principle. On the other hand, target designation is used to mark a target for laser guided bombs and missiles.

1.3 Components of a Laser Device

As stated before, laser is mainly composed of an active material, a pumping scheme and a resonator. However, the architecture of a laser device may change due to the specifications and working conditions of the laser device. Range finders and target designators are used in military applications. So, certain specifications of the laser device are more tight than lasers used in medicine and industry due to the harsh working conditions. For range finding and target designation, the laser should be stable under extreme temperature conditions such as -62ºC and +71ºC [7]. Also, the laser should withstand extreme mechanical shock, thermal shock and mechanical vibration. More specs that should be satisfied means more components and more considerations that should be in the laser device.

Components of a laser device can be grouped as;

- Optical Components; are the main components of a laser device. An optical component, for example; can be a mirror, a lens, a prism. By use of a mirror, a lens and a prism; a resonator can be constituted. Active material, one of the main elements of a laser device, is also an optical component.
- Electronic Components; are also critical for laser devices. Electronic components are used for pumping, timing of the pumping and providing the power for pumping.
- Mechanical Components; are used for the construction of the laser device. Temperature, vibration and shock exert static and/or dynamic forces on optical and mechanical components. These forces may cause deflections or dimensional changes which may result in misalignment [7]. As illustrated with an example in Section 1.8, laser is very sensitive to any misalignment. Mechanical components should be very stable under extreme temperatures,

thermal shock, mechanical shock and mechanical vibrations which makes the mechanical components critical.

For optical instruments, the materials typically used for mechanical components are aluminum alloys, beryllium, brass, invar, stainless steel and titanium [7].

1.4 Mounting Methods of Circular Optical Components (Lenses and Mirrors)

Main purpose of the lens-to-mount interface is holding the lens in its proper position and orientation within the optical instrument [7]. Optomechanical design is a multidisciplinary process that binds the optical design and mechanical design [8]. While designing an optomechanical mount, temperature, pressure, vibration and shock conditions should be considered [7]. These effects will mainly cause misalignment of the optical system and breakage of the optical components. Also humidity, corrosion and contamination should be considered in the design of the optomechanical mount [7]. For an optical instrument performing properly throughout a long useful life in such an environment, the design should be durable, reliable and simple [8]. Mechanical interfaces of lenses is mainly determined according to its size and its area of usage. There are two main types of mounts, mounting of lenses and mounting of small mirrors, in this category.

1.4.1 Mounting of Lenses

There are mainly three techniques for mounting of lenses. These techniques are classified as burnishing a lens into its cell, using an elastomer layer on the outer perimeter of the lens and using a retainer ring to hold the lens into the lens cell.

The burnishing method is conducted by cutting an inclined edge into the lens (Figure 1.5). The lens is then inserted into the lens housing and then burnished. This technique is permanent and is used in low precision applications. It is inexpensive and a reliable mounting technique. On the other hand, over stress may occur on the lens and lens may be tilted in its housing [9].

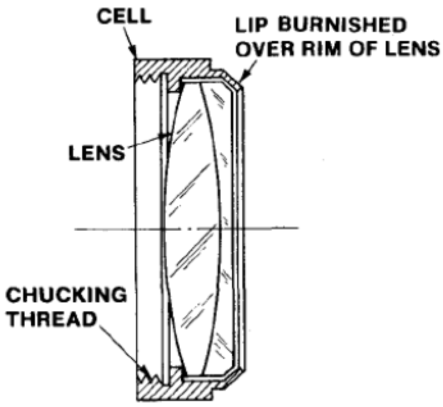


FIGURE 1.5 Burnishing Method for Mounting of Lenses [9]

In elastomer layer technique (Figure 1.6), lens is mounted in a housing that has diameter greater than the lens diameter. The lens is inserted into the housing, it is centered and than elastomer is inserted peripherally around the lens. In this design, it is important to determine the diameter of the housing since small housing results in mechanical stress on the lens. This stress is caused by thermal changes on the environment and causes the lens to break. If diameter of the housing of the lens is appropriate, lens stays unstressed in its housing. This technique is inexpensive and simple. On the other hand, decentration will occur under mechanical shock and mechanical vibration [9].

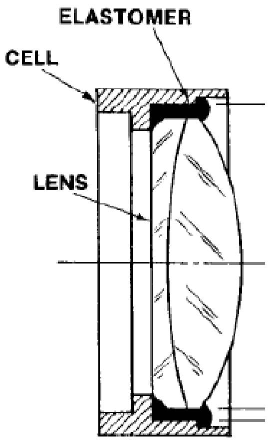


FIGURE 1.6 Elastomer Layer Technique for Mounting of Lenses [9]

Another method of mounting lenses is using a threaded retaining ring (Figure 1.7). This method is the most widely used method for mounting lenses. In this type of lens mount design, lens housing is manufactured to be compatible with the thread pattern of the retaining ring. In this design, lens is inserted in its housing and then a retainer ring is mounted. Retainer ring fixes the lens into its housing. This technique for mounting lenses is also reliable and easy for assembling and disassembling [9].

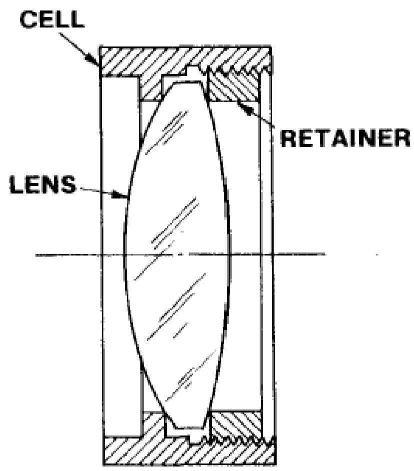


FIGURE 1.7 Threaded Retaining Ring Technique for Mounting of Lenses [9]

1.4.2 Mounting of Small Mirrors

Physical size of the mirror is determined according to the size and shape of the light beam to be reflected. Misalignment tolerances of the optical design and beam motion path are also important in the physical size of the mirror. Suitability of mechanical mounting design of a mirror depens on; tolerable movement and distortion of the reflecting surface, thermal effects, the flatness of the mounting surface, the rigidity and stability of the structure supporting the mount [8]. Small mirrors are mounted by using three techniques, namely, “clamped mirror mountings”, “bonded mirror mountings” and “flexure mirror mountings”.

Clamped mirror mountings are relatively simple technique for mounting a glass mirror to a metal surface (Figure 1.8). In this technique, the reflecting surface of the mirror is pressed against three coplanar machined surfaces, pads, by three spring clips. These clips should withstand environmental conditions such as mechanical shock and mechanical vibration while keeping the mirror in its position. On the other hand, these spring clips should not induce too much stress into the mirror. Lateral motions of the mirror on the mechanical pads and rotation about mirrors' normal are not constrained other than by friction in the design [8].

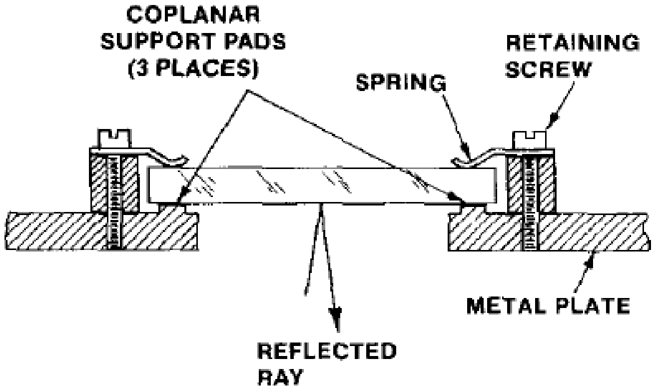
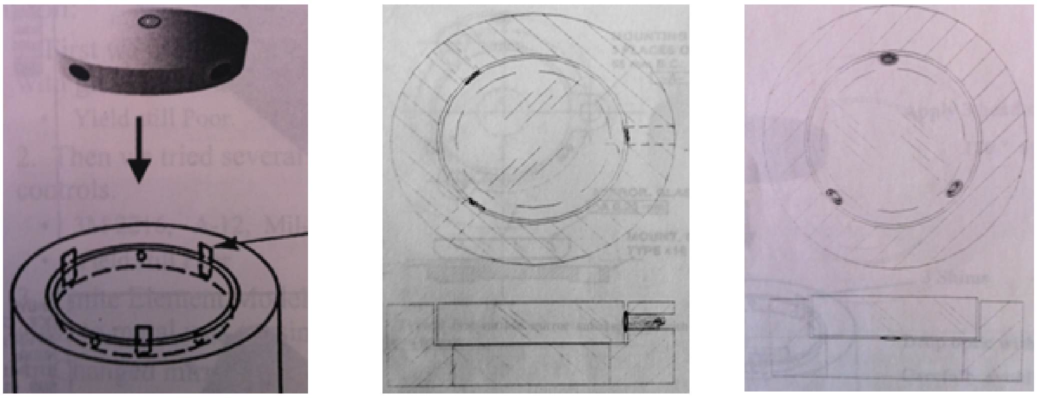


FIGURE 1.8 Clamped Mirror Mounting [8]

Bonded mirror mountings is a technique that is highly favored by optomechanical engineers for mounting small mirrors. In this technique, mirrors are mounted on their mechanical interface by use of adhesives resulting in reduced interface complexity and compact packaging while ensuring mechanical strength sufficient for withstanding shock, vibration and temperature changes characteristic of military and aerospace applications. While designing a bonded mirror mounting, designer should consider the characteristics of the chosen adhesive, the thickness of the adhesive layer, the cleanliness of the surfaces to be bonded and the dissimilarity of CTE (Coefficient of Thermal Expansion) for the materials to be bonded [8]. Mirror bonding can be performed mainly in three ways named as "3 point edge bond in counterbore cell mount" (Figure 1.9a), "3 point guided edge bond" (Figure 1.9b) and "3 point face bond" (Figure 1.9c). 3 point edge bond in counterbore cell mount is a good process, because of its simplicity and cheapness, where optic movement over temperature is not critical. On the other hand, 3 point guided edge bond is an easy process to control in which stress is reduced with free expansion of adhesive in fill hole. In 3 point face bond, stress may be projected parallel to the optical axis and not radially into the clear aperture [10].



(a) **(b)** **(c)**

FIGURE 1.9 Bonded Mirror Mountings a) 3 point edge bond in counterbore cell mount, b) 3 point guided edge bond, c) 3 point face bond [10]

In flexure mirror mountings (Figure 1.10), mirror is supported in a cell attached to flat flexure blades. Thermal expansion of the mounting occurs without stressing the mirror mounted. The main advantage of this technique of optomechanical design is that mirror tends to stay centered in the housing since the flexures are stiff in the direction perpendicular to the mirror face [8].

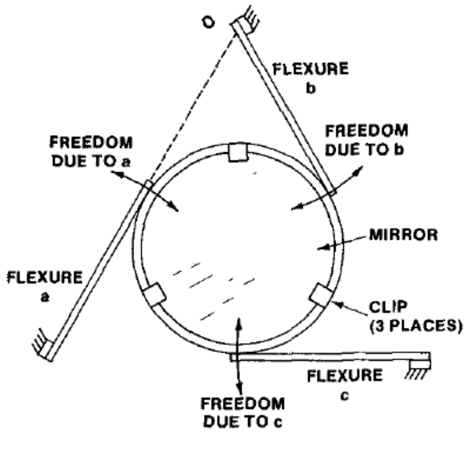


FIGURE 1.10 Flexure Mirror Mounting [8]

1.5 Mounting Methods of Prisms

There are many types of prisms designed for use in various optical instrument applications. They have different shapes depending on the geometry of the ray paths, reflection and refraction requirements, compatibility with manufacture, weight considerations and provisions for mountings. Prisms are mainly used for; [11]

- Bending light around corners
- Folding an optical system into a given shape or package size
- Providing proper image orientation
- Displacing the optical axis
- Adjusting optical path length
- Dividing or combining beams by intensity or aperture sharing at a pupil
- Dividing or combining images at an image plane
- Dynamically scanning a beam
- Dispersing light spectrally
- Modifying the aberration balance of the system

Mostly used optical prisms can be named as right-angle prism, beamsplitter cube prism, amici prism, porro prism, dove prism, thin wedge prisms. Right-angle prism is used for deviation of a beam by 90º. Beam splitter cube prism is the combination of two right angle prisms that are cemented together at their hypotenuse surfaces. Amici prism is a right-angle prism with its hypotenuse configured as 90º so a transmitted beam makes two reflections instead of one. Porro prism is also a right-angle prism in which beam enters and exits the hypotenuse surface. Dove prism is used to rotate the image by turning the prism about its optical axis. Thin wedge prisms are prisms with small apex angles [11]. They are used for deviating the beam passing through them by an angle determined by the wedge angle [12].

There are mainly four methods for mounting of prisms to mechanical structures. These methods are catogorized as kinematic mountings, semikinematic mountings, nonkinematic clamping and bonding.

In kinematic mounting (Figure 1.11a), all six degree of freedoms (DOFs) (Three positional DOFs, i.e., translations, three orientational DOFs, i.e., tilts) are controlled by six constraints at the prism interfaces with its mechanical surround. These constraints are provided by six point contacts of the mechanical interface with the prism mounted. In this method, six forces against six DOFs hold the prism in its position. Also, prism is mounted by compression in order to hold the prism at all temperatures. If the mechanical design of a kinematic mounting applies more than six forces against six DOFs on the prism (overconstrained, nonkinematic), distortions of the optical surfaces and stress on the optical surfaces occur [11].

Semikinematic mounting (Figure 1.11b) is similar to the kinematic mounting method besides in semikinematic mounting the point contacs are replaced by small-area square contacts on pads. Small-area square contacs should be very precise in order not to create line contact between pad and prism since line contact causes concentrated stress on the prism that is fragile.

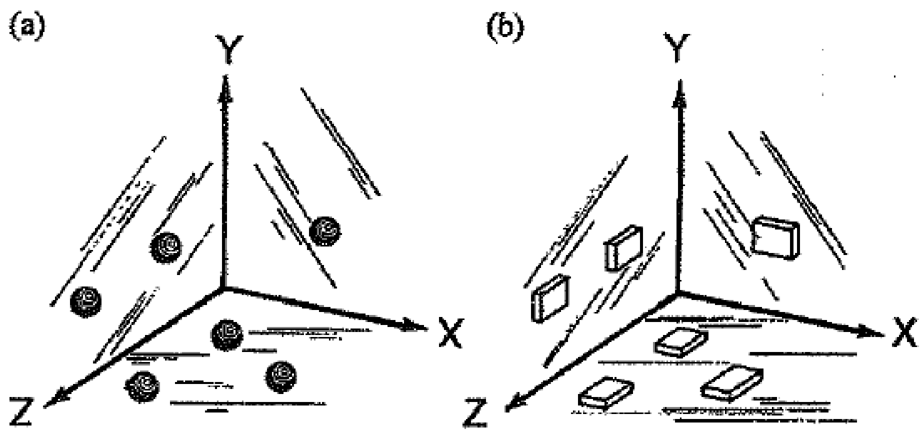


FIGURE 1.11 a) Kinematic Mounting, b) Semikinematic Mounting [11]

Nonkinematic mounting method is an another way for mounting prisms to mechanical structures (Figure 1.12). Springs or straps, typically made of spring steel, are used to hold prisms in place against extended flat interfaces in optical instruments. In military and consumer binoculars and telescopes, prisms are mounted with this method. In this mounting method, spring straps hold prism against a machined surface in a perforated aluminum mounting shelf.

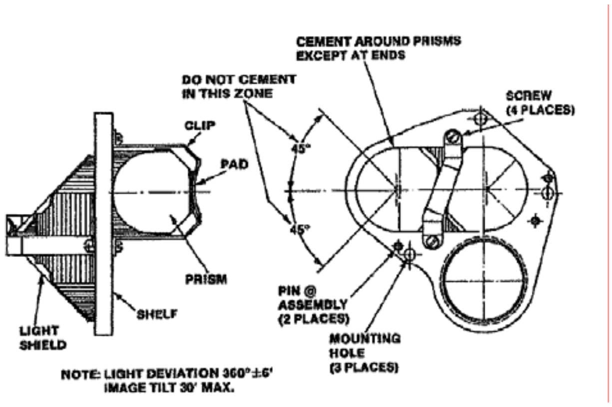


FIGURE 1.12 Nonkinematic Mounting Method (Clamping) [11]

Last method for mounting prisms is bonding. Many prisms are mounted by bonding their ground faces to mechanical pads using epoxy or similar adhesives. In this method, strong joints can be obtained with more simple mechanical design. If the mechanical design of a bonded prism mount is done carefully, it can withstand the severe shock and vibration, environmental conditions of military and aerospace applications. Main advantages of bonded prims mountings are simplicity and reliability [11]. In this type of mountings, the mismatch of the adhesive coefficient is not a problem since its thickness is small and the adhesive remains slightly flexible [8]. However, the mechanical designer of the mount should be careful about the thickness and area of the adhesive layer and the environmental conditions to be encountered [11]. In Figure 1.13, a porro prism bonded to a mechanical mount is seen.

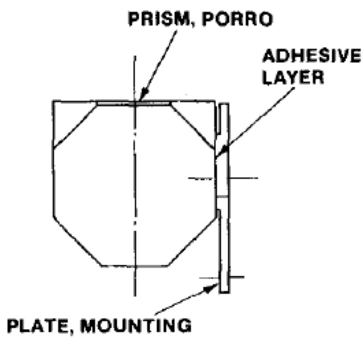


FIGURE 1.13 Bonding Method for Mounting of Prisms [11]

1.6 Adhesives Used in a Laser Device for Bonding Optical Components

Mostly, adhesives are used for mounting optical components such as prisms, lenses and mirrors. “Succesful implementation of adhesive mounts requires proper adhesive selection, correct application and process control.” Adhesive is defined as “A substance capable of causing one body to stick or adhere to another” [10]. Adhesives used in mounting of optical components are mostly structural adhesives (Adhesives are classified according to their chemistries, their form, their type and their load carrying capability. When adhesives’ laod carrying capability is considered, they are grouped as structural, semi-structural and non-structural adhesives [43]). Structural adhesive is “an adhesive of proven reliability in engineering structural applications in which the bond can be stressed to a high proportion of its maximum failing load for long periods without failure” [10]. The properties taken into account in adhesive selection for mounting optical components to mechanical components are viscosity, wetting, strength, CTE (Coefficient of Expansion), shrinkage during cure, Tg (Glass Transition Temperature) and out-gassing.

Viscosity is a measure of resistance to flow [10]. Viscosity is curicial for uncured adhesives since low viscosity adhesive will flow and spoil the clear aperture, “opening in the mount of an optical system that restricts the extent of the bundle of rays”, of the optical component [13,14].

Wetting is spreading on a solid surface (surfaces of the optical component and the mechanical component) of the uncured adhesive. This property is crucial for adhesion [14]. Strength of the cured adhesive is also important for carrying the optical component on its housing.

CTE of the cured adhesive is important in applications where wide temperature range exists. Different CTE values of mechanical component material, optical component material and adhesive will result in high stress on optical components that are brittle. In other words, different CTE values may cause breakage of the optical component. Also, stress can lead to birefringence on the optical component. Birefringence is “a property of an anisotropic material where two differing indices of refraction exist for orthogonal planes of incident polarization" [15]. Birefringence is especially important in lasers since they are polarization dependent systems.

Shrinkage during cure is the volume reduction of the adhesive during adhesive curing. This is a general property for all adhesives but amount of it may differ. Low shrink adhesives are chosen in optical systems since shrinkage causes movement of the optical element in the mechanical housing. Movement of the optical component leads to deterioration of positioning of the optical element [10]. Moreover, high shrinkage of the adhesive during cure may cause birefringence on the optical component.

Glass transition temperature is a range where most of the physical properties of the adhesive substantially changes. So, adhesives having Tg values out of the range of operating temperature are chosen in optomechanical applications [10].

Out-gassing is release of constituents of adhesive during cure or throughout the life-time. Out-gassing is a key factor especially for space applications and laser systems. It damages optical surfaces of laser systems. There are two measures of out-gassing named as TML (Total Mass Loss in %) and CVCM (Collected Volatile Condensable Material in %). NASA defines that an adhesive with TML<1% and CVCM<0.1% as low out-gassing adhesive. In optomechanical systems used in laser applications, low out-gassing adhesives are chosen [10,14].

Adhesives used in optical systems can be classified as Epoxy Resin Adhesives, Polyurethane's, Silicone-Based RTV's (RTV: Room Temperature Vulcanizing), Acrylic Adhesives and UV-Cured Adhesives [10].

Epoxy Resin Adhesives, thermosetting polymers, are mostly composed of two parts named as resin and hardener. The hardener can be named as activator since it is required for conversion to cured stage of the adhesive. These adhesives are generally considered as structural adhesives and they are widely used in optomechanical engineering for mounting optical components to mechanical components [16]. It should be noted that mix ratio of the resin and the hardener of epoxy resin adhesives is critical [10].

Polyurethane is an another type of adhesive used in mounting optical components to mechanical components. Polyurethanes' may be either in one component form or in two component form. Because of their flexibility, polyurethanes' are also used in the manufacture of gaskets, elastomeric wheels and tires, automotive suspension bushings [17].

Silicone-Based RTV is a type of silicone rubber that is composed of two parts. This type of adhesive cures at room temperature by vulcanization which is chemical process for converting rubber into more durable materials [18]. Silicone-Based RTVs are developed as sealants.

Acrylic adhesives are the "synthetic adhesives made from derivatives of acrylic, methacrylic and cyanoacrylic acids" [19]. Some types of acrylic adhesives can be rapidly cured by use of UV cure [10]. Rapid cure of the adhesive decreases the application time of the adhesive application. Also, acrylic adhesives have low modulus resulting in low stress on the optical bond, high strength and low shrinkage [20]. However, they have poor temperature performance [10].

UV-Cured adhesives are the ones that are mostly one part. They have low shrinkage and low-outgassing properties. UV-Cured adhesives cure in seconds with UV radiation and provide great adhesion on both optical component and mechanical component of the optomechanical assembly [10]. Since rapid cure is an advantage of UV-Cured adhesives, they are mostly used in positioning of the optical compounds [20].

In short; high strength, precise alignment stability, low stress birefringe, low out-gassing, convenient wetting, viscosity, CTE and Tg is expected from the adhesive used in laser system for mounting optical components to mechanical components.

1.7 Advantages and Disadvantages of Using Adhesives

Adhesive based mounting of optical components is attractive for optomechanical designers because it decreases interface complexity and provides compact packaging

[21]. Compact packaging and reduced interface complexity result in minimal parts in the assembly of optomechanical mount. Moreover, using adhesives provides uniform distribution of stress, shock and vibration dampening [10].

Using adhesives has also some disadvantages. In adhesive application, surface preparation of both optical component and mechanical component is critical. Surface preparation is done for achievement of required bond quality. For mechanical components, surfaces should be coated appropriately. (i.e., aluminum surfaces should be anodized, titanium surfaces should be anodized or vapor honed, stainless steel surfaces should be passivated.) Surface preparation of optical and mechanical components is done by ultrasonic cleaning. Moreover, acetone and/or methyl alcohol is applied to optical and mechanical surfaces for better surface preparation. Necessity of holding fixtures is an another disadvantage of using adhesives. Holding fixtures are required in order to be certain about the position of the optical component during cure of the adhesive [10].

1.8 Motivation of the Current Study

The laser system is very sensitive to any misalignment that will occur inside the cavity. So, optomechanical design, holding the lenses, prisms and mirrors inside the cavity, should be very stable.

In the systems that are designed in ASELSAN Laser Systems Design Department, it was encountered that adhesive layer assembling the prisms and optomechanical mounts broke off after mechanical shock exposure of the system (Mechanical shock applied to the system is 40g for 6ms). In order to understand the reason of the rupture of the adhesive layer, optomechanical designs of the prism mounts should be examined for a dynamic load of 40g. For the examination of the optomechanical designs, mathematical correlations derived by Yoder will be used.

Optomechanical designs for bonding based mounting of circular components (mirrors, lenses etc.), are also examined in this study. As stated before, the laser system is very sensitive to any misalignment. In an ideal laser cavity (Figure 1.14), active material, i.e. rod, slab, etc., and mirrors placed at both ends of the active material (these two mirrors construct the resonator) are parallel to each other. One of the mirrors is high reflector and the other one is partial reflector. Laser comes out of the resonator from the partial reflector mirror side.

FIGURE 1.14 Ideal Laser Cavity

Ideal laser cavity can be provided in an laboratory environment by use of precise alignment tools. A laser system designed for harsh environmental conditions can also be adjusted as an ideal laser cavity in production phase. However, due to harsh environmental conditions, angular movement of the mirrors occurs. Angular movement of the mirrors causes degradation of the laser beam. According to the specifications defined in Laser Systems Design Department, degradation of the laser beam should be less than 10%.

Consider a typical laser cavity that has a length of 45cm with an energy output of 100 mJ (For such a laser cavity, pulse width can be approximated as 15 ns) and one of the mirrors (i.e., mirror#2-high reflector mirror) is tilted by an angle of α. Also, the length and diameter of the active material (laser rod) is 100 mm and 6 mm, respectively. Simple representation of the cavity is shown in Figure 1.15.

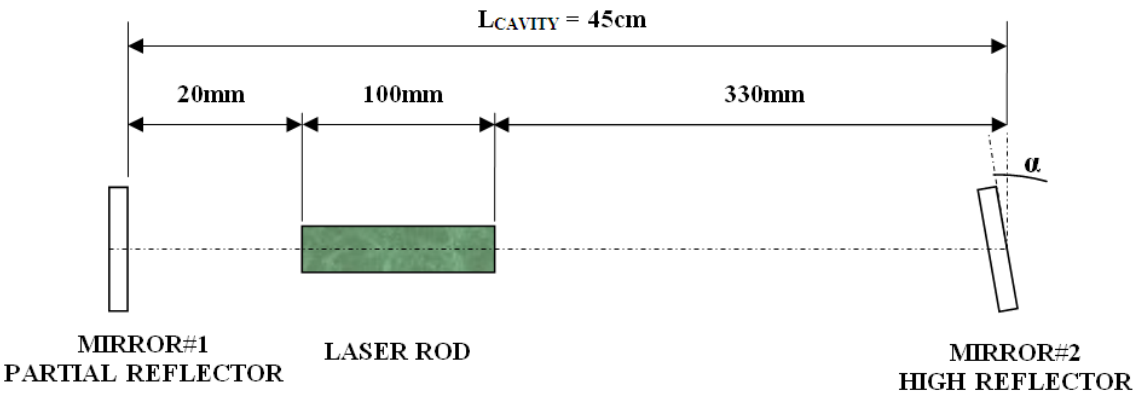


FIGURE 1.15 Sample Laser Cavity with High Reflector Tilted by an Angle of α

In order to determine the maximum angular movement (α) of the high reflector mirror to retain 90% of the laser power, number of rounds of the laser beam should be calculated. For the calculation of the bounce of the laser beam to each mirror, pulse width of laser beam, speed of light and cavity length should be known (Pulse width = 15 ns, speed of light = $3X10^8$ m/s and L_{CAVITY} = 45 cm). Then,

$$\text{Number of Bounces} = \frac{3\times10^{8}\times15\times10^{-9}}{45\times10^{-2}} = 10 \tag{1.1}$$

In each bounce, diameter of the laser beam, so the laser energy, decreases due to the tilted mirror. Diameter of the laser beam becomes in each bounce is calculated as follows;

$$D_0 = 6 \text{ mm} \tag{1.2}$$

$$D_1 = 6-(100+20)\tan(\alpha) \tag{1.3}$$

$$D_2 = D_1-(100+330)\tan(\alpha) \tag{1.4}$$

$$D_3 = D_2-(100+20)\tan(2\alpha) \tag{1.5}$$

$$D_4 = D_3-(100+330)\tan(2\alpha) \tag{1.6}$$

$$D_5 = D_4 - (100+20)\tan(3\alpha) \tag{1.7}$$

$$D_6 = D_5 - (100+330)\tan(3\alpha) \tag{1.8}$$

$$D_7 = D_6 - (100+20)\tan(4\alpha) \tag{1.9}$$

$$D_8 = D_7 - (100+330)\tan(4\alpha) \tag{1.10}$$

$$D_9 = D_8 - (100+20)\tan(5\alpha) \tag{1.11}$$

$$D_{10} = D_9 - (100+330)\tan(5\alpha) \tag{1.12}$$

When the laser beam bounces from the mirror that is tilted by an angle α, angle of the beam increases by α. Also, 90% of laser energy means that area of the beam while leaving the cavity from the partial reflector mirror is 0.9 times the laser rod area. Then, D_{10} can be calculated as;

$$D_{10} = \mathrm{sqrt}(0.9\times6^2) = 5.7 \text{ mm} \tag{1.13}$$

By use of the equations from 1.1 to 1.13,

$$D_{10} = 5.7 \text{ mm} = 6-[(550)\times(\tan(\alpha)+\tan(2\alpha)+\tan(3\alpha)+\tan(4\alpha)+\tan(5\alpha))] \tag{1.14}$$

By solving the equation 1.14,

$$\alpha = (2.08\times10^{-3})^{\circ} = 36.3\ \mu\text{rad} \tag{1.15}$$

From 1.15, it is seen that 36.3 μrad angular tilt of high reflector mirror causes 10% of laser energy loss in a flat-flat mirror laser cavity. In short, mounting of lenses and or mirrors causing the least angular movement under harsh environmental conditions will be examined in this study.

1.9 Outline of The Thesis

In this thesis, mounting methods of prisms and mirrors used in a laser system are investigated. While mounting both prisms and mirrors, bonding method is preferred and optomechanical analysis and experimental studies are carried out in bonded prism mounts and mirror mounts.

In Chapter 1, basic information about lasers such as laser definition and working principles of lasers, areas of usage of lasers and laser target designators and components of a laser device are introduced. Also, fundamental methods for mounting prisms and circular optical components (lenses and mirrors) are presented. Moreover, information about adhesives used for mounting lenses and prisms of a laser device and advantages and disadvantages of using adhesives are covered in this chapter. Then, the literature survey is presented in Chapter 2.

In Chapter 3, Mounting of Prisms, mounting of prisms with structural adhesives is examined and different optomechanical designs suitable for bonding different prisms are judged by use of some mathematical correlations. While judging the optomechanical designs, required bond area and designed bond area for prisms to withstand 40g acceleration are compared.

In Chapter 4, mounting of lenses with structural adhesives is covered. Optomechanical designs for bonding mirrors, adhesives selected for bonding and their mechanical properties are introduced in this chapter. Moreover, experimental set-up and results of the experiments for finding the most stable optomechanical design and adhesive combination are explained.

CHAPTER 2

LITERATURE SURVEY

There are many studies in mounting of optical components; some give general information about optomechanical mounting methods of lenses, prisms and mirrors and adhesives for bonding optical componentsa and others discuss the specific techniques for mounting optical components for specific environmental conditions.

Lake and Hachkowski [22] have written "Mechanism Design Principles for Optical-Precision, Deployable Instruments" for a guide for the design of "Microdynamically Quiet" deployment mechanisms for optical-precision structures. Main concern of the study was deployment mechanisms. However, there were some guidelines for optomechanical designs. In the study, it was stated that there should not be any direct load path on the optomechanical structure. Also, it was stated that mechanical interfaces of opto-mechanical mounts should be non-conforming in order to be certain about the stress on the mount. Non-conforming interface geometry was adviced since conforming ones were strongly dependent on the match of the surfaces mounted.

D.W. Coffey and V.J. Norris [23] studied Q-Switched Nd:YAG laser target designator and range finder systems. They described laser transmitter fundamentals i.e., excitation, resonator and q-switching and range receiver fundamentals i.e., receiving optics, photodetector, detector electronics and range counter. Moreover, they studied the effect of thermal gradients on the output energy of laser. Then, it was stated that angular movement of the resonator mirrors greater than 0.5 mrad reduces output energy at least 10%.

Bayar [24], in Lens Barrel Optomechanical Design Principles, presented the task of optomechanical engineer in the design of lens barrel. Barrel design was classified as barrel material selection, element mounting techniques and special optomechanical tasks. In barrel material selection part, he investigated some extensively used materials, i.e., aluminum, stainless steel, titanium and beryllium, and the reasons for using these materials. In element mounting techniques, he explained the methods for mounting of lenses under radial constraints and axial constraints. Also, he explained cementing of lenses (doublets) and lens-sealing in special optomechanical tasks section.

Fisher [25] designed an ultra-precise projection lens that had a storage temperature range of -55ºC and +95ºC. The tolerances of the optical systems was tight so the optomechanical design should not cause tilt and decentration of the lens system. For the optomechanical design, he tested different materials such as stainless steel, titanium and aluminum at temperature extremes. Based on the experiments, he decided to use titanium as the optomechanical design material. However, with guidance of Daniel Vukobratovich, he decided to bond each lens with an adhesive, 3M-2216, to a subcell, made of stainless steel, then mount to the housing. All optomechanical materials in the design were stainless steel and it was seen that the design worked well. Also, he recommended such mechanical design and lens mounting in his paper.

Freitas, Abreu, Rodrigues and Carvalho [26] investigated the effects of mechanical vibrations on the profile and shape of laser beams. In order to determine the effects of mechanical vibrations that airborne laser systems were subjected, especially for the ones installed on jet airplane in the forward half of the fusalage, they conducted experimental study. Experimental set-up of the study was composed of a shaker, a laser emitter, a CID (Charge Injection Device) camera and a computer. After measurements, it was stated by the authors that divergence of the laser beam for the static case and vibratory case were different. In the measurements, they monitored variation of the area of the laser beam and they observed that the area of the laser beam increases. They noticed that enlarged laser beam reduces the performance of the laser system.

In the study “Some Thoughts on Lens Mounting” [27], Robert E. Hopkins presented different methods of mounting and centering lenses into lens barrels with a collimator (Collimator is mostly used to calibrate optical devices and align optical systems). According to him, precision and tight tolerances were not required on all dimensions of the lens barrel, lenses and spacers for excellent centering of lenses. Also, he stated that it was more difficult to manufacture precise lens barrel, lens and spacer than centering them with a collimator. By use of collimator set-up, he could assemble different lens groups with different methods in nearly exact centration. On the other hand, the method he presented complicated the assembly procedure.

Blanchard [28] described a precise lens mounting technique to withstand thermal changes, thermal shock, mechanical vibrations and mechanical shock. He compared lens mounting with retaining ring technique and lens mounting with elastomer material (adhesive). He preferred to mount lenses with adhesive since it was more advantageous under extreme environmental conditions. Moreover, he described different methods for centering lenses (i.e., mechanical shimming and optical centering device).

Bachmann, Arnold and Langer [15] compared Epoxy adhesives and UV-Cured adhesives in terms of shrinkage on cure, coefficient of thermal expansion (CTE) and glass transition temperature (Tg). They defended and analyzed that an optical adhesive should have low shrinkage on cure, convenient CTE and small Tg effect. Also, they stated that high shrinkage on cure, high CTE and high Tg effect were the causes of stress on an optical element. Finally, effects of stress on optical elements were sampled.

Jones [29] developed a mounting method for lenses demanding high performance. Firstly, he described the needs for developing precise mounting technique. The needs were high resolution, large f numbers (focal ratio) and wide environmental specifications. The technique required to maintain both optical and mechanical performance stable during all environmental tests. He tried his mounting technique design at an existing lens system in order to designate its influence in technical and economical aspects. Then, he mounted an optical system of aerial survey and a infrared objective lens system. In both, he mounted lenses into a cell by use of silicone rubber adhesive. Both had achieved the predicted performance with long term stability and resistance to environmental damage.

Krevor, Vazirani and Xu [30] reviewed environmental conditions that optical adhesives sustain in military applications. They also reported differences and similarities of the adhesives used in civilian and military applications. Moreover, they grouped military environment as climatic environment and manmade environment. They discussed temperature, humidity and rain, fungus, solar radiation and salt atmosphere effects as climatic environmental effects. On the other hand, they discussed the effects of aircraft fluids, chemical warfare agents, vibration and shock as manmade environment. Finally, they emphasized the importance of adhesive selection to be used in military environment.

Krim [31] presented differences between past space-based optical systems and recent space-based optical systems. He stated that the main difference was at economical aspect. Moreover, he reviewed difficulties of optical systems for space operation. He grouped difficulties of space-based optical systems as cost, weight and mirror mechanical design, mirror support systems, drawings, modeling and analysis. For each group of difficulties, he provided a guide for the space-based optical system more economically.

John G. Lecuyer [32] investigated optomechanical mounting techniques for optical systems that have to withstand high shock situations. He examined mounting systems in both optical and mechanical aspects. From optical aspect, he concentrated on nonuniform index of refraction, residual strain, incorrect radius of lens and incorrect centration. According to him, optical errors were beyond the influence of the designer. Also, he concentrated on lens spacing, nonperpendicularity of lens system to the optical axis and eccentricity of lens to the optical axis as mechanical aspect. He mainly concentrated on element spacing, element decentring and element tilt since he was looking for an analytical method. However, uniqueness of each lens system retained him. Then, with the knowledge of the effects of spacing, decentring and tilt on the system performance, he studied and tested different mounting techniques of lenses and mirrors. In short, he expressed different mounting techniques for mounting lenses and mirrors satisfying required element spacing, decentring and tilt without any loss in system performance under high shock environment.

Rhodes [20] compared early generated (first generation) UV adhesives, epoxies and newly generated UV aerobic acrylic adhesives. He mainly discussed the advantages of UV aerobic acrylic adhesives over first generation UV adhesives and epoxies in terms of cure speed, shrinkage on cure, modulus and strain. Also, he explained the effects of modulus and shrinkage of an adhesive on the optical bond stress. Moreover, he presented types of curing lamps for UV aerobic acrylic adhesives, their properties and importance of selecting optimal curing system. Finally, he stated some uses of these adhesives.

Gibb [16] examined two part epoxy adhesives. Firstly, he described basic properties of two part epoxy adhesives, their advantages and their application areas. Although there are wide variety of application areas of two part epoxy adhesives, he concentrated on the use of them for optomechanical applications. He also presented some vendors of two part epoxy adhesives and some properties of those vendors' products. Moreover, he explained ways of applying and removing those adhesives on different substrates.

John G. Daly and Damien J. Daly [14] investigated the bonding performance of UV-Cured adhesives in terms of angular stability at different environmental conditions. They compared properties of UV-Cured adhesives, their ease of use with the adhesives generally used in opto-mechanical engineering. In the paper; they firstly introduced progresses in adhesive industry, types of adhesives and adhesive properties. Then, they clarified the methodology used in adhesive comparison. They conducted several tests to observe the angular stability of optomechanical bonding under thermal exposure, vibration and shock exposure and post cure. For the tests, they used 1" diameter with 0.25" thickness lenses made of BK-7, Pyrex and Fused Silica mounted on 5 different geometries, i.e., flat plate, three-raised plane pads, counter-bored recessed cell with a through hole, counter-bored opening with a through hole and side holes for injected edge bonding and flexure designed bond, made of three different materials (black anodized aluminum, titanium and gold plated invar). In the tests, angular movement of lenses were monitored with an autocollimator with respect to diamond-polished mirror surfaces that appeared on each test plate. Finally, they presented the test results of black anodized aluminum plates for different glass materials, different adhesives and different bonding geometries. Also, they supported that UV adhesives could be a substitute for traditional adhesives.

In “Design Guidelines for Bonding Prisms to Mounts”, Paul R. Yoder, Jr. [21] derived formulas relating prism clear aperture, prism material density, loading due to acceleration to minimum bond area for an epoxy for several prism types (i.e., monolithic cube, beamsplitter cube assy., right angle prism, rhomboid prism, amici prism, schmidt prism, penta prism, roof penta prism, harting-dove prism, “reversion” assy. prism, pechan assembly prism, delta prism, porro prism, porro erecting assy. prism, abbe prism, abbe erecting assy. prism). Since the formulas derived by Yoder were based on some predictions, they should be assumed as fore design step. The formulations were based on 3M EC-2216 A/B epoxy’s specified shear strength and for different adhesives a correction factor should be added to formulations. In the formulations, he stated required bond area, maximum bond area for circular and racetrack adhesion surfaces for 16 different prism types stated above. Moreover, he made a sample calculation for a cube prism bonding to represent how to use the derived formulas.

Paul R. Yoder, Jr. also [8] covered the reason of durable optomechanical design for application in industrial environment. Firstly, he discussed the optomechanical design process in subtopics as “conceptualization, performance specifications and design constraints, preliminary design, design analysis and computer modeling, error budgets and tolerances, experimental modeling, finalizing the design, design reviews, evaluating the end product and documenting the design”. Then, he expressed some industrial areas where optical systems are used. Moreover, he explained different methods for mounting lenses, mirrors and prisms to mechanical interfaces. He also stated sealing methods for optical systems.

In the literature, different mounting techniques for mounting of lenses, mirrors and prisms were investigated. Effects of harsh environmental conditions, i.e., thermal shock, mechanical vibrations and mechanical shock, on optical systems and precautions for these effects has been learnt. In other words, different approaches for mounting of optical components for harsh environmental conditions have been learnt from the literature. Mainly, bonding methods for mounting of optical components were searched in the literature. So, adhesive types for bonding optical components were surveyed. Moreover, effects of military environment on optical adhesives were investigated. According to the sources about adhesives used for optical bonding, it has been learnt that mainly UV-Cured adhesives and epoxies are used for bonding optical components.

"Design Guidelines for Bonding Prisms to Mounts" [21] and "Structural Adhesives for Bonding Optics to Metals: A Study of Opto-mechanical Stability" [14] were the primary studies forming this thesis. From [21], some mathematical correlations used for examination of bonding of prisms were learnt. As stated before, mathematical correlations were obtained for 3M EC-2216 A/B epoxy adhesive in [21]. However, in this study, mathematical correlations will be modified for different adhesives. From [14], methodology used for measuring angular movement of mirrors was learnt. In this study, the methodolgy have been used to monitor the effects of adhesive cure, thermal shock, mechanical vibrations and mechanical shock.

CHAPTER 3

MOUNTING OF PRISMS

This chapter explains mounting of prisms by using adhesives named as “Bonding Method”. Firstly, prism types and adhesives used in the study are introduced. Also, bonding areas of prisms with different adhesives are compared in order to determine suitability of the optomechanical design for vibrational effects.

3.1 Mounting of Prisms with Structural Adhesives

Mounting method decision in optical systems is the first step for the design phase. Prisms can be mounted mainly in four ways (i.e, kinematic mounting, semikinematic mounting, nonkinematic clamping and bonding). In this study, bonding method is selected because of the small dimensions of the prisms to be mounted. In kinematic mounting, semikinematic mounting and nonkinematic clamping methods, it is hard to control stress on small optical components. Stress on optical components causes stress-birefringence zones that are harmful for polarization dependent systems. Since our concern in this study is a laser system (polarization dependent), any stress on the optical element will cause laser beam to deteriorate. Also, it should be noted that bonding method is the simplest, cheapest and least volume covering method among four methods mentioned. However; optomechanical design, adhesive selection and application of the adhesive are critical points of this method.

Optomechanical design for mounting optical components should be secure and reliable. For secure and reliable design;

- Clear aperture of the optical component should not be blocked,

- CTE of the mechanical component material and the optical component material should match,
- Mechanical component should not stress the optical component,
- Mechanical design should provide easy bonding,
- Mechanical design should provide required bonding area,
- Bonding area should be on the ground surface (surface on which polishing is not applied) of the optical component to provide proper bonding,
- Mechanical desing should operate at the environmental conditions required.

Adhesive is the main and the only component carrying the optical component load in bonding so adhesive selection is important. While selecting an adhesive to be used to mount prisms to mechanical components in a laser system, it should be considered that;

- Adhesive should be a structural adhesive,
- Adhesive should be low-outgassing,
- Adhesive should be suitable for bonding optical components to metal components,
- Working temperature range of the adhesive should be suitable with the system operating and storage temperature range,
- Glass Transition Temperature (Tg) of the adhesive should not be within the operating temperature range of the system,
- Viscosity of the adhesive should be appropriate for the application such that adhesive should not leak through the clear aperture of the optical component,
- Adhesive shrinkage during cure should not be high in order not to stress the optical component.

Application of the adhesive is also critical in bonding method. During the application process of the adhesive, it is important that;

- The optical component's surface to be bonded (ground surface) should be clean (clean mechanical surface can be achieved by wiping the optical surface by acetone and/or methanol),
- The mechanical component to be bonded should be clean (clean mechanical surface can be achieved by cleaning the mechanical part in an ultrasonic cleaner),
- Leakage of the adhesive through the surfaces of the optical component rather than the surface to be bonded should be prevented.

Prisms bonded to their mechanical mounts are used in a laser system whose storage temperature is between -40ºC and +70ºC. The system operating temperature range is -32ºC and +52ºC. Moreover, the system is designed for a 40g acceleration level. With the help of the rules about optomechanical design and adhesive selection stated above, two different adhesives are selected to bond seven different prisms to seven different mechanical components. Adhesives selected for bonding those prisms are named as "MILBOND" from SUMMERS OPTICAL and "MASTERBOND-EP21TDC-2LO" from MASTERBOND INC. These adhesives are selected for bonding prisms because of their operating temperature range and viscosity. For bonding prisms, the adhesives should be less viscous than the adhesives selected for bonding lenses. It is also important that these two adhesives are low out-gassing.

Prisms that are bonded with the adhesives stated above are Beamsplitter Cube Assembly, Harting Dove Prism, Porro Bend Prism, Porro Cut Prism, Two Different Retro Reflector Prisms and Right Angle Prism (Figure 3.1).

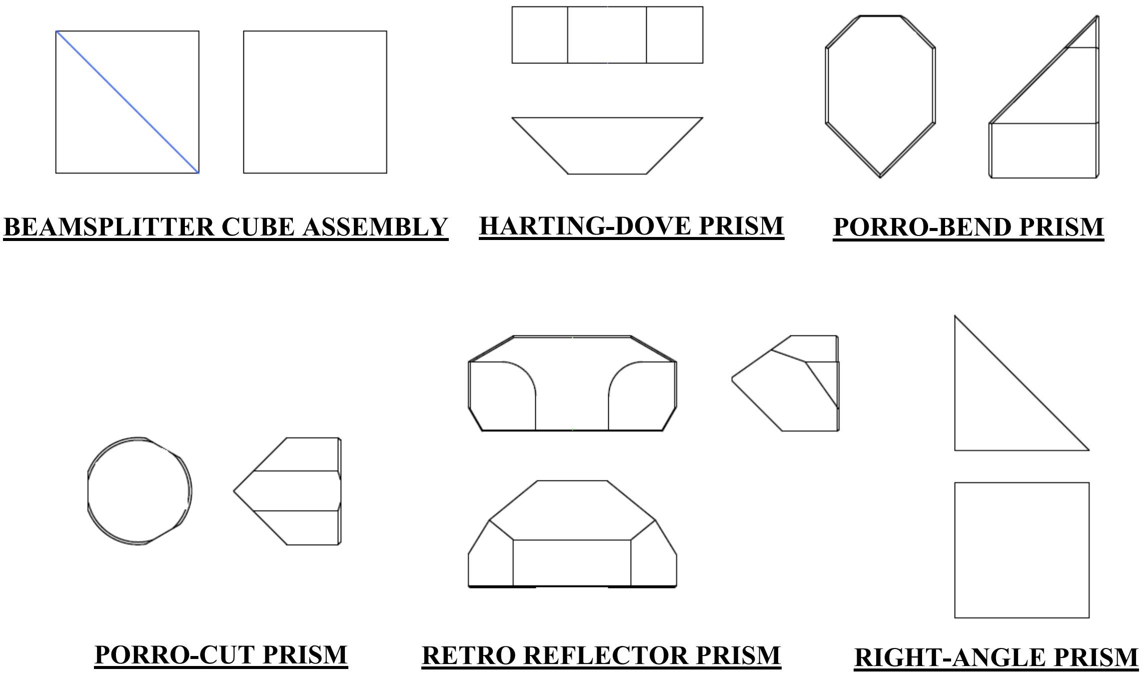


FIGURE 3.1 Prisms Examined in This Study

In the optomechanical design for bonding, mechanical material is selected as titanium since material of all the prisms stated above are Schott N-BK7 Glass. Titanium has CTE of 8.9 µm/m-ºC and Schott N-BK7 Glass has CTE of 7.1 µm/m-ºC [33, 40]. In the design of mechanical mounts for bonding prisms, CTE of the prisms and mechanical mount is considered because there are mechanical contact areas between the prisms and the mechanical mounts. In other words, CTE match of the prism material and mechanical mount material is considered while selecting the mechanical mount material because of the mechanical contact between the prism and mechanical mount.

3.2 Design Calculations for Prism Mounts for Vibrational Effects

In this study, optomechanical mounting of six different prisms with bonding method are analytically examined for a dynamic load of 40g. Dynamic load is determined according to MIL-STD-810F (Table 3.1). MIL-STD-810F is a military standart in which all environmental specifications, such as temperature, vibration, shock etc., are specified for worst conditions.

TABLE 3.1 Test Shock Response Spectra [38]

Test Category	Peak Acceleration (g's)	T_e (ms)	Cross-over Frequency (Hz)
Functional Test for Flight Equipment	20	15-23	45
Functional Test for Ground Equipment	40	15-23	45
Crash Hazard Test for Flight Equipment	40	15-23	45
Crash Hazard Test for Ground Equipment	75	8-13	80

In Table 3.1, peak acceleration represents the acceleration level applied to the system to be tested. Te represents the duration of the mechanical shock and cross-over frequency represents the frequency at which the maximum acceleration level should be applied. For example, for functional test for flight equipment, 20g mechanical shock profile is applied to the system for 15-23 ms and 20g acceleration level should be achieved at 45 Hz.

Prism mounts designed are used in both ground laser systems and air laser systems. In Table 3.1, it is seen that functional mechanical shock test for flight equipment requires 20g acceleration whereas functional mechanical shock test for ground equipment requires 40g acceleration. Dynamic load for the optomechanical system is selected as 40g since it is the highest acceleration level for functional mechanical shock tests. The quality of the bonding to survive under 40g dynamic load is examined with a method explained in “Design Guidelines for Bonding Prisms to Mounts” [21]. Although this method is used as a preliminary design guide for bonding prisms to optomechanical mounts, it tells the designer that whether bonding area is adequate or not for the dynamic loading specified. In [21], 16 different prisms are considered and design parameters for those prisms are given. However, 6 different prisms (prisms mostly used in the systems designed in ASELSAN Laser Systems Design Department) and their optomechanical mounts are examined in this study. Prisms that are examined are, as stated before, Beamsplitter Cube Assembly, Harting-Dove Prism, Porro-Bend Prism, Porro-Cut Prism, Retro Reflector Prism and Right-Angle Prism. Also, it should be stated that in [21] all mathematical correlations are given for 3M EC-2216 A/B adhesive's shear strength. So, for different adhesives as MILBOND and MASTERBOND–EP21TDC-2LO, a correction factor is applied. Correction factor for different adhesives is calculated as;

$$\text{Correction Factor, } C = \frac{\text{Shear Strength of 3M EC-2216 A/B}}{\text{Shear Strength of Other Adhesive}} \tag{3.1}$$

Shear strength values of the cured adhesives and correction factor for those three adhesives are calculated according to 3.1 as in Table 3.2.

TABLE 3.2 Shear Strength and Correction Factor Values for Selected Adhesives

ADHESIVE	SHEAR STRENGTH (GPa)	CORRECTION FACTOR (C)
3M EC-2216 A/B	13.8	1.000
MASTERBOND EP-21TDC-2LO	6.8	2.042
MILBOND	14.5	0.952

Mathematical correlations given for 3M EC-2216 A/B for the prisms considered in this study are given in Table 3.3.

TABLE 3.3 Mathematical Correlations for Bond Area Calculation of Prisms [21]

PRISM TYPE	*VOLUME (cm^3)*	*REQUIRED BOND AREA(cm^2)*	*MAXIMUM BOND AREA-CIRCULAR (cm^2)*
ABBE	$1.84A^3$	$2.62 \times 10^{-5} \times A^3 \times d \times G$	$0.46A^2$
PORRO	$1.29A^3$	$1.83 \times 10^{-5} \times A^3 \times d \times G$	$0.51A^2$
HARTING-DOVE	$3.90A^3$	$5.54 \times 10^{-5} \times A^3 \times d \times G$	$0.95A^2$
RIGHT-ANGLE	$0.50A^3$	$7.10 \times 10^{-6} \times A^3 \times d \times G$	$0.27A^2$
BEAMSPLITTER CUBE ASSY.	A^3	$1.42 \times 10^{-5} \times A^3 \times d \times G$	$0.27A^2$

In order to illustrate the technique used for derivation of the mathematical correlations, consider a cube prism which is similar to the beamsplitter cube assembly prism (Figure 3.1). Let an edge length of this prism as A [cm] and so the volume of the prism is A^3 [cm^3]. Also, consider the density of the glass material (d) as in unit g/cm^3. If one assumes the minimum bond area as Q [cm^2], acceleration exposed to the bonding as G times gravitational acceleration and shear stress unit in N/m^2, then shear stress on the bonding is expressed as $9.81\times A^3\times d\times G/Q$. As stated before, Yoder derived mathematical correlations for 3M EC-2216 A/B adhesive which has a maximum allowable shear strength of 1.38×10^{10} [N/m^2] (13.8 GPa). So, by considering maximum allowable shear strength of the adhesive and shear stress on the bonding with a safety factor of 2, minimum bond area (Q) is computed as $1.42\times10^{-5}\times A^3\times d\times G$.

Different types of prisms on different optomechanical mounts will be compared in terms of adhesive amount under mechanical vibration. Comparison is done according to calculations that are included in [21].

3.2.1 Design Calculations for Beamsplitter Cube Assembly Prism

For the beamsplitter cube assembly, the mathematical correlation is given as in Table 3.4.

TABLE 3.4 Mathematical Correlations for Bond Area Calculation of Beamsplitter Cube Assembly Prism [21]

PRISM TYPE	*VOLUME (cm^3)*	*REQUIRED BOND AREA(cm^2)*	*MAXIMUM BOND AREA-CIRCULAR (cm^2)*
BEAMSPLITTER CUBE ASSY.	A^3	$1.42 \times 10^{-5} \times A^3 \times d \times G$	$0.27A^2$

Since beamsplitter cube assembly prism is made of BK-7 glass, optomechanical mount material is chosen as titanium for CTE match. Moreover, "***d***" in the formulation for required bond area represents the density of prism material. Density of BK-7 is 2.51 [g/cm^3] [33]. For this study, optomechanical mount design is as in Figure 3.2.

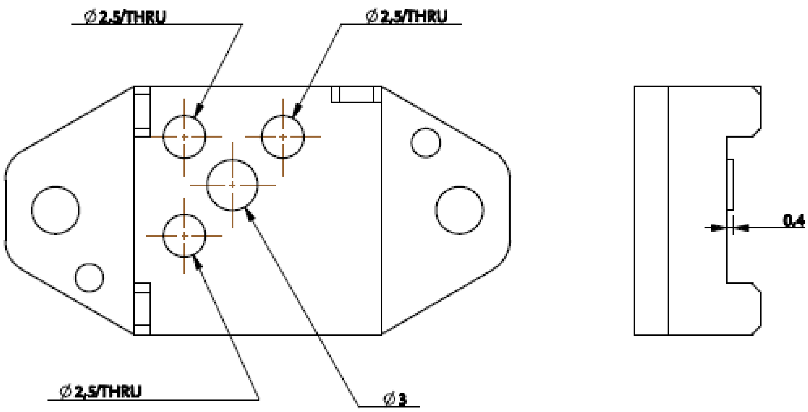


FIGURE 3.2 Optomechanical Mount Drawing for Beamsplitter Cube Assy.

Above, there are three Ø2.5 mm through holes for bonding prism to the mechanical mount. Also, Ø3 mm boss with height of 0.4 mm is done to satisfy the required bond thickness of the adhesive. For the design calculations, beamsplitter cube prism assembly dimensions such as volume or side length should be known. Beamsplitter cube assembly prism dimensions are as in Figure 3.3 (dimensions of the beamsplitter cube assembly are in mm).

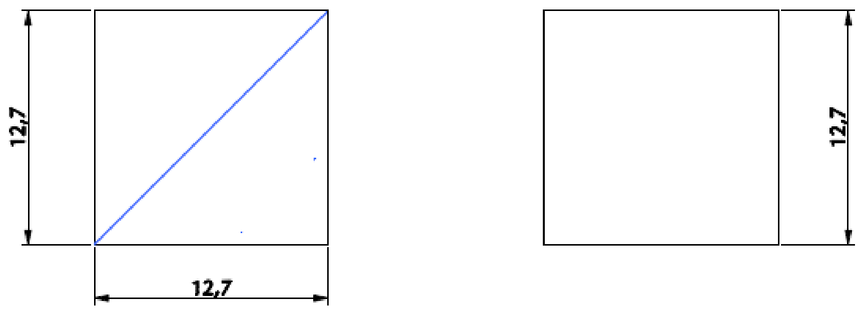


FIGURE 3.3 Engineering Drawing of Beamsplitter Cube Assembly Prism

$$\text{Volume of Beamsplitter Cube Assembly Prism} = (1.27)^3 = 2.05\ \text{cm}^3 \tag{3.2}$$

$$\text{Required Bond Area} = 1.42\times10^{-5}\times2.05\times2.51\times40 = 2.92\times10^{-3}\ \text{cm}^2 \tag{3.3}$$

Above, required bond area is calculated for 3M EC-2216 A/B adhesive since correlations are derived for that adhesive (Note that required bond area represents minimum bond area). So, the result calculated above should be corrected for different adhesives. Then,

$$\text{Required Bond Area for MILBOND} = 2.92\times10^{-3}\times0.952 = 2.78\times10^{-3}\ \text{cm}^2 \quad (3.3)$$

$$\text{Required Bond Area for MASTERBOND} = 2.92\times10^{-3}\times2.042 = 5.96\times10^{-3}\ \text{cm}^2 \quad (3.4)$$

The optomechanical design for Beamsplitter Cube Prism Assembly provides a bond area of 3 holes with a diameter of Ø2.5 mm. It can be named as "***Design Bond Area***". Then, provided design bond area is calculated as;

$$\text{Design Bond Area} = (3\times\pi\times0.25^2) / 4 = 0.147\ \text{cm}^2 \quad (3.5)$$

$$\text{Maximum Bond Area (Circular-cm}^2) = 0.27\times1.27^2 = 0.435\ \text{cm}^2 \quad (3.6)$$

With the results of the calculations, safety factor for the provided design bond area for the 40g condition can be calculated. (Safety Factor = Design Bond Area/Required Bond Area) For different adhesives, calculations are as follows.

$$\text{Safety Factor for MILBOND} = 0.147/(2.78\times10^{-3}) = 52.9 \quad (3.7)$$

$$\text{Safety Factor for MASTERBOND} = 0.147/(5.96\times10^{-3}) = 24.7 \quad (3.8)$$

It is also important to note that in [21], correlations were derived for a safety factor of at least 2. Then, overall safety factor is calculated as;

$$\text{Safety Factor for MILBOND} = 2\times52.9 = 105.8 \quad (3.9)$$

$$\text{Safety Factor for MASTERBOND} = 2\times24.7 = 49.4 \quad (3.10)$$

All results for the calculations are tabulated in Table 3.5.

TABLE 3.5 Safety Factor Values for the Bonding Design of Beamsplitter Cube Assembly Prism for Different Adhesives

ADHESIVE	*PRISM VOLUME (cm^3)*	*REQUIRED BOND AREA (cm^2)*	*DESIGN BOND AREA (cm^2)*	*MAXIMUM BOND AREA (cm^2)*	*SAFETY FACTOR*
3M EC-2216 A/B	2.05	0.00292	0.147	0.435	100.7
MILBOND	2.05	0.00278	0.147	0.435	105.8
MASTERBOND	2.05	0.00596	0.147	0.435	49.3

From Table 3.5, it can be concluded that optomechanical design is adequate for bonding Beamsplitter Cube Prism Assembly for an environment having a vibration level of 40g. In other words, it can be stated that the bonding supplied by the optomechanical design can support the beamsplitter cube assembly prism up to accelerations that are 4232 and 1972 times gravitational acceleration if bonded by MILBOND and MASTERBOND, respectively.

3.2.2 Design Calculations for Harting-Dove Prism

Mathematical formulation for calculating requried bond area and maximum bond area for Harting-Dove prism under vibration is as in Table 3.6.

TABLE 3.6 Mathematical Correlations for Bond Area Calculation of Harting-Dove Prism [21]

PRISM TYPE	*VOLUME (cm^3)*	*REQUIRED BOND AREA(cm^2)*	*MAXIMUM BOND AREA-CIRCULAR (cm^2)*
HARTING-DOVE	$3.90A^3$	$5.54 \times 10^{-5} \times A^3 \times d \times G$	$0.95A^2$

Material of this prism is also BK-7 glass so it has a density of 2.51 [g/cm^3]. Moreover, optomechanical mount material is titanium and design of the optomechanical mount is shown in Figure 3.4.

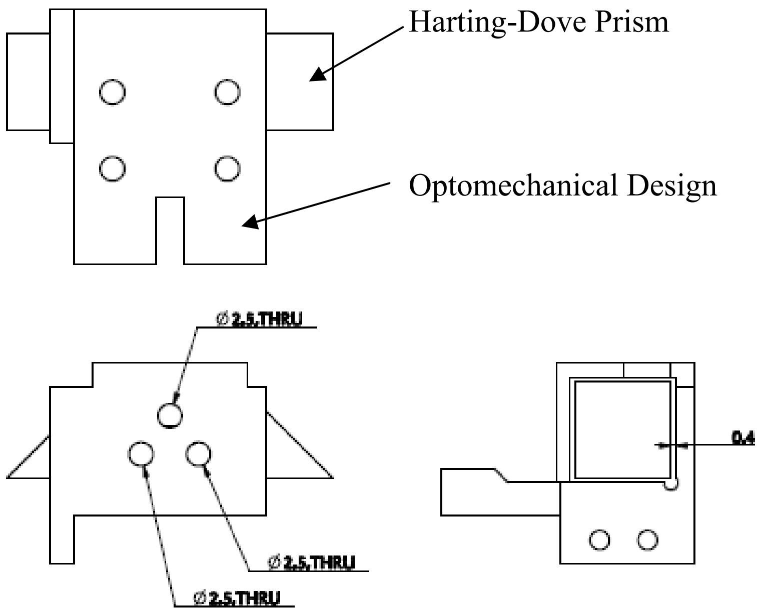


FIGURE 3.4 Optomechanical Mount Drawing for Harting-Dove Prism

In the design, there are three Ø2.5 mm through holes for bonding the prism to the optomechanical part. Also, there should be 0.4 mm thickness between optomechanical mount and the prism in order to satisfy adhesive requirement of 0.4 mm bonding thickness. This requirement is achieved by mechanical shimming in this design. After adhesive is cured, mechanical shims are removed from the assembly. In order to justify the design in terms of bonding area, volume and/or dimensions of the prism should be known. Harting-Dove prism drawing (dimensions on the drawing are in mm) is seen in Figure 3.5.

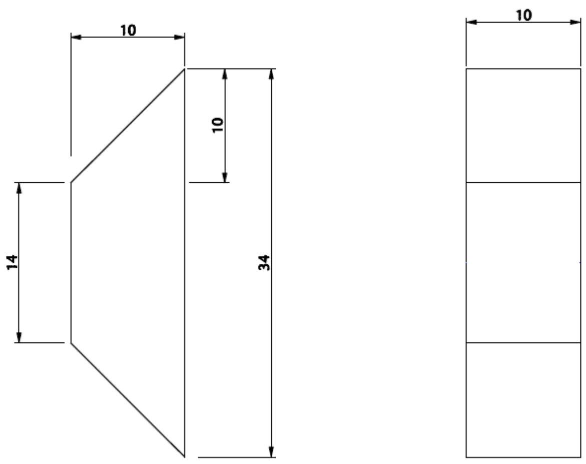


FIGURE 3.5 Engineering Drawing of Harting-Dove Prism

From the dimensions of the prism, volume can be easily calculated as;

$$\text{Volume of Harting-Dove Prism} = 2.4 \text{ cm}^3 \tag{3.11}$$

By using the correlations for Harting-Dove prism; required bond area, maximum bond area and safety factor can be tabulated for different adhesives as in Table 3.7.

TABLE 3.7 Safety Factor Values for the Bonding Design of Harting-Dove Prism for Different Adhesives

ADHESIVE	*PRISM VOLUME (cm^3)*	*REQUIRED BOND AREA (cm^2)*	*DESIGN BOND AREA (cm^2)*	*MAXIMUM BOND AREA (cm^2)*	*SAFETY FACTOR*
3M EC-2216 A/B	2.4	0.00342	0.147	0.687	85.9
MILBOND	2.4	0.00326	0.147	0.687	90.2
MASTERBOND	2.4	0.00699	0.147	0.687	42.1

Table 3.7 shows that optomechanical design for bonding Harting-Dove prism is can withstand accelerations up to 1684 times gravitational acceleration if bonded with Masterbond.

3.2.3 Design Calculations for Porro Bend Prism

Porro Bend prism that is used in this study is similar to Abbe prism mentioned in [21]. So, the correlations for the Abbe prism are used for Porro Bend prism in order to verify optomechanical mount and bonding technique used. Mathematical formulations about bonding area under vibration for Abbe prism is shown in Table 3.8.

TABLE 3.8 Mathematical Correlations for Bond Area Calculation of Porro Bend Prism [21]

PRISM TYPE	*VOLUME (cm^3)*	*REQUIRED BOND AREA(cm^2)*	*MAXIMUM BOND AREA-CIRCULAR (cm^2)*
ABBE	$1.84A^3$	$2.62 \times 10^{-5} \times A^3 \times d \times G$	$0.46A^2$

Materials of the prism and optomechanical mount are BK-7 and titanium, respectively. Engineering drawing for optomechanical mount is as in Figure 3.6.

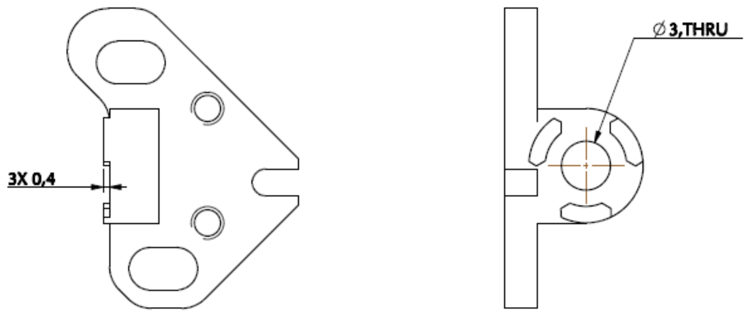
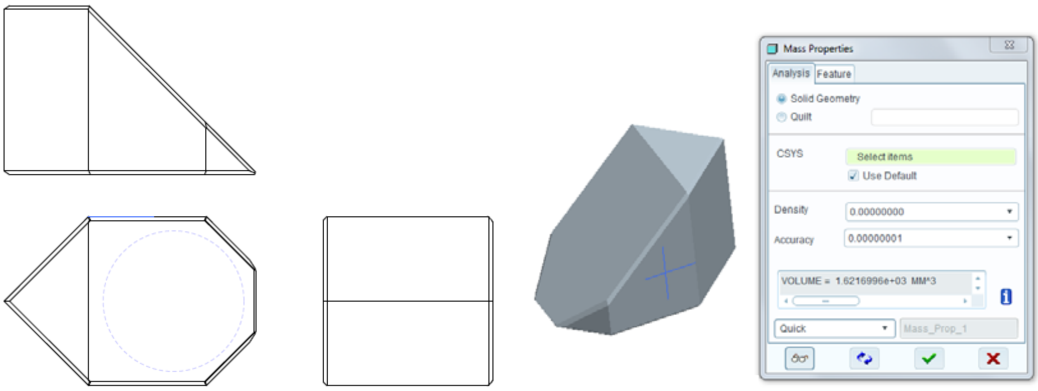


FIGURE 3.6 Optomechanical Mount Drawing for Porro Bend Prism

There are three bosses with height of 0.4 mm to satisfy required bond thickness of the adhesive. Moreover, optomechanical design provides Ø3 mm through hole to apply adhesive and bond the prism to optomechanical mount. Porro bend prism volume is required to calculate safety factor of the optomechanical design for different adhesives. Porro bend prism drawing and volume calculation is seen in Figure 3.7.



(a) **(b)**

FIGURE 3.7 a) Engineering Drawing of Porro Bend Prism, b) Volume Calculation Screen in PRO-ENGINEER®

Volume of the Porro Bend Prism is received directly from solid model done in PRO-ENGINEER WILDFIRE4®. Then,

$$\text{Volume of Porro-Bend Prism} = 1.6217 \text{ cm}^3 \tag{3.12}$$

By use of mathematical formulations for Abbe prism, all results can be tabulated as in Table 3.9.

TABLE 3.9 Safety Factor Values for the Bonding Design of Porro Bend Prism for Different Adhesives

ADHESIVE	*PRISM VOLUME (cm^3)*	*REQUIRED BOND AREA (cm^2)*	*DESIGN BOND AREA (cm^2)*	*MAXIMUM BOND AREA (cm^2)*	*SAFETY FACTOR*
3M EC-2216 A/B	1.6217	0.00232	0.071	0.423	61.0
MILBOND	1.6217	0.00221	0.071	0.423	64.1
MASTERBOND	1.6217	0.00473	0.071	0.423	29.9

Safety factor values for different adhesives used in the design indicates that optomechanical design for Porro Bend prism is adequate for vibration level of 40g. It can be concluded also that the bonding can withstand accelerations up to 2564 times gravitational acceleration if MILBOND is used as the adhesive for bonding the Porro Bend Prism.

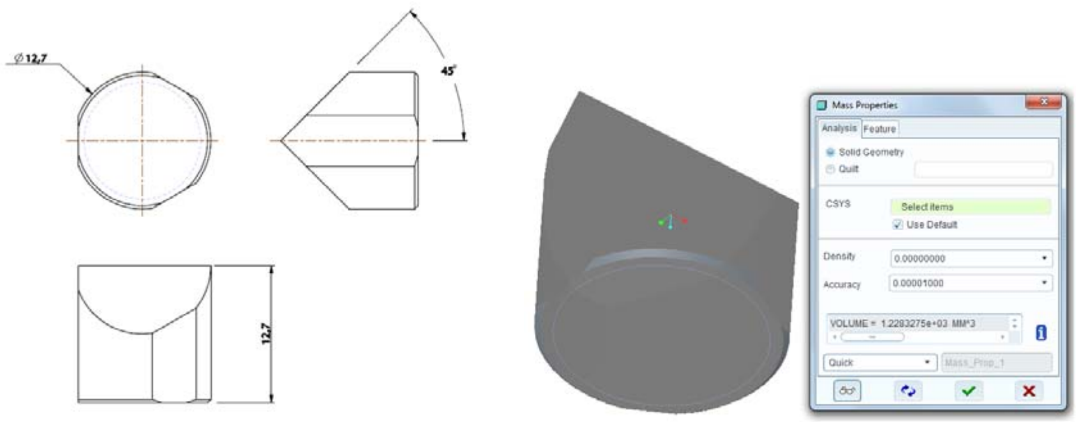
3.2.4 Design Calculations for Porro Cut Prism

For Porro Cut prism, the correlation given in the Table 3.10 is used.

TABLE 3.10 Mathematical Correlations for Bond Area Calculation of Porro Prism [21]

PRISM TYPE	***VOLUME (cm^3)***	***REQUIRED BOND AREA(cm^2)***	***MAXIMUM BOND AREA-CIRCULAR (cm^2)***
PORRO	$1.29A^3$	$1.83 \times 10^{-5} \times A^3 \times d \times G$	$0.51A^2$

Porro Cut prism is made of BK-7 and optomechanical mount is made of titanium. Mechanical drawing for both Porro Cut prism and optomechanical mount are as in Figure 3.8 and Figure 3.9, respectively.



(a) **(b)**

FIGURE 3.8 a) Engineering Drawing of Porro Cut Prism, b) Volume Calculation Screen in PRO-ENGINEER®

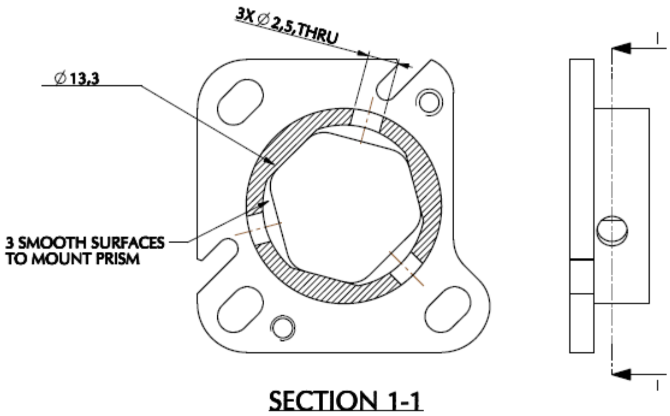


FIGURE 3.9 Optomechanical Mount Drawing for Porro Cut Prism

$$\text{Volume of Porro Cut Prism} = 1.2283 \text{ cm}^3 \quad (3.13)$$

From the figures, it is seen that there are 3 through holes with Ø2.5 mm for bonding Porro Cut prism to optomechanical mount. Moreover, it is seen that Porro Cut Prism is placed inside the optomechanical mount on three surfaces with a clearence of 0.3 mm. 0.3 mm clearence is calculated by subtracting the prism diameter (12.7 mm) from optomechanical mount inner diameter (13.3 mm) and dividing the difference (0.6 mm) by 2. Then, by using the correlations given for Porro prism all results can be calculated as in Table 3.11.

TABLE 3.11 Safety Factor Values for the Bonding Design of Porro Cut Prism for Different Adhesives

ADHESIVE	*PRISM VOLUME (cm^3)*	*REQUIRED BOND AREA (cm^2)*	*DESIGN BOND AREA (cm^2)*	*MAXIMUM BOND AREA (cm^2)*	*SAFETY FACTOR*
3M EC-2216 A/B	1.2283	0.00175	0.147	0.4936	168.4
MILBOND	1.2283	0.00167	0.147	0.4936	176.8
MASTERBOND	1.2283	0.00357	0.147	0.4936	82.4

So, the optomechanical design for bonding Porro Cut prism is safe for a vibration level of 40g.

3.2.5 Design Calculations for Retro Reflector Prisms

In this study, two different retro reflector prisms and their optomechanical mounts are examined. These prisms are different in terms of their dimensions. In other words, two retro reflector prisms with different masses and dimensions are investigated for a vibrational environment of 40g. Retro reflector prism's shape is similar to porro prism's shape. So, correlations of porro prism is used to justify optomechanical design and the bonding area of Retro Reflector prisms. Moreover, materials of prisms and optomechanical mounts are BK-7 glass and titanium, respectively. The mathematical correlations for prisms are in Table 3.12.

TABLE 3.12 Mathematical Correlations for Bond Area Calculation of Retro Reflector Prisms [21]

PRISM TYPE	*VOLUME (cm^3)*	*REQUIRED BOND AREA(cm^2)*	*MAXIMUM BOND AREA-CIRCULAR (cm^2)*
PORRO	$1.29A^3$	$1.83 \times 10^{-5} \times A^3 \times d \times G$	$0.51A^2$

Same optomechanical mount is used for bonding the prisms. Engineering drawing of the optomechanical mount is as in Figure 3.10.

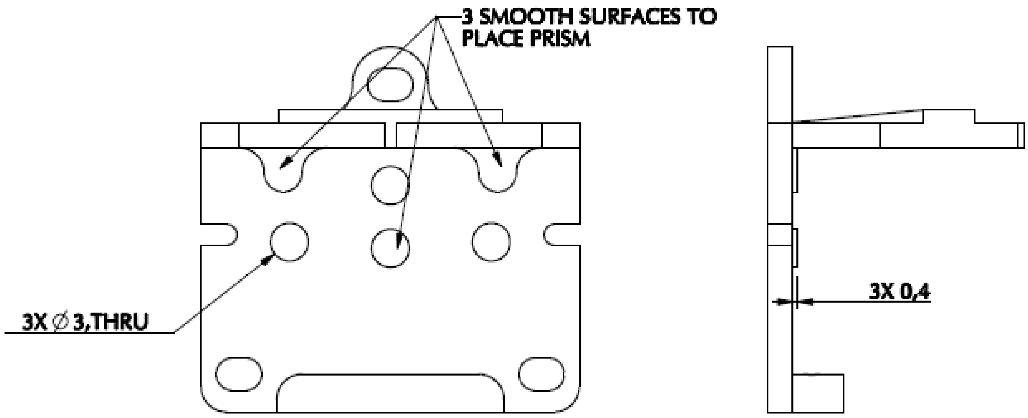
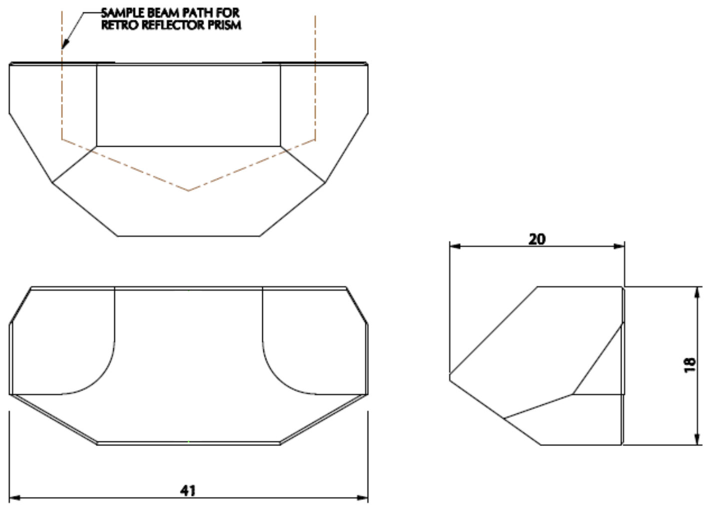
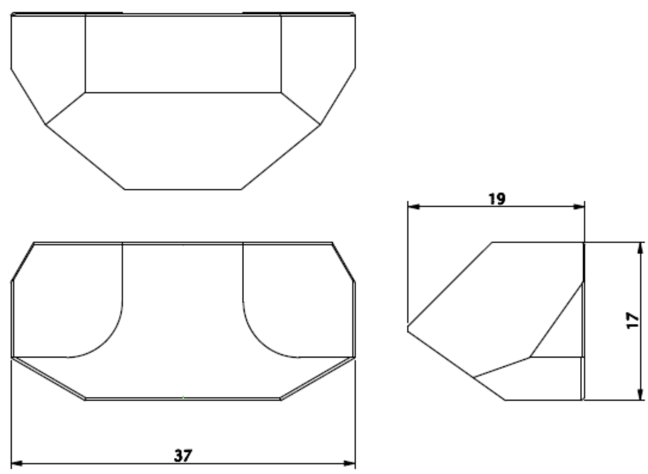


FIGURE 3.10 Optomechanical Mount Drawing for Retro Reflector Prisms

From the drawing, there are three Ø3 mm through holes in order to apply the adhesive. Also, three smooth surfaces (0.4 mm height) are in the design for providing the required bond thickness and easy assembling of the prisms. As stated before, two different (in terms of dimensions) retro reflector prisms are investigated in this study. Their engineering drawings are as in Figure 3.11.



(a)



(b)

FIGURE 3.11 Engineering Drawings of; a) 41mm Retro Reflector Prism, b) 37mm Retro Reflector Prism

One can name the prisms as 41 mm retro reflector prism and 37 mm retro reflector prism. Volume of these prisms are 8.27 cm^3 for 41 mm retro reflector prism and 6.63 cm^3 for 37 mm retro reflector prism (Volume of prisms are taken directly from PRO-ENGINEER®). By use of the volume of the prisms and designed bonding area, required bond areas, maximum bond area and safety factor can be calculated and tabulated as in Table 3.13 for 41 mm Retro Reflector Prism and Table 3.14 for 37 mm Retro Reflector Prism.

TABLE 3.13 Safety Factor Values for the Bonding Design of 41 mm Retro Reflector Prism for Different Adhesives

ADHESIVE	*PRISM VOLUME (cm^3)*	*REQUIRED BOND AREA (cm^2)*	*DESIGN BOND AREA (cm^2)*	*MAXIMUM BOND AREA (cm^2)*	*SAFETY FACTOR*
3M EC-2216 A/B	8.27	0.0118	0.212	1.76	35.9
MILBOND	8.27	0.0112	0.212	1.76	37.8
MASTERBOND	8.27	0.0241	0.212	1.76	17.6

TABLE 3.14 Safety Factor Values for the Bonding Design of 37 mm Retro Reflector Prism for Different Adhesives

ADHESIVE	*PRISM VOLUME (cm^3)*	*REQUIRED BOND AREA (cm^2)*	*DESIGN BOND AREA (cm^2)*	*MAXIMUM BOND AREA (cm^2)*	*SAFETY FACTOR*
3M EC-2216 A/B	6.63	0.0094	0.212	1.519	44.9
MILBOND	6.63	0.0089	0.212	1.519	47.2
MASTERBOND	6.63	0.0193	0.212	1.519	22.0

If Table 3.13 and Table 3.14 are compared in terms of the safety factor datas, it can be seen that 37 mm Retro Reflector Prism bond is more safe than 41 mm Retro Reflector Prism bond. This is due to the fact that 41 mm Retro Reflector Prism is heavier than 37 mm Retro Reflector Prism and these two prisms are bonded on the same optomechanical mount. However, 41 mm Retro Reflector Prism bond can still withstand accelerations up to 1512 times gravitational acceleration (This is the case when the prism is bonded with MILBOND).

3.2.6 Design Calculations for Right Angle Prism

For right angle prism, the correlation is as in Table 3.15.

TABLE 3.15 Mathematical Correlations for Bond Area Calculation of Right Angle Prism [21]

PRISM TYPE	*VOLUME (cm^3)*	*REQUIRED BOND AREA(cm^2)*	*MAXIMUM BOND AREA-CIRCULAR (cm^2)*
RIGHT-ANGLE	$0.50A^3$	$7.10 \times 10^{-6} \times A^3 \times d \times G$	$0.27A^2$

Right angle prism is made of BK-7 glass and its engineering drawing is in Figure 3.12.

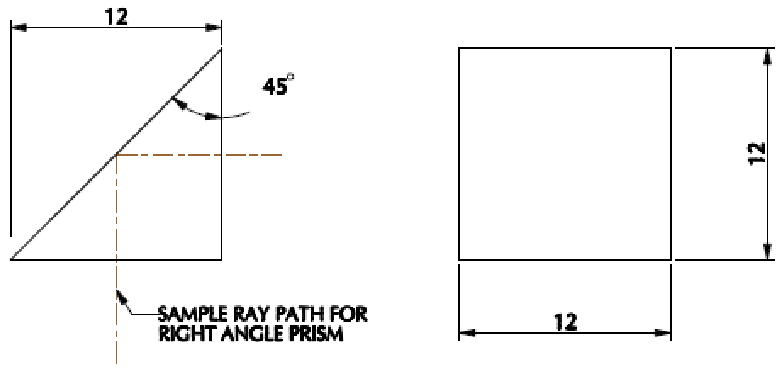


FIGURE 3.12 Engineering Drawing for Right Angle Prism

From engineering drawing of the right angle prism, volume of it can be calculated easily as;

$$\text{Volume of Right Angle Prism} = 0.864 \text{ cm}^3 \tag{3.14}$$

Moreover, engineering drawing for the bonding area of the optomechanical design is as in Figure 3.13.

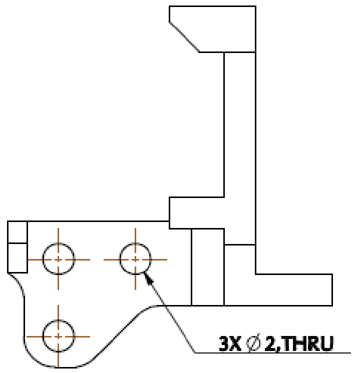


FIGURE 3.13 Optomechanical Mount Drawing for Right Angle Prism

There are three through holes with a diameter of 2 mm in order to bond the prism to the optomechanical mount. As seen from the mechanical drawing, there is no bosses to satisfy the required bond thickness of 0.4 mm. In this design, required bond thickness is provided by using shims. Then, by using the correlations in Table 3.15 for bonding right angle prism;

TABLE 3.16 Safety Factor Values for the Bonding Design of Right Angle Prism for Different Adhesives

ADHESIVE	***PRISM VOLUME (cm^3)***	***REQUIRED BOND AREA (cm^2)***	***DESIGN BOND AREA (cm^2)***	***MAXIMUM BOND AREA (cm^2)***	***SAFETY FACTOR***
3M EC-2216 A/B	0.864	0.0012	0.0943	0.3888	153.0
MILBOND	0.864	0.0012	0.0943	0.3888	160.7
MASTERBOND	0.864	0.0025	0.0943	0.3888	74.9

Then, from Table 3.16, it can be concluded that optomechanical design for bonding right angle prism is satisfactory since safety factor values for bonding with MILBOND is 160.7 and for bonding with MASTERBOND is 74.9. Safety factor of 160.7 means that the prism bond can withstand accelerations up to 160.7×40=6428 times gravitational acceleration.

It has been specified in Section 1.8 (Motivation of the Current Study) that failure of prism bonds had been encountered after mechanical shock having an acceleration level of 40g. The mathematical calculations represented in Chapter 3 shows that mechanical designs for bonding the stated prisms are sufficient if only bonding area is concerned. So, it can be concluded that bonding process and adhesives should be checked in the process rather than the optomechanical design. However, it should also be noted that safety factor values are high. The least safety factor of the bond is 37.8 for 41 mm retro reflector prism when bonded with milbond and 17.6 for the same prism when bonded with masterbond-2lo for a vibration level of 40g. These safety factor values are high because of the diameter of the through holes where the adhesives are applied. In order to apply the adhesives easily, those through holes have at least 2 mm diameter.

CHAPTER 4

MOUNTING OF LENSES

There are mainly three methods for mounting of small lenses and mirrors. These methods are clamped mountings, bonded mountings and flexure mountings. In this study, bonded mountings are investigated in terms of angular stability for harsh environmental conditions. In order to determine the most stable, angular, bonded mounting for harsh environmental conditions, five different optomechanical designs are tested with five different structural adhesives. In this chapter, optomechanical designs, adhesives used for bonding lenses, experimental set-up and results of the experiments are explained. Firstly, five optomechanical designs and five adhesives are described. Then, experimental set-up and measurement method of angular movement of lenses are clarified. Finally, effects of adhesive cure, thermal shock, mechanical vibration and mechanical shock on angular movement of mirrors are discussed.

4.1 Mounting Lenses with Structural Adhesives

Mounting lenses with structural adhesives is a method named bonded mountings. Bonded mountings are simple in terms of mechanical design. Moreover, optomechanical design of this mounting method is cheap and light. However, requirement of angular stability under harsh environmental conditions complicates optomechanical design. Also, it is an another complicating factor that the bonded lenses are going to be used in a laser system so the adhesives have to be low outgassing. Optomechanical design and adhesive selection are important in order to overcome these complicating factors.

4.1.1 Optomechanical Designs

Bonding of small mirrors are done mainly in three methods. These methods are 3 point edge bond in counterbore cell mount, 3 point guided edge bond and 3 point face bond. Four of the designs are different implementations of these three bonding methods. Fifth method, used mostly for bonding lenses into their barrels, is implementation of “elastomer layer on the outer diameter of the lens” technique.

All optomechanical designs are placed on the same plate made of aluminum for comparison. There is also a diamond point turned surface (DPT) with Ø12.7 mm at the center of the barrels. The DPT surface is used as the reference mirror in the experiments. Rather than mounting a mirror on the test plate, DPT surface is used as the reference mirror to compansate the angular movement of the reference mirror and take more accurate measurements. In Figure 4.1, the test plate used in the experiments is seen. There are 6 different optomechanical designs for mounting mirrors and a DPT surface. Barrel#6 is a design on which mirror is mounted mechanically, by use of a retainer ring, rather than bonding. So, barrel#6 is not considered in the experiments.

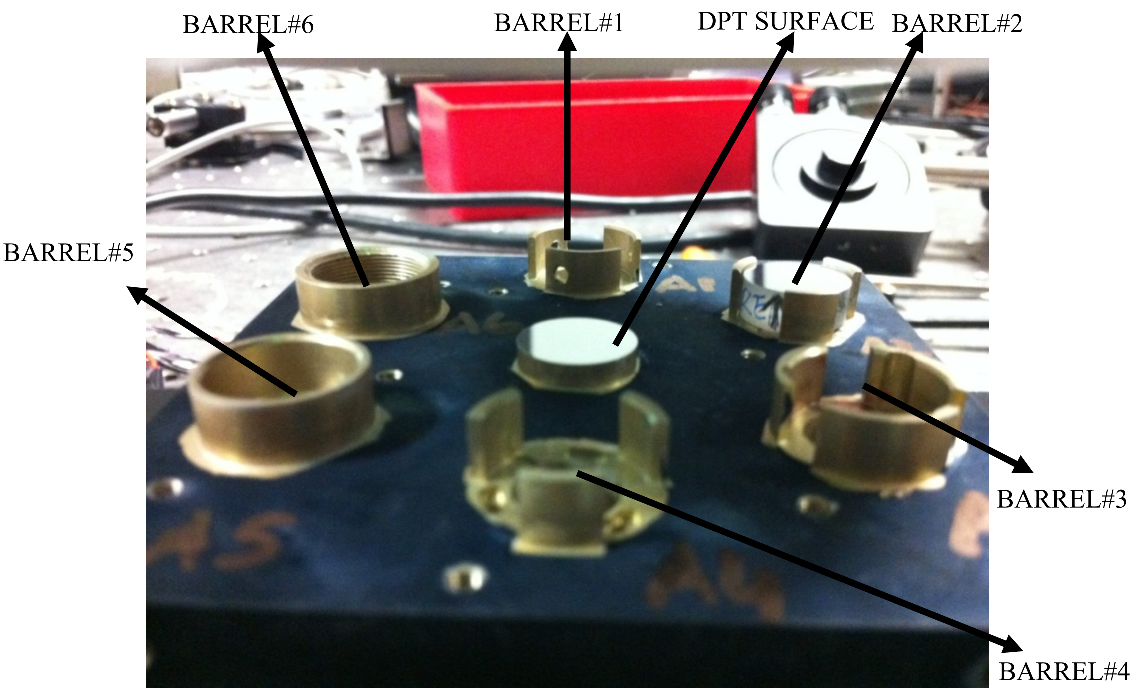


FIGURE 4.1 A View of the Optomechanical Designs Located on the Test Plate

Each optomechanical design shown in Figure 4.1 are explained as follows.

4.1.1.1 Optomechanical Design of Barrel#1

Optomechanical design of barrel#1 is implementation of 3 point guided edge bond. Mounting of lenses and/or mirrors with this method is advantageous since this method simplifies adhesive application. Moreover, stress on the lens and/or mirror is less in this design. However, there are some disadvantages of this design. In this design, adhesives with low viscosity may flow under the mirror and may cause uncontrolled tilt of it. Engineering drawing of barrel#1 is shown in Figure 4.2 (Dimensions are in mm). All of the dimensions are not specified in the figures below so they are named as simple engineering drawing.

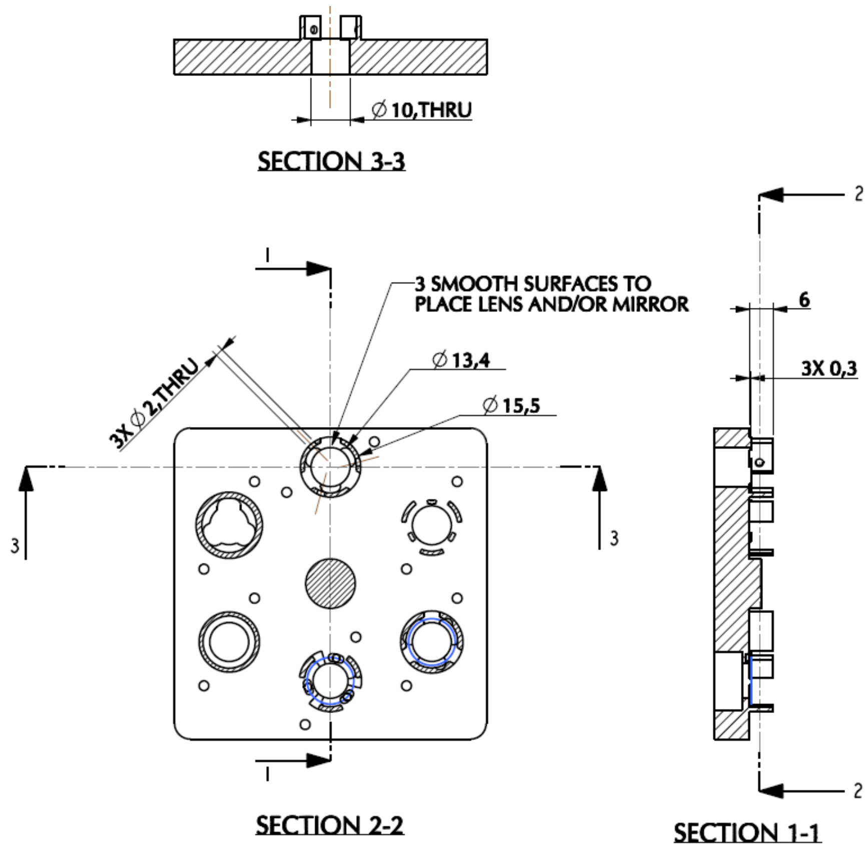


FIGURE 4.2 Simple Engineering Drawing of Barrel#1

In Section 2-2, it is seen that there are three Ø2 mm through holes. These through holes are placed 120º apart to provide symmetricity and designed for applying the adhesive. Also, there is a Ø13.4 mm counterbored hole with a depth of 6 mm. This hole is the barrel of a Ø12.7 mm with 5 mm thickness mirror. 0.35 mm radial space between optomechanical mount and mirror is left intentionally to mount the mirror easily. Centration of the mirror inside the barrel is satisfied by mechanical shimming. Moreover, 3 smooth surfaces of height 0.3 mm are designed to be sure about the parallelism of the mirror.

4.1.1.2 Optomechanical Design of Barrel#2

Barrel#2 design is modified imlementation of 3 point edge bond in counterbore cell mount. In 3 point edge bond in counterbore cell mount, adhesive is firstly applied on the edges of the mirror from 3 point and then mirror is placed to its barrel. This type of bonding of a lens and/or mirror is disadvantageous since adhesive leakage through clear aperture of the mirror is not easily controlled. However, in optomechanical design of barrel#2, adhesive leakage can be controlled. In this design, mirror is firstly placed into its barrel and centered by mechanical shims, then adhesive is applied from three edges of the mirror. Mechanical drawing of the optomechanical design of barrel#2 for this study is shown in Figure 4.3 (Dimensions are in mm).

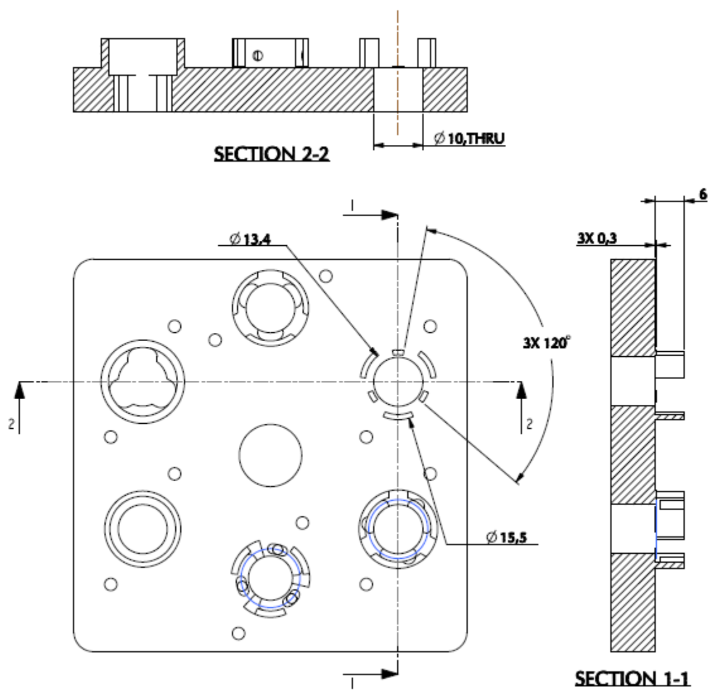


FIGURE 4.3 Simple Engineering Drawing of Barrel#2

In Figure 4.3, it is seen that there are 3 equally spaced (placed 120º apart from each other) bosses of height 0.3 mm. These surfaces are precisely machined so as to satisfy parallelism of the mirror when it is placed into its barrel. Also, it seen in the figure that there are three bosses of height 6 mm with inner diameter of 13.4 mm and outer diameter of 15.5 mm. These bosses are designed to easily place mechanical shims. Mechanical shims are used to center the mirror with Ø12.7 mm and 5 mm thickness in its barrel. In this design, adhesive is applied from three edges of the mirror which are sitting on precisely machined surfaces.

4.1.1.3 Optomechanical Design of Barrel#3

In optomechanical design of barrel#3, both 3 point edge bond in counterbore cell mount and 3 point guided edge bond methods are considered. Barrel#3 design is similar to 3 point edge bond in counterbore cell mount, since adhesive is applied to upper edge of the mirror in counterbore cell mount. On the other hand, this design is analogous to 3 point guided edge bond since there are counterbore holes guiding the adhesive in bonding process. Engineering drawing of barrel#3 is shown in Figure 4.4.

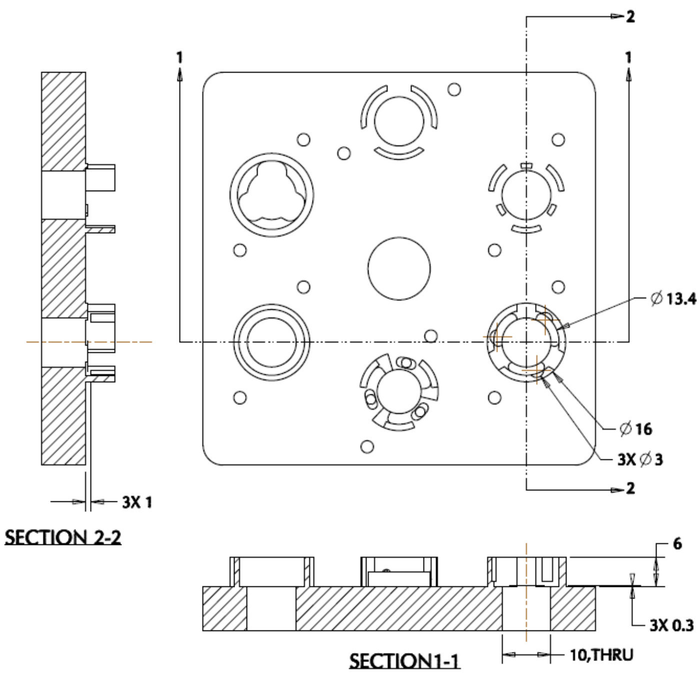


FIGURE 4.4 Simple Engineering Drawing of Barrel#3

As with the designs of barrel#1 and barrel#2; in barrel#3 mirror is placed into a barrel of Ø13.4 mm of height 6 mm. However, in barrel#3 design, outer diameter of barrel is 16 mm rather than 15.5 mm (In barrel#1 and barrel#2 designs, outer diamter of the barrels is 15.5 mm). Because, adhesive is applied from the 3 holes of Ø3 mm located on the barrel edge. These holes are 5 mm in depth, not the same as barrel height, in order to prevent the adhesive from leaking into the bottom of the mirror. Moreover, there are three bosses of height 0.3 mm. These bosses are also precisely machined as in the designs of barrel#1 and barrel#2. In barrel#3 design, bonding of the mirror with adhesive is performed after locating the mirror on three precisely machined surfaces and centering it.

4.1.1.4 Optomechanical Design of Barrel#4

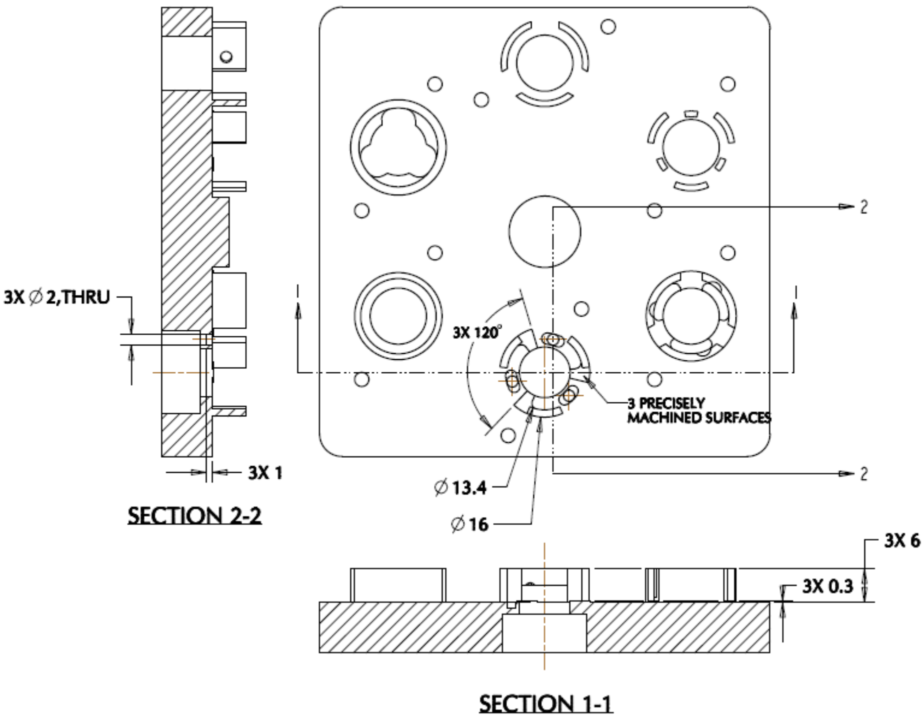


FIGURE 4.5 Simple Engineering Drawing of Barrel#4

Optomechanical design of barrel#4 is modified implementation of 3 point face bond. Bonding mirrors and lenses with 3 point face bond is advantageous since stress caused from bonding does not project through the clear aperture of the mirror.

However, direct implementation of 3 point face bond is not desired because adhesive leakage should be controlled. In design of barrel#4, adhesive application is easy and can be controlled. Control of adhesive leakage is provided by application of the adhesive from three through holes with counterbore openings located behind the mount. In Figure 4.5, engineering drawing of barrel#4, unit is mm, is seen.

In barrel#4 design, the mirror is placed on 3 precisely machined surfaces. These surfaces are 0.3 mm in height and they are equally spaced in the design so as to provide symmetricity. Moreover, there are 3 equally spaced (120º apart from each other) Ø2 mm through holes and 1 mm depth racetrack slots. Ø2 mm through holes are designed to apply the adhesive easily and racetrack slots are designed to prevent leakage of it through the clear aperture of the mirror. Also, 6 mm height, equally spaced, bosses are designed to implement centration of the mirror by mechanical shims. In this barrel design, mirror is placed into its barrel and then it is centered by mechanical shims. Finally, adhesive is applied throught Ø2 mm through holes until racetrack slots are filled with it.

4.1.1.5 Optomechanical Design of Barrel#5

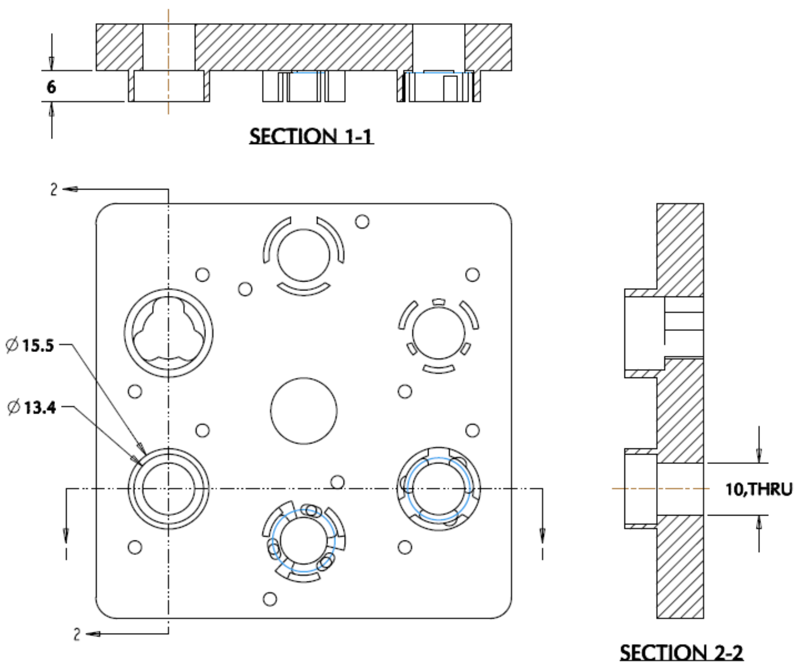


FIGURE 4.6 Simple Engineering Drawing of Barrel#5

Barrel#5 design is used for application of an elastomer layer on the outer diameter of the lens. In this method, radial spacing about 0.25 mm to 0.50 mm is required to provide sufficient adhesive bond. Engineering drawing of barrel#5 design is as in Figure 4.6.

From engineering drawing of barrel#5, it is seen that Ø12.7 mm mirror is placed into a Ø13.4 mm housing (height of the housing is 6 mm). This design provides 0.35 mm radial space between the mirror and the mounting. Although the optomechanical design of barrel#5 is easier and cheaper with respect to other barrel designs, it is harder to apply the adhesive. Because adhesive application process is a two step process. In order to apply the adhesive, mirror is firstly placed into its barrel and then it is centered by mechanical shims. Afterwards, adhesive is applied through the radial space between the mirror and the barrel. After the adhesive applied through the radial space is cured, mechanical shims are removed from the assembly and adhesive is again applied to fulfill the spaces that mechanical shims were.

4.1.2 Adhesives and Their Mechanical Properties

There are many types of adhesives in the market. However, structural adhesives suitable for bonding optical components to metal components are surveyed in this study. While searching for a suitable adhesive; mainly outgassing properties, shrinkage upon cure and working temperature range of the adhesives are considered. Infrastructure of the test environment is considered for curing the adhesives since curing of some adhesives are long (as a week) at room temperature. Also, adhesives having different viscosity values are selected in order to gain experience in bonding of mirrors.

For this study, 5 different adhesives from different suppliers are obtained. These adhesives are ELC-1043, EP21TDC-2LO, MILBOND, OP-67-LS and EP21TDC-2ND.

ELC-1043 is supplied from ELECTRO-LITE CORPORATION. This adhesive is a one part, UV-Cured adhesive (Cure of the adhesive lasts only about 15-20 seconds). It has high viscosity, low shrinkage, low outgassing and good bonding for glass to metal. Moreover, ELC-1043 is a suitable adhesive for a temperature range of -40ºC and 225ºC.

EP21TDC-2LO is supplied from MASTER BOND INC. EP21TDC-2LO is a two part epoxy adhesive (Mixing ratio of these two parts are 3:1). This adhesive is suitable for bonding metals, glass, ceramics, rubber and plastics, sealing, coating and encapsulation. It has high viscosity, paste, low outgassing, thermal shock resistance and impact resistance properties. It’s operating temperature range is between -269ºC and 120ºC. EP21TDC-2LO is cured at room temperature (25ºC) for 2-3 days or at about 65ºC for 3-4 hours.

MILBOND is supplied from SUMMERS OPTICAL. It is an epoxy system rather than an epoxy adhesive since it is composed of a two part primer and two part adhesive. While applying MILBOND epoxy system, primer components are mixed by ratio of 1:1 in volume and adhesive components are mixed by ratio of 1:1 in weight. Primer of this adhesive cures at room temperature after 24 hours and adhesive cures at room temperature after 7 days or at 71ºC after 3 hours. Although MILBOND has complex application process, it provides good and stable adhesion under mechanical shock, mechanical vibration and temperature cycling. Moreover, it is a low outgassing adhesive with operating temperature range of -62ºC and 88ºC.

OP-67-LS, one part and UV-Cured adhesive, is supplied from DYMAX. This adhesive is suitable for precise applications, as most of the UV-Cured adhesives, since it can be cured in seconds. While choosing OP-67-LS, it’s low outgassing, low CTE and low shrinkage properties are taken into consideration. Moreover, OP-67-LS has a working temperature range of -54ºC and 154ºC.

EP21TDC-2ND is also supplied from MASTER BOND INC. as EP21TDC-2LO. These two adhesive has similar mechanical properties but EP21TDC-2ND has higher viscosity than EP21TDC-2LO (EP21TDC-2ND is non-drip, paste adhesive but EP21TDC-2LO has a viscosity of 70,000-80,000 cP). Moreover, EP21TDC-2LO is an thermal conductive adhesive whereas EP21TDC-2ND is thermal insulator adhesive.

All the adhesives stated above are used in experiments in order to bond mirrors into the barrels whose designs were explained before. Mechanical properties of these adhesives are tabulated in Table 4.1.

TABLE 4.1 Mechanical Properties of the Selected Adhesives

ADHESIVE	ELC-1043	EP21TDC-2LO	MILBOND	OP-67-LS	EP21TDC-2ND
SUPPLIER	ELECTRO-LITE	MASTER BOND	SUMMERS OPTICAL	DYMAX	MASTER BOND
TYPE	1-PART	2-PART EPOXY	ELASTOMERIC-EPOXY SYSTEM	1-PART	2-PART EPOXY
COMMENTS	LOW SHRINKAGE, ADHESION TO GLASS,METALS AND PLASTICS	LOW OUTGASS,FLEXIBLE AND TOUGH	LOW OUTGASS, SHOCK AND TEMPERATURE RESISTANT	LOW OUTGASS, LOW CTE, LOW SHRINKAGE	HIGHLY FLEXIBLE, LOW OUTGASS
CURE	UV LIGHT	ROOM TEMPERATURE OR FASTER IN ELEVATED TEMPERATURE	ROOM TEMPERATURE OR FASTER IN ELEVATED TEMPERATURE	UV LIGHT	ROOM TEMPERATURE OR FASTER IN ELEVATED TEMPERATURE
VISCOSITY [cP]	100	70,000-80,000	25	135	PASTE
WORK LIFE	n/a	90 minutes	30 minutes	n/a	75 minutes
DUROMETER	D 65	D 36	n/a	D 80	D 35
SHRINKAGE UPON CURE	n/a but known to be low shrinkage	n/a	1%	0.2%	n/a
GLASS TRANSITION TEMPERATURE	n/a	n/a	100^0C to 115^0C	n/a	n/a
CTE	n/a	$90\text{-}100X10^{-6}/^0C$	$62\text{-}72X10^{-6}/^0C$	$\approx 200X10^{-6}/^0C$	n/a
TML%	<1	0.55	0.98	<1	0.01
CVCM%	<0.1	0.02	0.03	<0.1	<0.1
TEMPERATURE RANGE	-40^0C to 225^0C	-269^0C to 120^0C	-62^0C to 88^0C	-54^0C to 150^0C	-269^0C to 120^0C

4.2 Experimental Set-up

The aim of this study is to find most stable optomechanical design and adhesive combination that withstands military level temperature shock, mechanical vibration and mechanical shock. The movement of the mirrors due to adhesive cure is also investigated. To this end, mirror movements are monitored via an autocollimator. "An autocollimator is an optical instrument for non-contact measurement of angles. They are typically used to align components and measure deflections in optical and mechanical systems. An autocollimator works by projecting an image onto a target mirror, and measuring deflection of the returned image against a scale" [34]. In combination with the autocollimator, a camera and a monitor is also used to measure the angular movements of the mirrors with respect to the reference mirror, for the sake of convenience (Reference mirror is the DPT Surface located on the test plate). Autocollimator, test plate, camera and monitor used in the experiments are seen in Figure 4.7 and Figure 4.8.

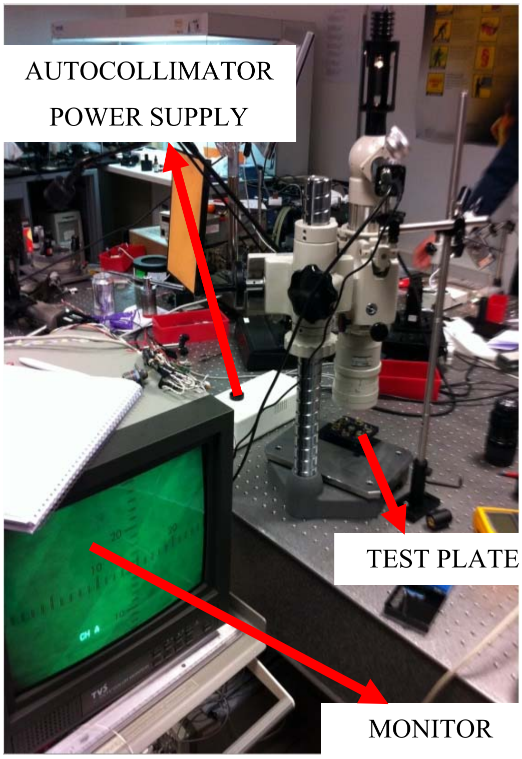


FIGURE 4.7 A View of the Autocollimator, Test Plate and Monitor Used

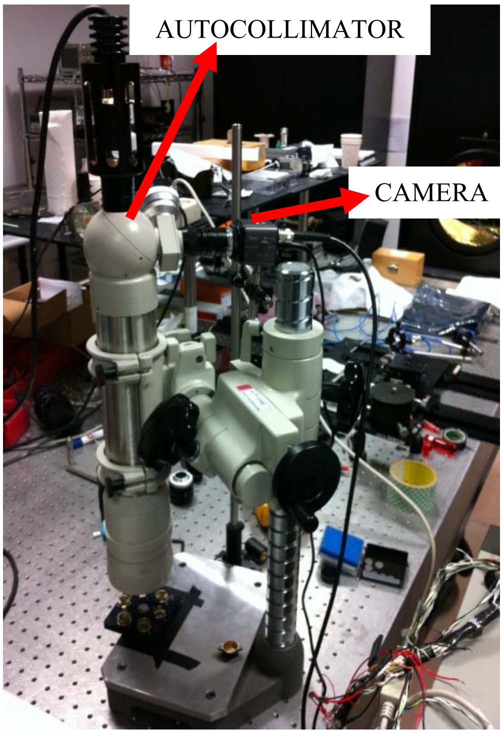


FIGURE 4.8 A View of the Autocollimator and Camera Used

Before bonding of the mirrors to optomechanical mounts, all two-part adhesives are mixed at the ratio specified by the supplier. Then, they are vacuumed in a vacuum chamber to remove air bubbles formed during mixing of the adhesive. In the vacuum process, according to the recommendations of the suppliers of the adhesives, mixed adhesives are brought to −200 mbar in the vacuum chamber, kept in there for 3 minutes and this is repeated for 5 times. In Figure 4.9 and Figure 4.10, adhesives inside the vacuum chamber during vacuum process and vacuum chamber are seen, respectively.

FIGURE 4.9 A View of the Adhesives Inside the Vacuum Chamber During Vacuum

FIGURE 4.10 A View of the Vacuum Chamber

To bond the mirrors to the barrels, they should be centered. Mirrors are shimmed after placing them into their barrels for centering them. Centration of the mirrors inside the barrels is important so as to prevent non-uniform bonding. Non-uniform bonding cause unrestrained angular movement and wrong measurements. In Figure 4.11, shimmed mirrors inside the barrels is seen.

FIGURE 4.11 A View of the Shimmed Mirrors Inside the Barrels

Shimmed and centered mirrors are appropriate for bonding. As stated before, five different adhesives are used to bond mirrors to five different barrels designed. In other words, five mirrors with same dimensions are bonded to five different barrels with the same adhesive and this is done for all the adhesives so there are 25 samples. Following the application, the adhesives are cured according to their cure schedules. Some of the adhesives used in this study are cured at elevated temperatures, EP21TDC-2LO and EP21TDC-2ND are cured at 65ºC and MILBOND is cured at 71ºC, whereas some of them, namely, ELC-1043 and OP-67-LS, are cured by UV light. A furnace is used for curing the adhesives at elevated temperatures and UV light source is used for UV-Cure adhesives are seen in Figure 4.12 and 4.13, respectively.

FIGURE 4.12 A View of the Furnace Used for Curing the Adhesives

FIGURE 4.13 A View of the UV Light Source Used for Curing the Adhesives

In the experiments, effect of the thermal shock on angular movement of bonded mirrors is also observed. Thermal shock is rapid temperature change (temperature change in thermal shock is 22ºC/min) and it is applied to the bonded mirrors at a temperature range of -40ºC and 70ºC. Thermal shock is applied to the bonded mirrors in furnace shown in Figure 4.12.

Moreover, the effects of mechanical vibration and mechanical shock are observed in the experiments. In order to apply random vibration and mechanical shock to the test plates, two different shakers are used. One of the shakers is used for applying random vibration and mechanical shock in +X, -X, +Y and –Y directions whereas the other one is used -Z and +Z directions. In Figure 4.14, shaker used in X and Y directions on which test plates are mounted is seen.

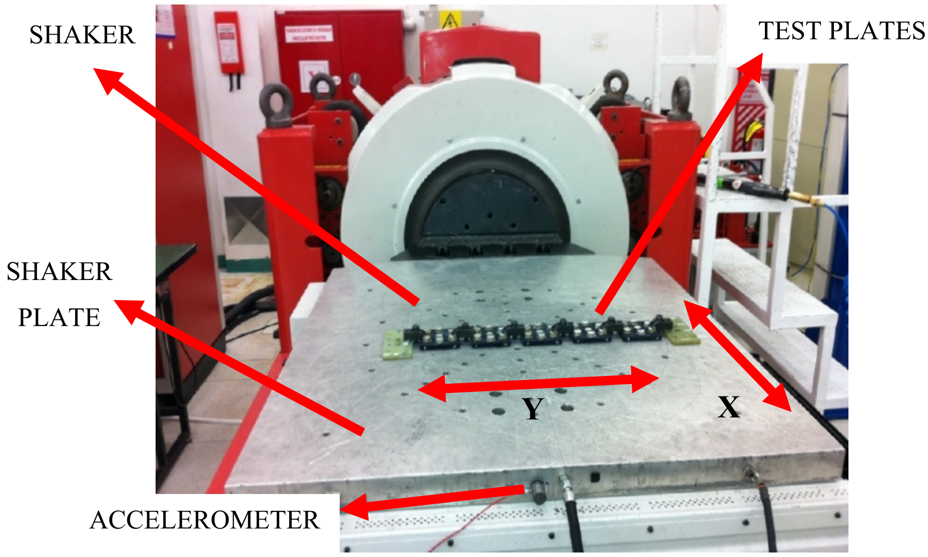


FIGURE 4.14 A View of the Shaker Used in X and Y Directions

The shaker used in Z direction and test plates mounted on it are seen in Figure 4.15.

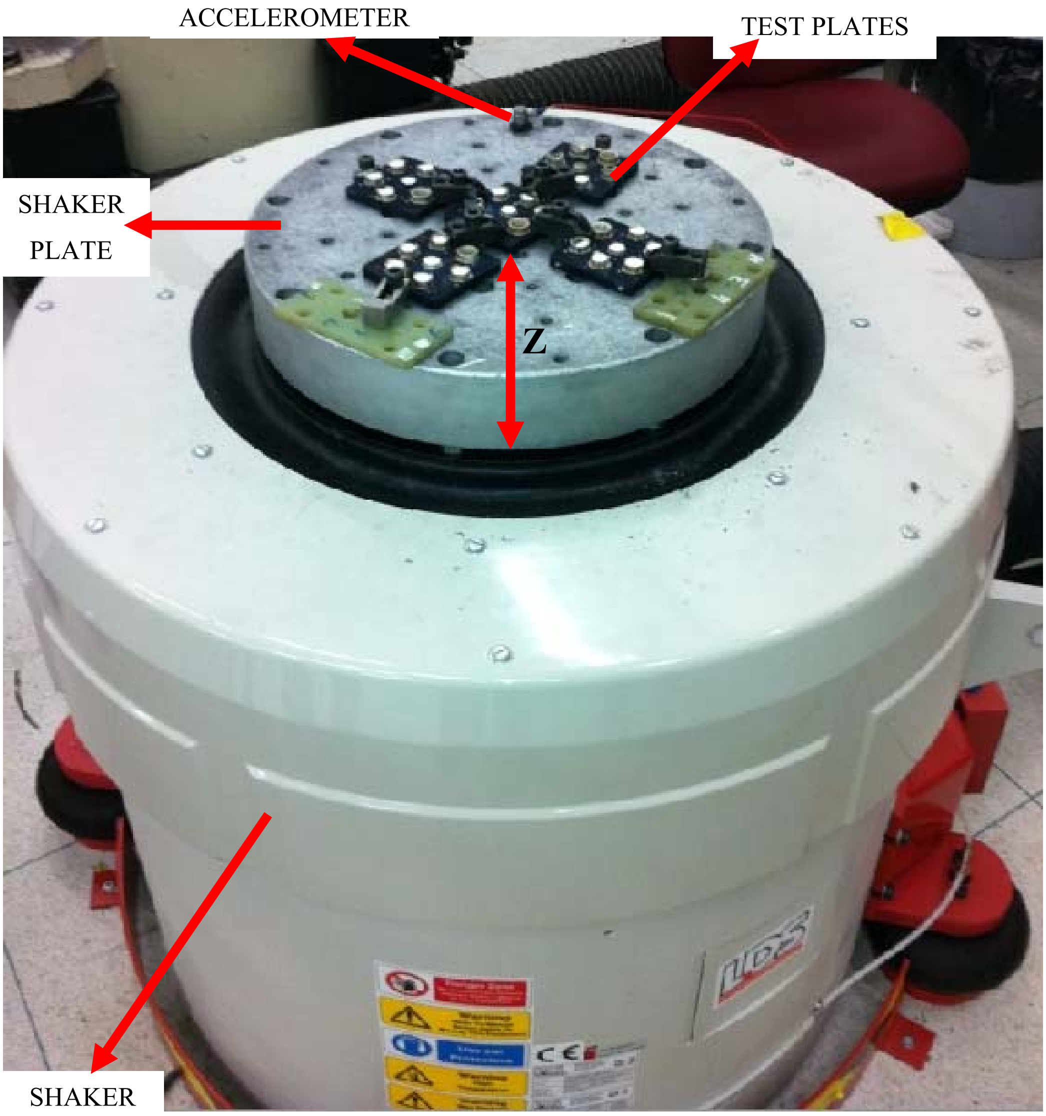


FIGURE 4.15 A View of the Shaker Used in Z Direction

In order to validate the autocollimator measurements, a precisely controlled and scaled gimbal, used for angular positioning of a mirror, is used. Thorlabs GM100 gimbal, has two knobs for angular rotation of the mirror mounted on it in two directions, is selected for the verification of angular measurements of autocollimator (Figure 4.16).

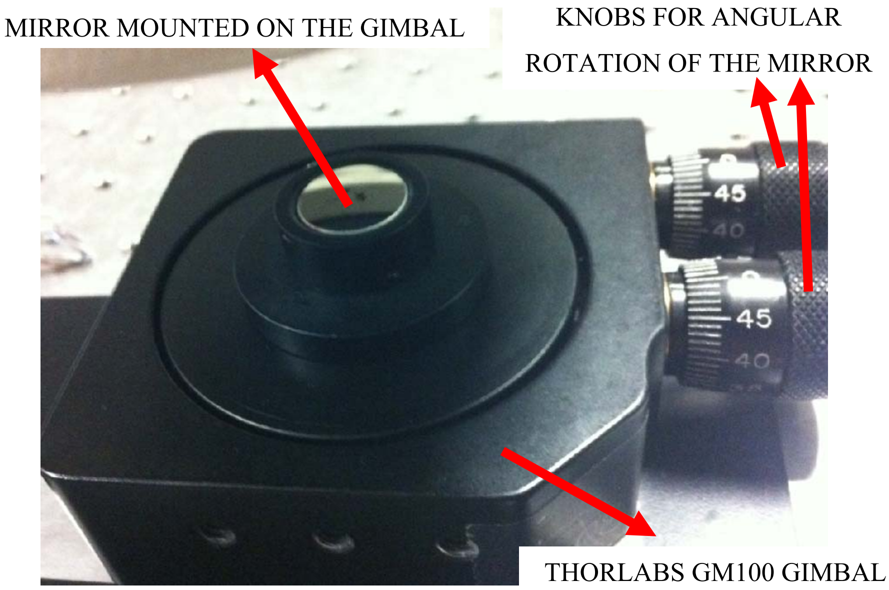


FIGURE 4.16 A View of the Gimbal and Mirror for Verification of Autocollimator Measurements

Both two knobs of the gimbal is divided into 50 divisions per revolution and one revolution of each provides 0.35º angular movement. For the verification of autocollimator measurements, a mirror with Ø12.7 mm is mounted on the gimbal and one of the knobs is rotated for 10 divisions. It is known from GM100 datasheet that 10 divison rotation of a knob provides 0.07º angular movement. In the measurements, both knobs and autocollimator reading are firstly adjusted to their reference positions. In Figure 4.17, image of the autocollimator output at reference position on monitor is seen (each line in the figure shows 1 minarc angular movement).

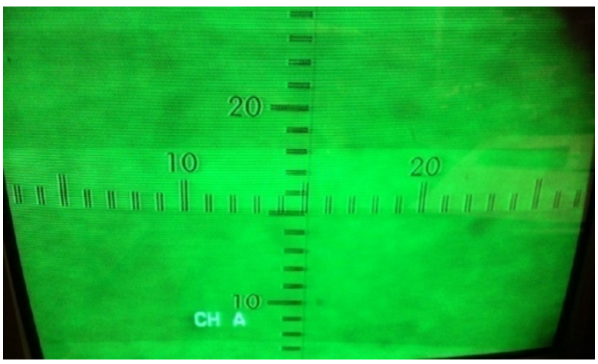


FIGURE 4.17 Image of the Autocollimator Output

Then, one of the knobs is rotated for 10 divisions and autocollimator reading is noted. After the reading of the angular movement by autocollimator, knob is rotated back to its reference position and measurement is taken. It is important in the second reading, knob rotated is brought to its reference position, that autocollimator reading is also at the reference position. Measurements taken for verification of autocollimator readings and Thorlabs GM100 datasheet are in APPENDIX G. 10 different measurements were taken by using GM100 gimbal and it was seen that most of the angular measurements were about 0.07º. However, some of the measurements were different. The most difference from 0.07º was recorded as 0.067º. So, it can be said that there was an error about 0.003º (about 0.2 minarc). Since autocollimator output is easily read at each 1 minarc, it is normal to have 0.2 minarc error. Then, it can be concluded that 0.2 minarc originated from reading errors.

Up to now in Section 4.2, devices used in the experiments and their purposes of use are introduced. However, they are used with a specific sequence in order to measure angular movement of mirrors bonded with different adhesives to different mounts. The procedure and the sequence of the experiments is as follows;

1. Center mirrors by shims after placing them into barrels.
2. Take measurements by autocollimator to determine the inital angular position of the mirrors with respect to the reference mirror.
3. Mix two part adhesives according to mixing ratios indicated by the supplier.
4. Vacuum mixed adhesives inside the vacuum chamber.
5. Apply adhesives from desired locations of the designs (While applying the adhesive, work life of it should be taken into account).
6. Cure adhesives according to the procedures stated by the supplier.
7. Remove shims that are mounted to center the mirrors before bonding.
8. Take measurements by autocollimator to determine the angular movement of the mirrors with respect to the reference mirror. It should be noted that these values represent sum of initial angular position and angular movement due to

adhesive cure. To detect the effect of adhesive cure, initial measurements should be subtracted from these values.

- Close all the mirrors bonded with a cap and adjust reference mirror reflection to the reference position. Then, only open the cap on the mirror that measurements to be taken (Figure 4.18). Use of cap while taking measurements is required since reflection of all the mirrors on the test plate complicates the measurement process. If all the mirrors rather than the mirror to be measured is closed, only two reflections are seen as the output (one the reflections is due to reference mirror and the other one is the mirror to be measured).

FIGURE 4.18 Measurement of Angular Movement in the Mirror Mounted to Barrel#1

9. Apply thermal shock desired to the bonded mirrors inside the furnace.
10. Take measurements by autocollimator to determine the angular movement of the mirrors with respect to the reference mirror. It should be noted that these values show total angular movement due to initial condition, adhesive cure and thermal shock. In order to detect only the effect of thermal shock, these

measurements should be subtracted from measurements taken after adhesive cure.

11. Apply mechanical vibration to the bonded mirrors in +x, -x, +y, -y, +z, -z directions according to the desired random vibration profile.
12. Take measurements by autocollimator to determine the angular movement of the mirrors with respect to the reference mirror. It should be noted that these values show total angular movement due to initial condition, adhesive cure, thermal shock and mechanical vibration. In order to detect only the effect of mechanical vibration, these measurements should be subtracted from measurements taken after thermal shock.
13. Apply mechanical shock to the bonded mirrors in +x, -x, +y, -y, +z, -z directions according to the desired acceleration level and time.
14. Take measurements by autocollimator to determine the angular movement of the mirrors with respect to the reference mirror. It should be noted that these values show total angular movement due to initial condition, adhesive cure, thermal shock, mechanical vibration and mechanical shock. In order to detect only the effect of mechanical shock, these measurements should be subtracted from measurements taken after mechanical vibration.

4.3 Results of The Experiment

In experimental study, 4 different effects on angular movement of a mirror are investigated. These effects are Effect of Adhesive Cure, Effect of Thermal Shock, Effect of Mechanical Vibration and Effect of Mechanical Shock. In this part, angular movement measurements are expressed for the effects stated. In the figures, representing the angular movement of the mirrors due to the effects stated, angular movement axis is scaled between 0 and 400 μrad to compare the effects easily.

4.3.1 Effect of Adhesive Cure

In order to measure the effect of adhesive cure on angular movement of the mirrors, two measurements are taken from each mirror. First measurement is taken from the mirrors that are centered, shimmed, and the second mesaurement is taken from mirrors that are bonded (in measurement of bonded mirrors, shims are removed). Then, absolute difference between measurements are calculated. These measurements and calculations are done for 25 mirrors bonded with 5 different adhesives to 5 different barrels.

Graphical display of the angular movements are named as Effect of Cure of Milbond, Effect of Cure of Masterbond-2ND, Effect of Cure of Masterbond-2LO, Effect of Cure of OP67-LS and Effect of Cure of ELC-1043. Measurement values for effect of adhesive cure is in APPENDIX I. Graphical display of Effect of Cure of Milbond is in Figure 4.19.

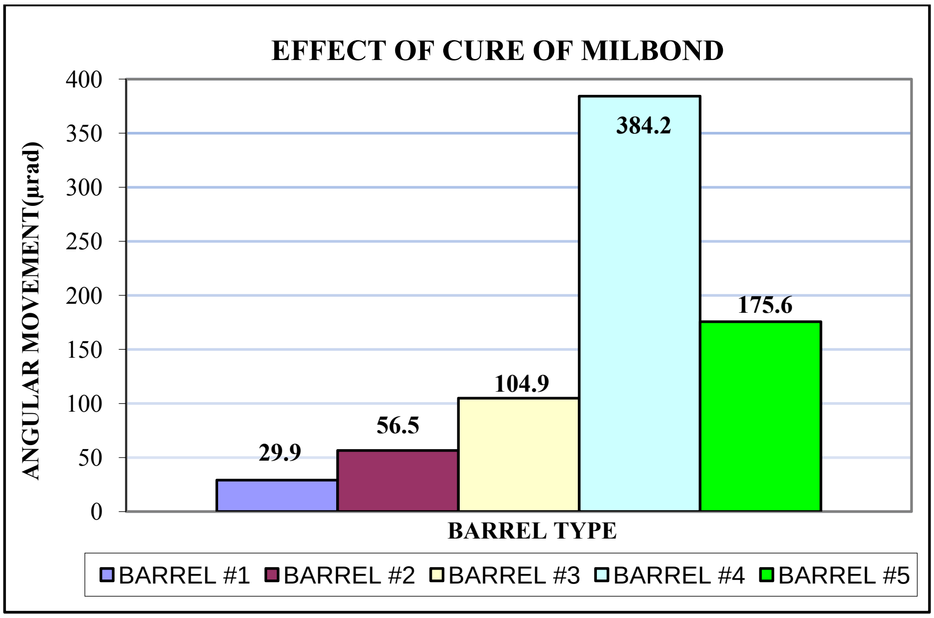


FIGURE 4.19 Effect of Cure of MILBOND

According to the graphical representation of angular movement due to cure of Milbond, it is seen that Barrel#1 design is more suitable than other barrels for bonding a mirror with Milbond for minimum angular movement (29.9 µrad).

Graphical display of Effect of Cure of Masterbond-2LO is seen in Figure 4.20.

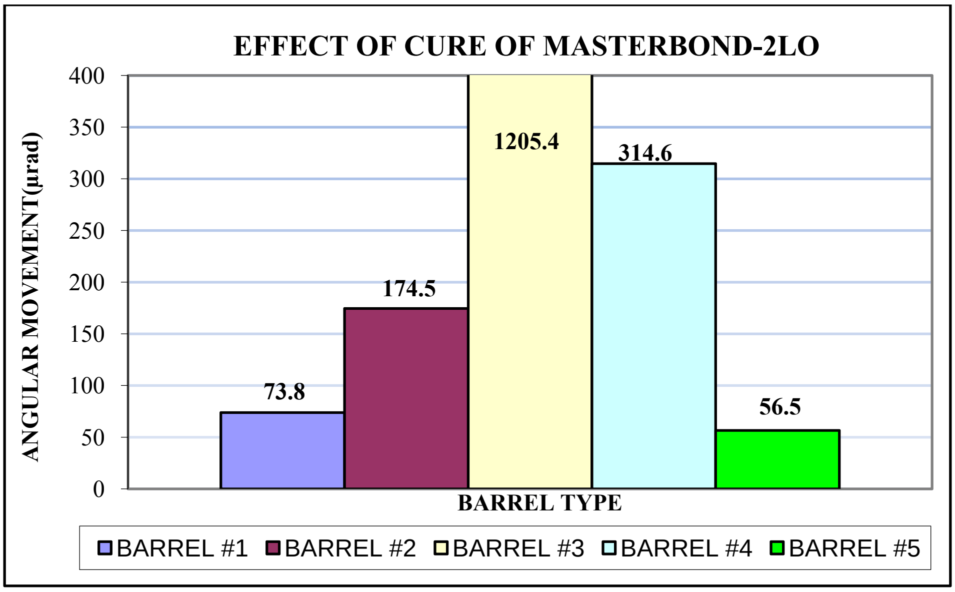


FIGURE 4.20 Effect of Cure of MASTERBOND-2LO

In Figure 4.20, it is seen that mirror bonded to Barrel#5 with Masterbond-2LO has less angular movement than the mirrors bonded to other barrels.

Angular measurements are also taken for the mirrors bonded to the barrels with Masterbond-2ND. In Figure 4.21, effect of Cure of Masterbond-2ND is shown.

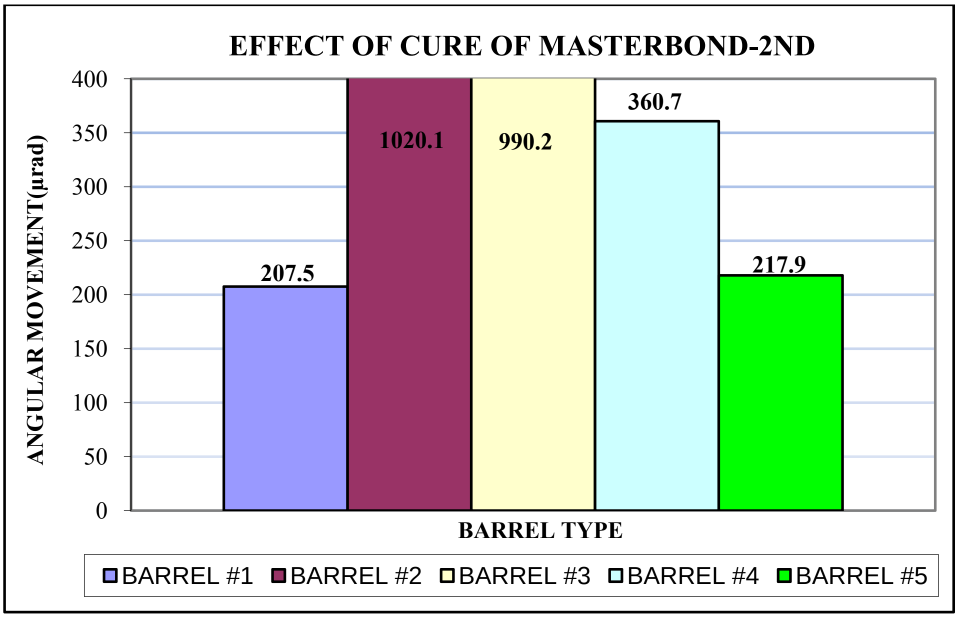


FIGURE 4.21 Effect of Cure of MASTERBOND-2ND

In measurements of the angular movement of mirrors that are bonded with Masterbond-2ND to designed barrels, more angular movements due to cure of the adhesive is observed with respect to the previous measurements. Also, it is observed that barrel#1 and barrel#5 designs are more suitable for bonding mirrors with Masterbond-2ND than the other barrels.

In Figure 4.22, angular movement measurements due to effect of cure of OP-67-LS is seen.

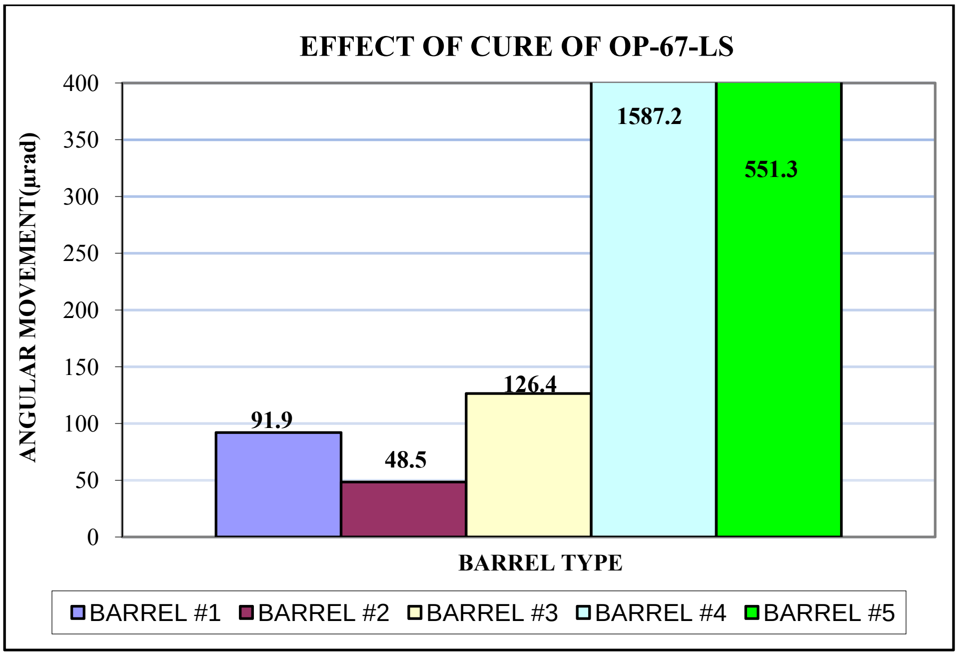


FIGURE 4.22 Effect of Cure of OP-67-LS

According to measurement results of angular movement of mirrors due to cure of OP-67-LS, it is observed that barrel#2 design results less angular movement. Mirror bonded to barrel#2 with OP-67-LS moved 48.5 µrad whereas mirrors bonded to barrel#1, barrel#3, barrel#4 and barrel#5 moved 91.9 µrad, 126.4 µrad, 1587.2 µrad and 551.3 µrad, respectively. Also, it should be stated that bonding a mirror with OP-67-LS to barrel#4 is the most affected combination by adhesive cure.

Effect of cure of ELC-1043 on angular movement of mirrors is also investigated in this study. Measurement results are shown in Figure 4.23.

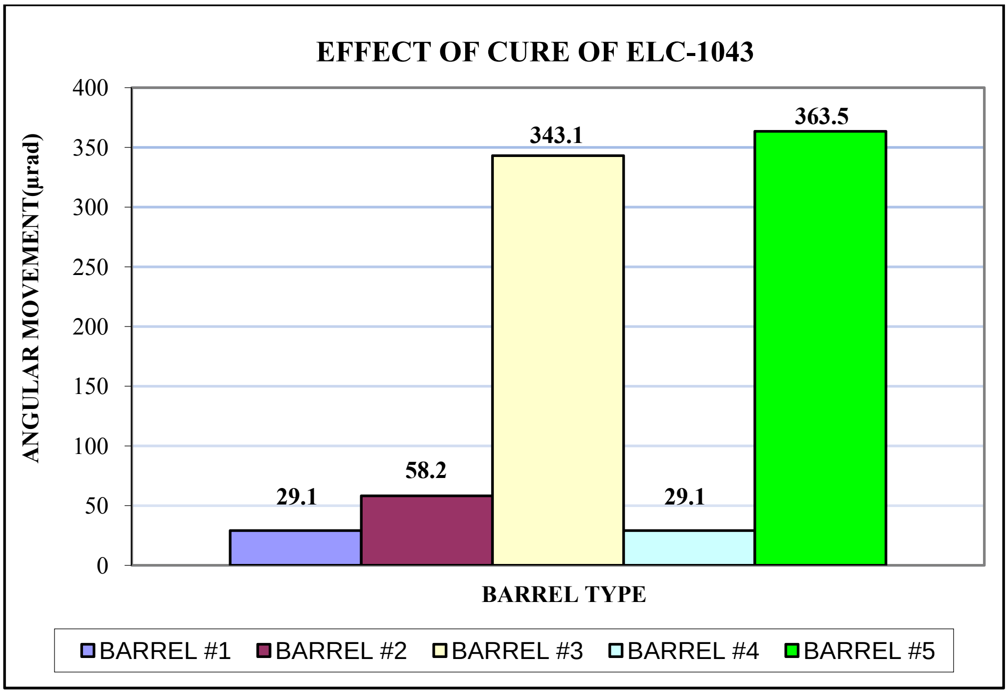


FIGURE 4.23 Effect of Cure of ELC-1043

It is seen from Figure 4.23 that mirrors bonded with ELC-1043 to barrel#1 and barrel#4 moves less than the mirrors bonded with ELC-1043 to barrel#2, barrel#3 and barrel#5.

4.3.2 Effect of Thermal Shock

In military environment, strentgh of an optical system to thermal shock is a critical parameter. So, thermal shock effect is also observed in this study. By use of the furnace (Figure 4.12), thermal shock is applied on the test plates. Thermal shock profile is shown in Figure 4.24.

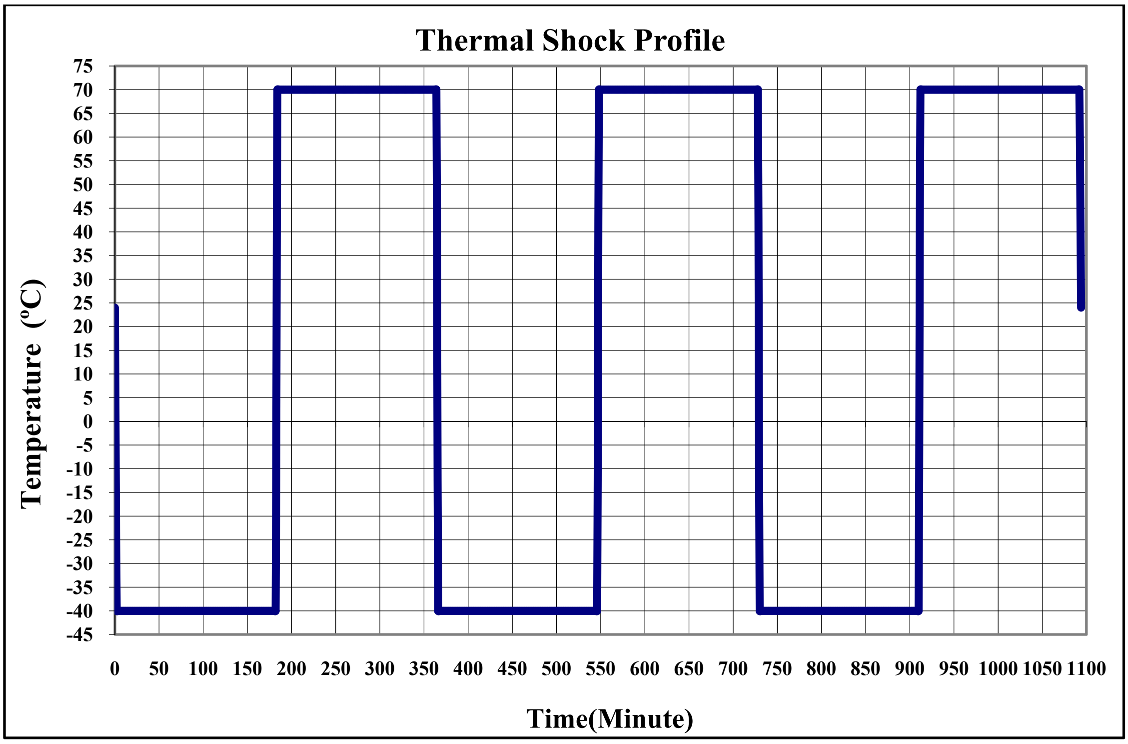


FIGURE 4.24 Thermal Shock Profile

Thermal shock, profile shown in Figure 4.24, is applied to the test plates according to MIL-STD-810F. It is the thermal shock profile of airborne laser devices that are used at heights up to 30000 feet (9144 m). In this profile, furnace is brought to 70ºC from -40ºC in 5 minutes. Then, the test plates stay at 70ºC for 3 hours and then it is brought to -40ºC in 5 minutes. Test plates also stay at -40ºC for 3 hours and this process is repeated for 3 times.

After the application of the thermal shock, measurements are taken by autocollimator. In order to determine only the effect of thermal shock, absolute difference between the measurements taken after thermal shock is subtracted from the measurements taken after cure of the adhesives. Measurements taken after thermal shock for each barrel and adhesive combination is in APPENDIX J.

Graphical representation of the effect of thermal shock on angular movement of mirrors that are bonded with Milbond is shown in Figure 4.25.

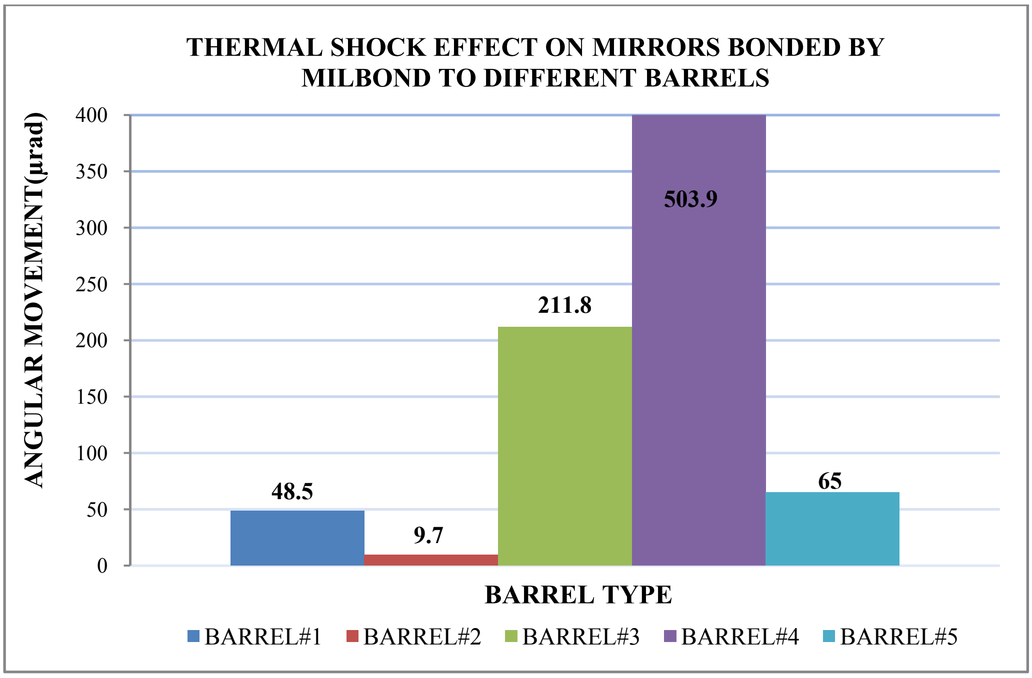


FIGURE 4.25 Thermal Shock Effect on Mirrors Bonded by MILBOND

From the measurements of the mirrors that are bonded with Milbond to the designed barrels, mirror bonded to barrel#2 movement (only 9.7 µrad) is less than the other mirrors. It is also clearly seen that mirror bonded to barrel#4 movement is high (503.9 µrad).

Angular movement of mirrors bonded with Masterbond-2LO due to thermal shock is also investigated in this study. Graphical representation of the angular movement of mirrors bonded to designed barrels due to thermal shock is shown in in Figure 4.26.

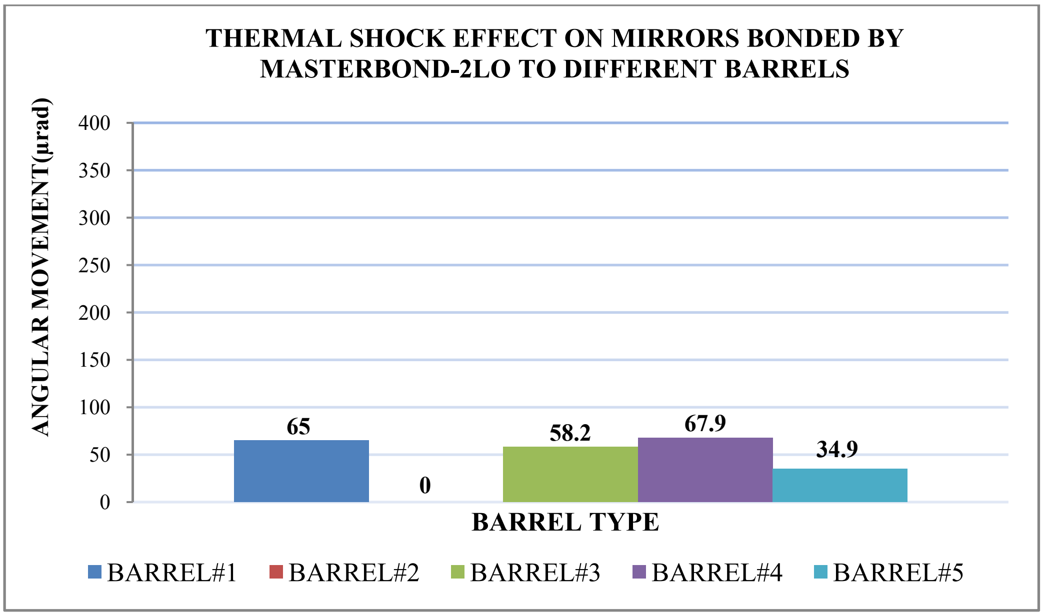


FIGURE 4.26 Thermal Shock Effect on Mirrors Bonded by MASTERBOND-2LO

From measurement results, it is seen that mirrors bonded with Masterbond-2LO to barrel#1, barrel#2, barrel#3, barrel#4 and barrel#5 moves angularly due to thermal shock as 65 µrad, 0 µrad, 58.2 µrad, 67.9 µrad and 34.9 µrad, respectively.

Effect of thermal shock on mirrors bonded to the barrels with Masterbond-2ND is as in Figure 4.27.

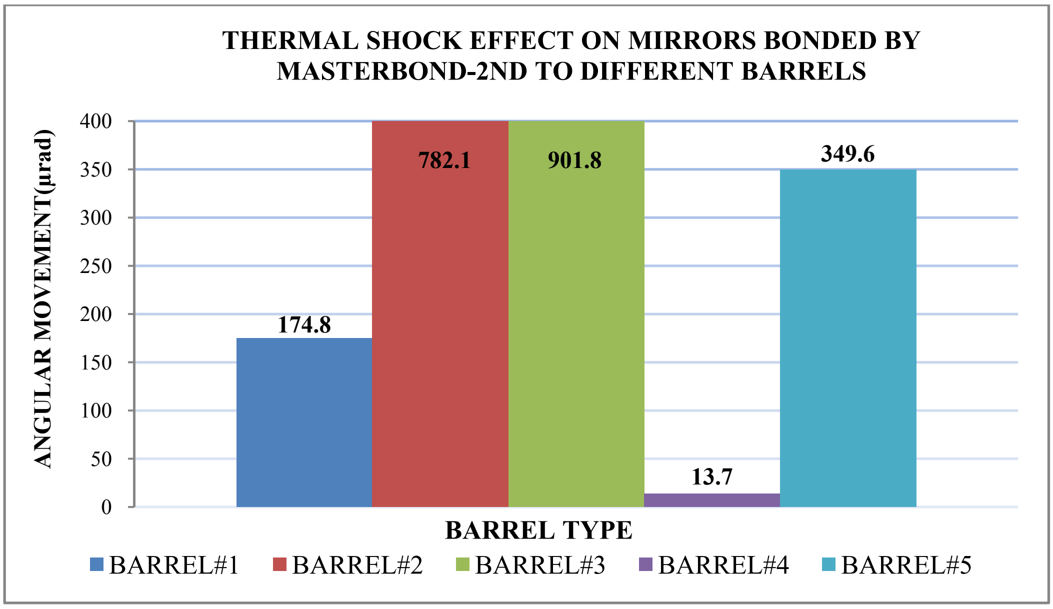


FIGURE 4.27 Thermal Shock Effect on Mirrors Bonded by MASTERBOND-2ND

Measurement results indicate that mirror bonded to barrel#4 with Masterbond-2ND moves less than the other mirrors bonded to other barrels due to thermal shock.

Angular movement of mirrors that are bonded with OP67-LS is also measured after thermal shock. Effect of thermal shock on mirrors bonded by OP67-LS is represented graphically in Figure 4.28.

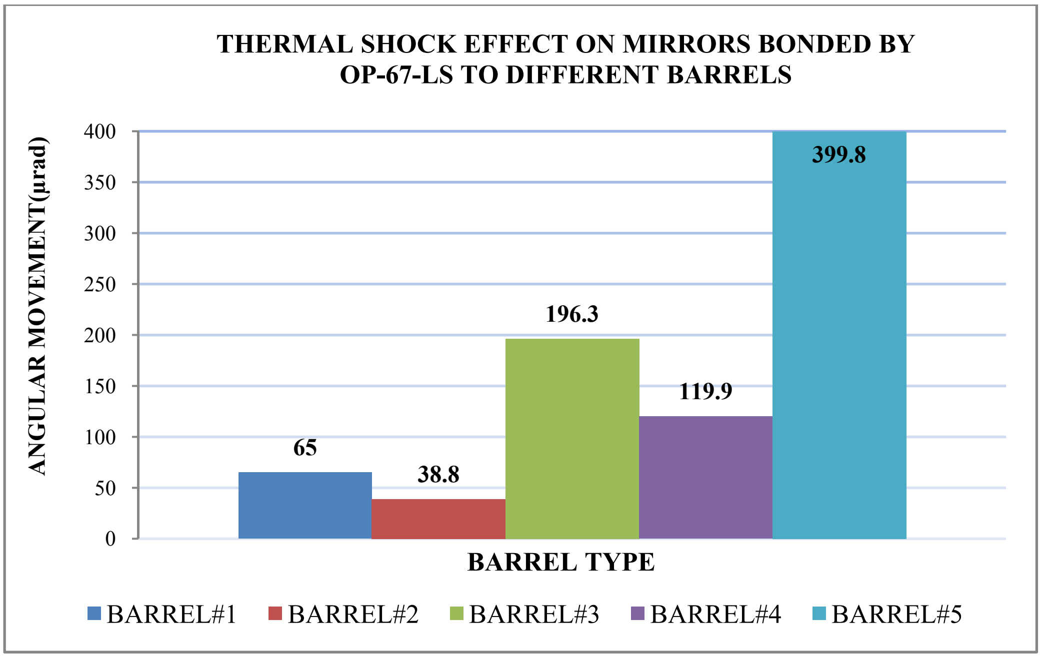


FIGURE 4.28 Thermal Shock Effect on Mirrors Bonded by OP-67-LS

Angular movement of 65 µrad, 38.8 µrad, 196.3 µrad, 119.9 µrad and 399.8 µrad are observed at the mirrors bonded with OP67-LS to barrel#1, barrel#2, barrel#3, barrel#4 and barrel#5, respectively. From the measurements, it is understood that barrel#2 design is more suitable to bond a mirror with OP67-LS than the other barrels for the thermal shock applied on the test plates.

Angular movement of mirrors bonded with ELC-1043 is also measured in this study. Measurement results are shown graphically in Figure 4.29.

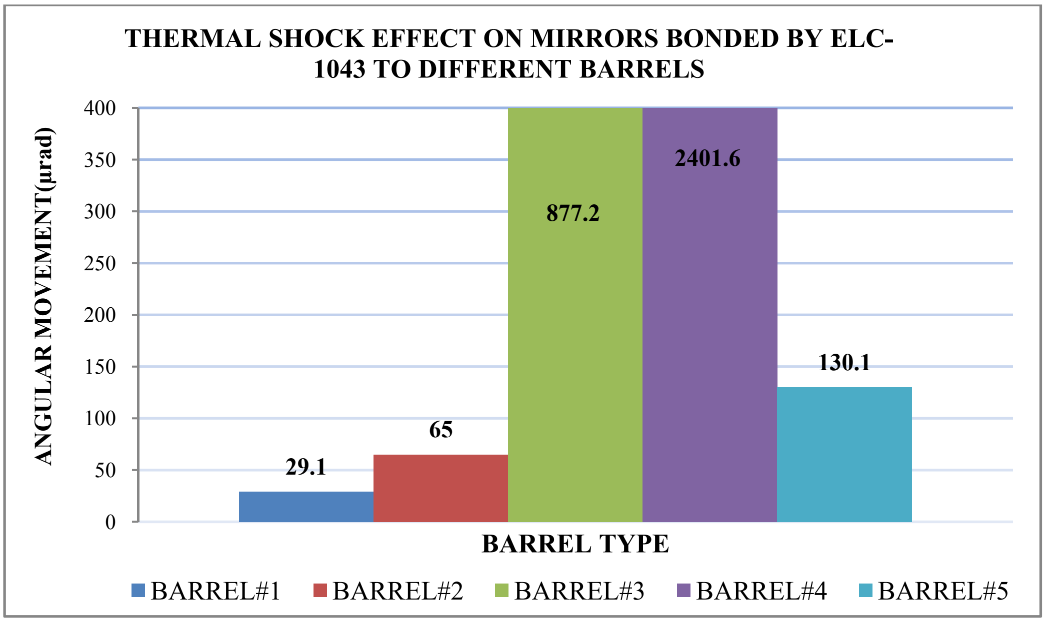


FIGURE 4.29 Thermal Shock Effect on Mirrors Bonded by ELC-1043

In Figure 4.29, it is clearly seen that movement of the mirror bonded with ELC-1043 to barrel#4 (2401.6 µrad) is maximum among all the measurements after thermal shock. On the other hand, movement of the mirror bonded to barrel#1 with ELC-1043 is acceptable (29.1 µrad).

4.3.3 Effect of Mechanical Vibration

Strength of an optical system to mechanical vibrations is also an important consideration. Mechanical vibrations is applied on the test plates in +x, -x, +y, -y, +z and –z directions to monitor the effect of mechanical vibrations. Random vibration data and profile applied to the test plates are shown in Table 4.2 and Figure 4.30, respectively.

TABLE 4.2 Random Vibration Data [38]

FREQUENCY (Hz)	**g^2 / Hz**
0-20	0
20-60	0.15
60-160	0.0004
160-260	0.01
260-400	0.001
400	0.0046
1400-2000	0.2

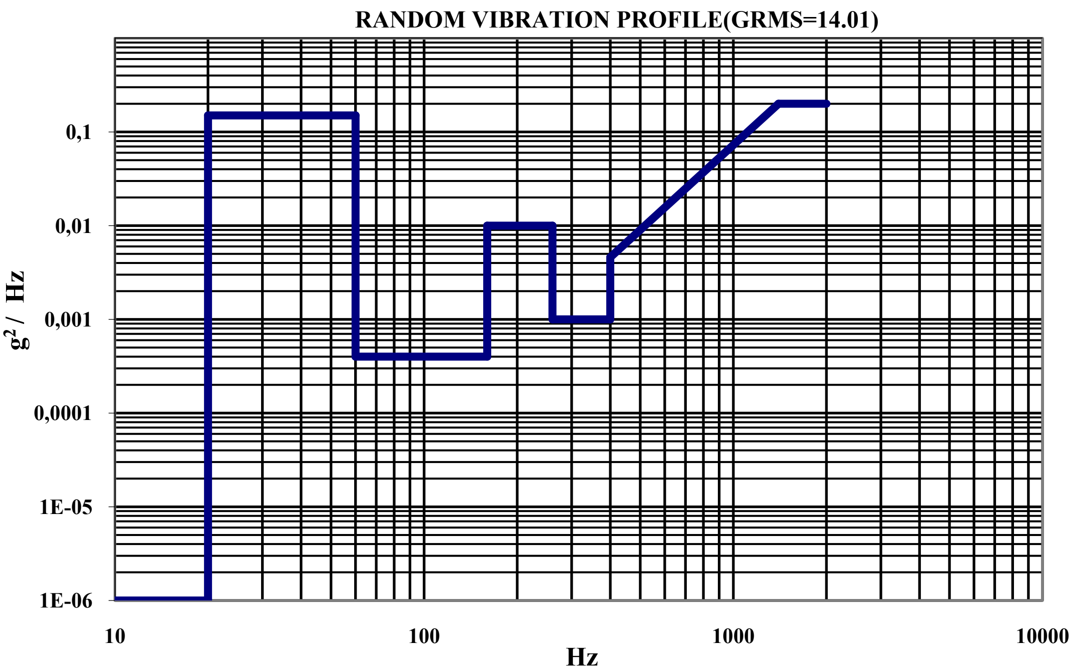


FIGURE 4.30 Random Vibration Profile [38]

After application of random vibration in X, Y and Z directions to the test plates, angular movement of the mirrors is measured by autocollimator. Measurements are taken for 25 mirrors, i.e. each adhesive and barrel combination, 5 different adhesives and 5 different barrels, are shown in APPENDIX K.

In Figure 4.31, angular movement of the mirrors bonded with MILBOND due to random vibration is seen.

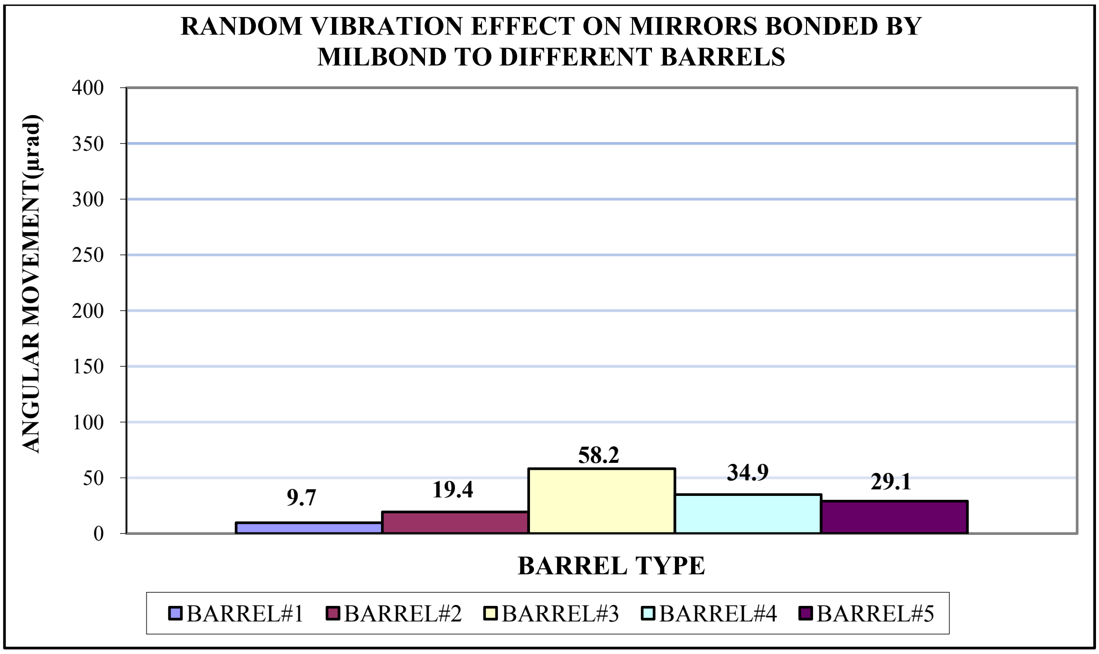


FIGURE 4.31 Random Vibration Effect on Mirrors Bonded by MILBOND

Measurement results of the angular movement of the mirrors, bonded with MILBOND to the designed barrels, due to random vibration indicates that least movement occurs on the mirror bonded to barrel#1 (9.7 µrad). Moreover, it is observed that mirrors bonded to barrel#2, barrel#3, barrel#4 and barrel#5 moves angularly 19.4 µrad, 58.2 µrad, 34.9 µrad and 29.1 µrad, respectively.

Angular movement of the mirrors that are bonded with MASTERBOND-2LO to the barrels is also observed after the test plates are exposed to mechanical vibration. Measurement results are shown graphically in Figure 4.32.

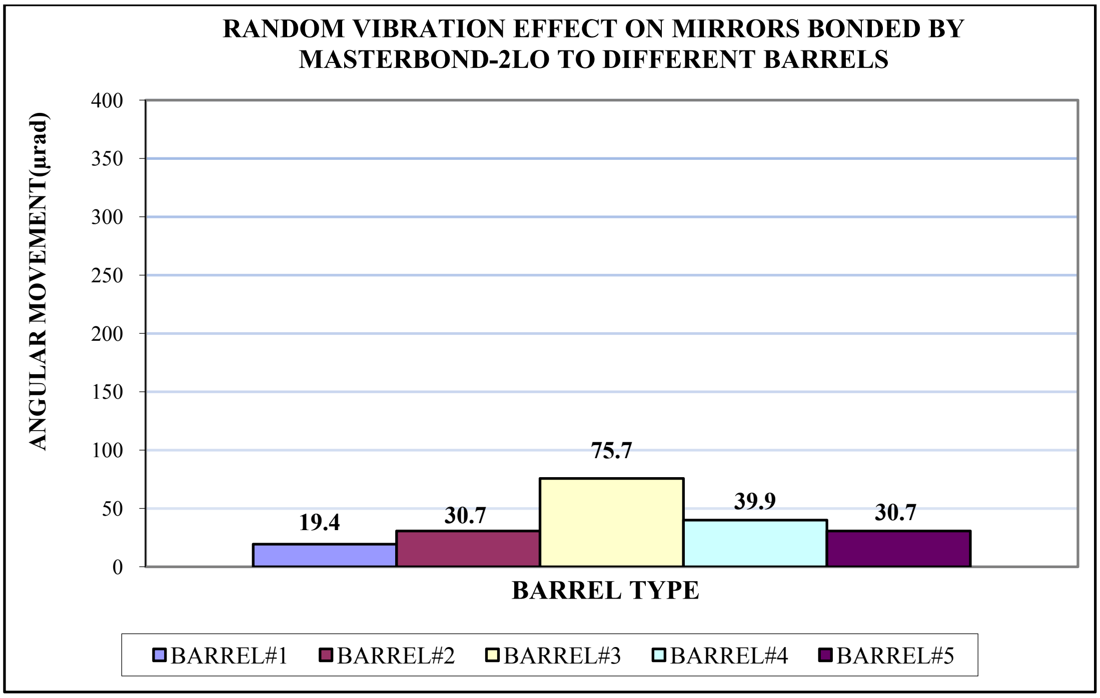


FIGURE 4.32 Random Vibration Effect on Mirrors Bonded by MASTERBOND-2LO

From the measurement results, it is seen that mirror bonded to barrel#5 moves 75.7 µrad. This is the most angular movement among the mirrors bonded with MASTERBOND-2LO. On the other hand, least movement of the mirrors bonded with MASTERBOND-2LO is observed at the mirror bonded to barrel#1 (19.4 µrad).

Angular movement of the mirrors bonded to the barrels with MASTERBOND-2ND is also measured in this study. Measurement results are shown in Figure 4.33.

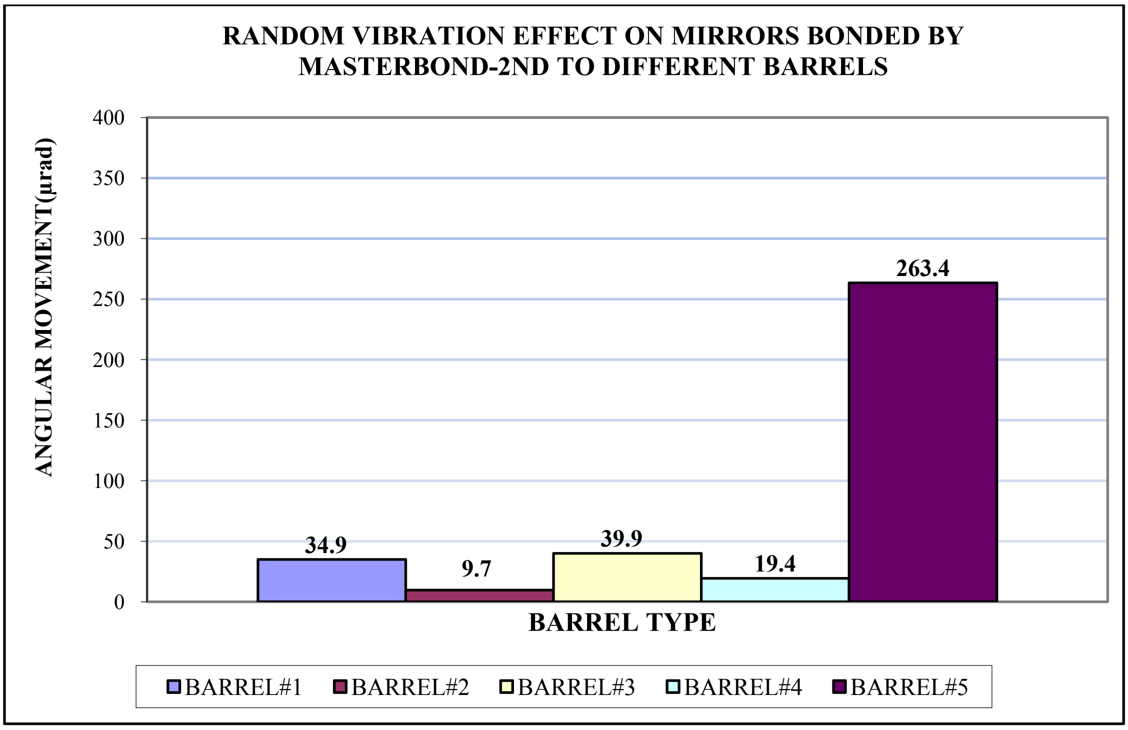


FIGURE 4.33 Random Vibration Effect on Mirrors Bonded by MASTERBOND-2ND

Differently, in the measurements of the angular movement of the mirrors that are bonded to the barrels with MASTERBOND-2ND, least movement and most movement of the mirrors is observed on the mirrors bonded to barrel#2 and barrel#5, respectively. In the previous measurements (on mirrors bonded with MILBOND and MASTERBOND-2LO), least movement and most movement is observed on the mirrors bonded to barrel#1 and barrel#3, respectively. Angular movement of the mirrors that are bonded with MASTERBOND-2ND to barrel#1, barrel#2, barrel#3, barrel#4 and barrel#5 is 34.9 µrad, 9.7 µad, 39.9 µrad, 19.4 µrad and 263.4 µrad, respectively.

Angular movement of the mirrors that are bonded with OP-67-LS is also recorded in this study. Angular movement of the mirrors bonded with OP-67-LS to the barrels is shown in Figure 4.34.

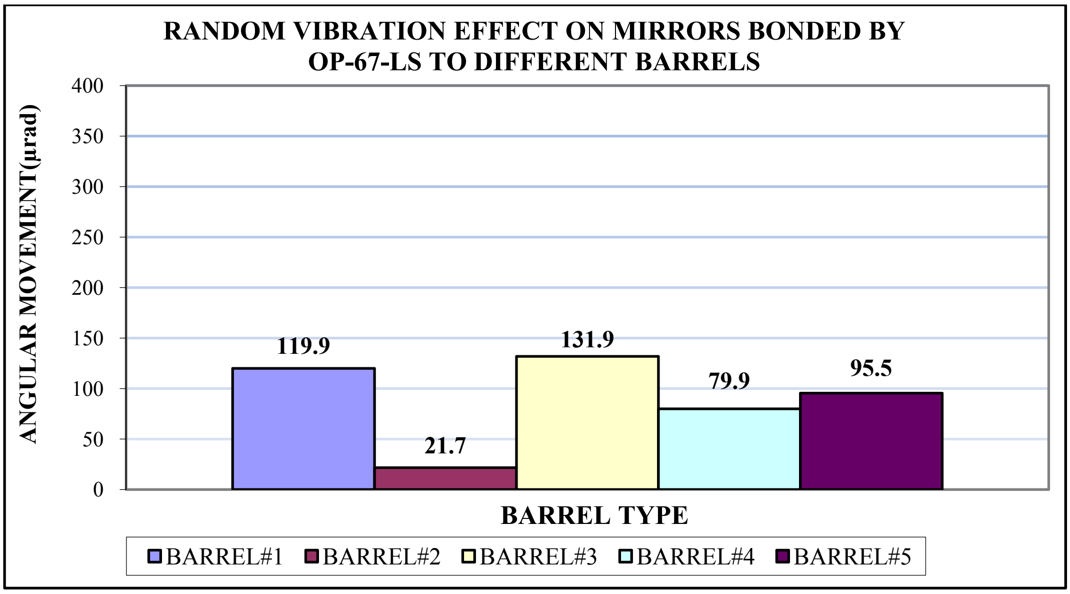


FIGURE 4.34 Random Vibration Effect on Mirrors Bonded by OP-67-LS

According to the measurement results of the angular movement of the mirrors bonded with OP-67-LS, mirror movements on barrel#1, barrel#2, barrel#3, barrel#4 and barrel#5 are 119.9 µad, 21.7 µrad, 131.9 µrad, 79.9 µrad and 95.5 µrad, respectively.

Angular movement of the mirrors bonded with ELC-1043 to the barrels is also measured in this study (Figure 4.35).

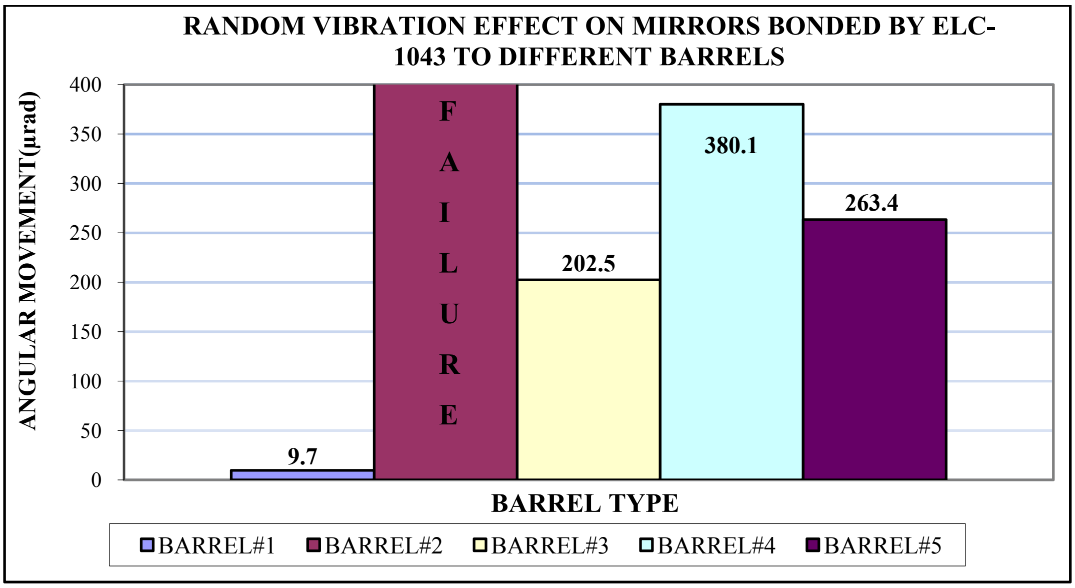


FIGURE 4.35 Random Vibration Effect on Mirrors Bonded by ELC-1043

In measurement of angular movement of the mirrors that are bonded with ELC-1043, it is seen that mirror bonded to barrel#2 is splitted from adhesive. So, it can be said that mirror bonded with ELC-1043 to barrel#2 fails in random vibration test. This failure may be caused from rupture of the adhesive whether due to random vibration or misapplication of the adhesive. In order to be sure about the cause of the failure, a one more test should be done on a mirror bonded to barrel#2 with ELC-1043. However, due to inadequate supply, the test could not be repeated. On the other hand, mirror bonded to barrel#1 with ELC-1043 moves 9.7 μrad, angularly. Moreover, angular movement of the mirrors bonded to barrel#3, barrel#4 and barrel#5 with ELC-1043 is 202.5 μrad, 380.1 μrad and 263.4 μrad, respectively.

4.3.4 Effect of Mechanical Shock

"A mechanical shock is a sudden acceleration or deceleration caused, for example, by impact, drop, kick, eartquake, or explosion" [41]. Mechanical shock is also an important consideration for optical systems used for military applications. In order to determine the effect of mechanical shock on the angular movement of the mirrors, mechanical shock of 40g acceleration for 6 ms is applied on the test plates in +X, -X, +Y, -Y, +Z and –Z directions by using the shakers shown in Figure 4.14 and 4.15. Then, angular movement of the mirrors is measured by autocollimator. However, in these measurements 24 mirror movement is recorded since one of the mirrors, mirror bonded to barrel#2 with ELC-1043, failed while applying mechanical vibration. Angular movement measurements of 24 mirrors are in APPENDIX L.

Angular movement of the mirrors, bonded with MILBOND to the designed barrels, due to mechanical shock is shown in Figure 4.36.

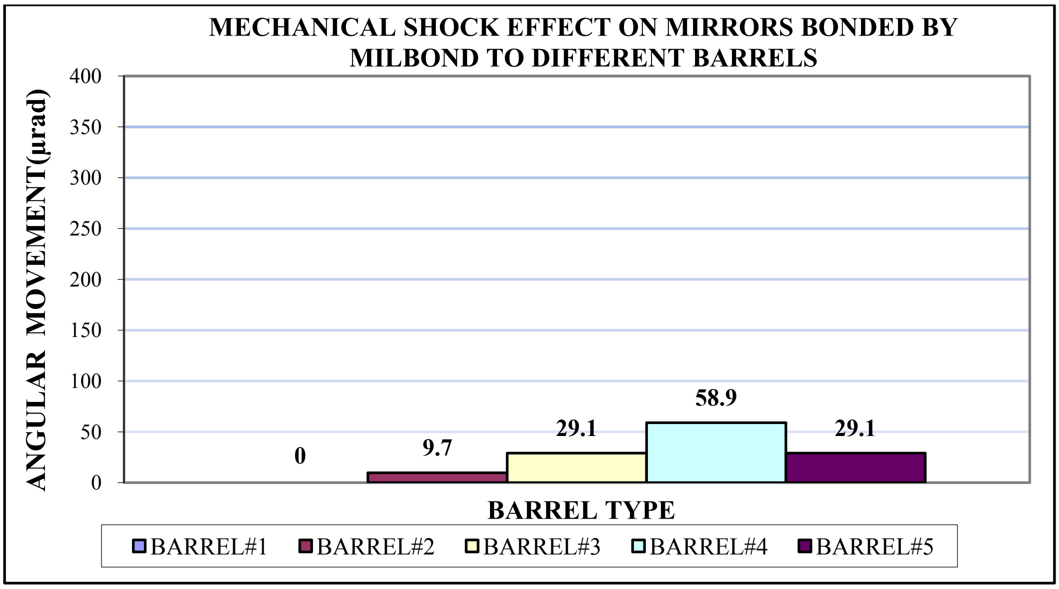


FIGURE 4.36 Mechanical Shock Effect on Mirrors Bonded by MILBOND

Mirror bonded with MILBOND to barrel#1 is not affected from the mechanical shock applied to the test plate. However, mirrors bonded to barrel#2, barrel#3, barrel#4 and barrel#5 moves angularly at 9.7 µrad, 29.1 µrad, 58.9 µrad and 29.1 µrad, respectively.

In order to determine the effect of mechanical shock, mirrors bonded with MASTERBOND-2LO are also investigated. Angular movement of the mirrors bonded with this adhesive is shown graphically in Figure 4.37.

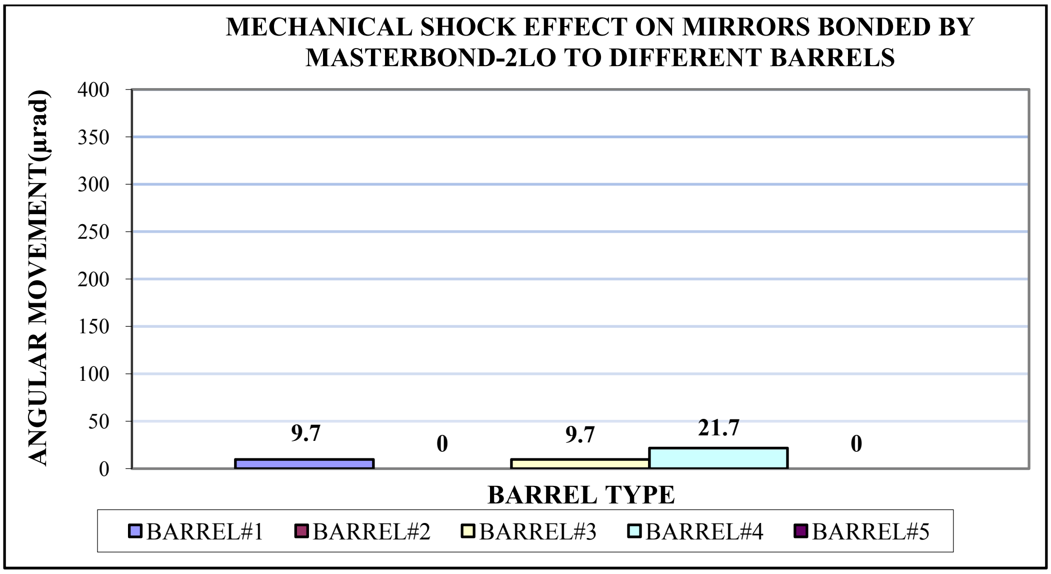


FIGURE 4.37 Mechanical Shock Effect on Mirrors Bonded by MASTERBOND-2LO

Measurement results of the mirrors bonded by MASTERBOND-2LO shows that mirrors bonded to barrel#2 and barrel#5 do not move angularly due to mechanical shock. However, angular movement of the mirrors bonded to barrel#1, barrel#3 and barrel#4 is recorded as 9.7 µrad, 9.7 µrad and 21.7 µrad, respectively.

Angular movement of the mirrors bonded with MASTERBOND-2ND after mechanical shock exposure is shown in Figure 4.38.

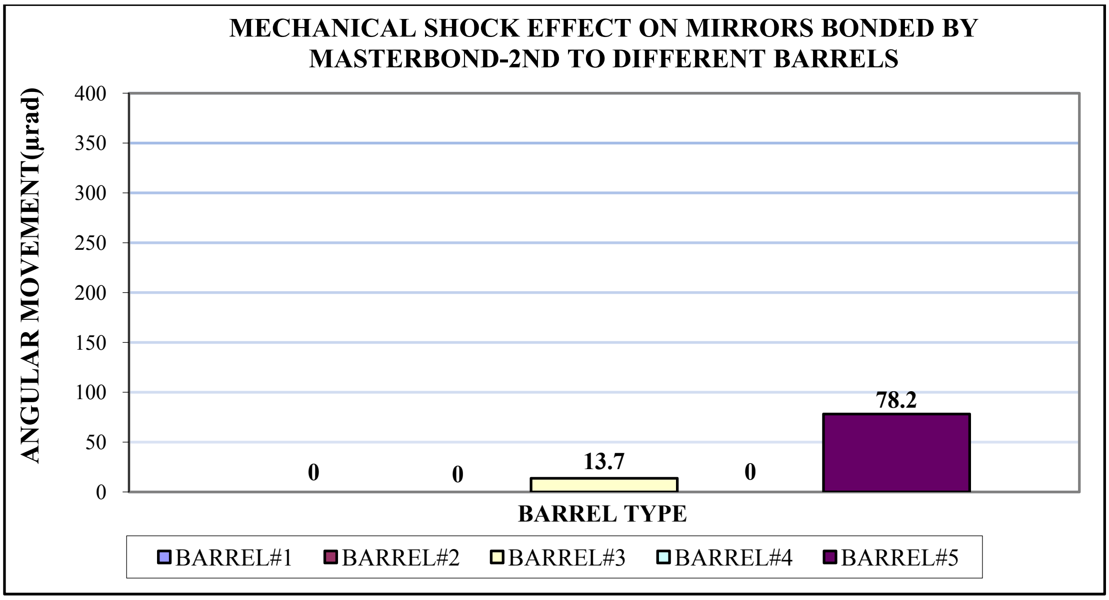


FIGURE 4.38 Mechanical Shock Effect on Mirrors Bonded by MASTERBOND-2ND

It is seen from the measurements that mirrors bonded to barrel#1, barrel#2 and barrel#4 with MASTERBOND-2ND are not affected from exposure of mechanical shock. However, mirrors bonded to barrel#3 and barrel#5 are affected from mechanical shock and moved angularly 13.7 µrad and 78.1 µrad, respectively.

Measurement of angular movement of the mirrors bonded with OP-67-LS to the barrels is shown in Figure 4.39.

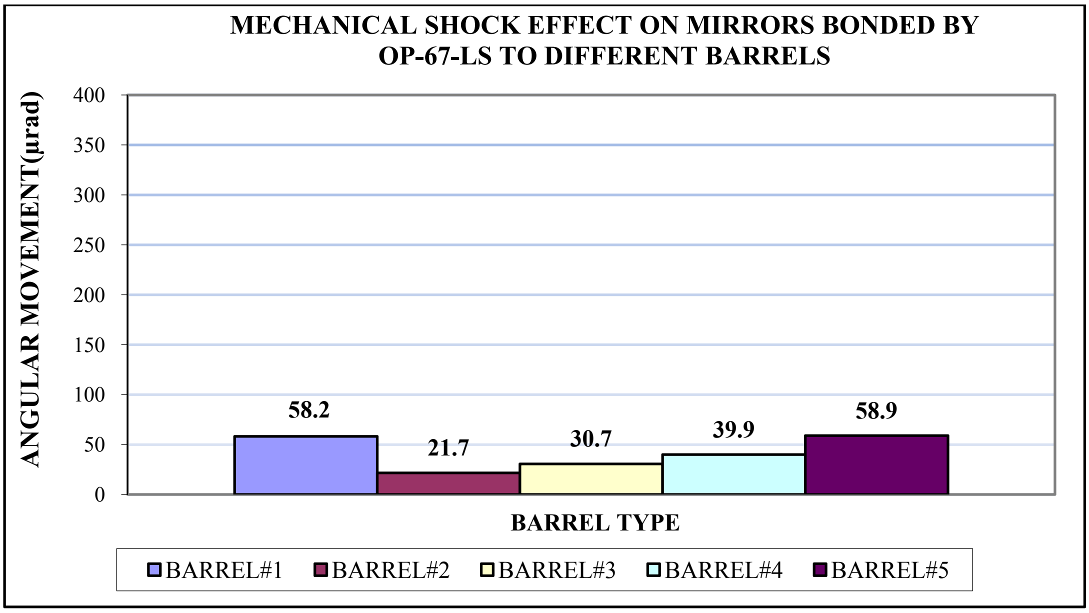


FIGURE 4.39 Mechanical Shock Effect on Mirrors Bonded by OP-67-LS

According to the measurement results, mirror bonded to barrel#2 moves least whereas mirror bonded to barrel#5 moves most angularly among the mirrors bonded with OP-67-LS due to mechanical shock. Mirrors bonded with this adhesive to barrel#1, barrel#3 and barrel#4 moves angularly 58.2 μrad, 30.7 μrad and 39.9 μrad, respectively, due to mechanical shock.

After exposure of the test plates to mechanical shock, angular movement of the mirrors bonded with ELC-1043 is also measured. Measurement results are shown graphically in Figure 4.40.

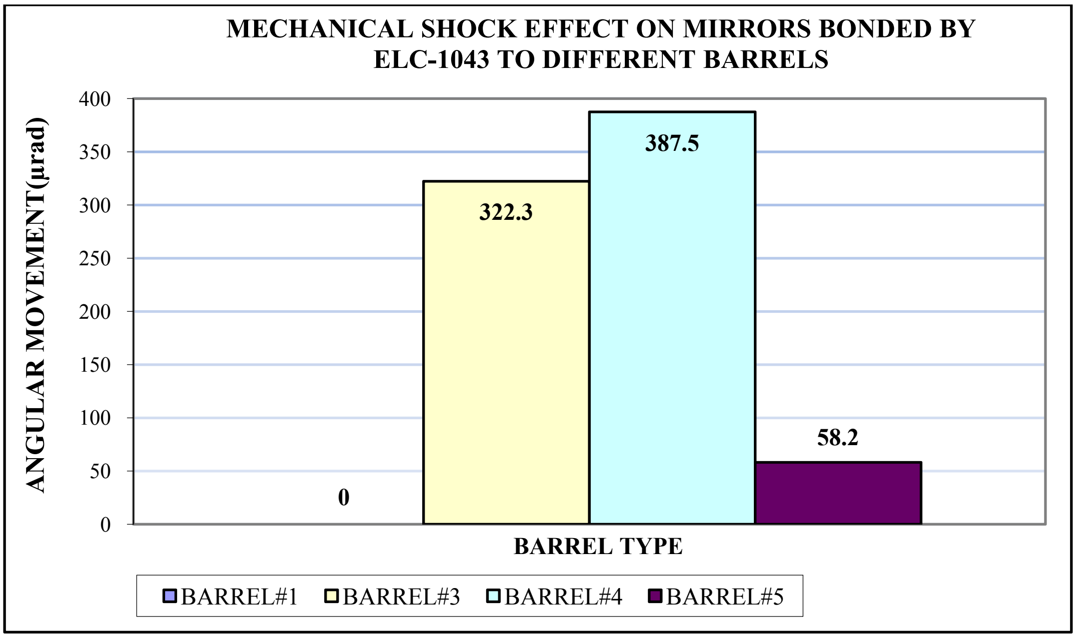


FIGURE 4.40 Mechanical Shock Effect on Mirrors Bonded by ELC-1043

In the figure, it is seen that there are only 4 measurements because the mirror bonded to barrel#2 is splitted during exposure of random vibration. So, only the remaining mirrors, mirrors bonded to barrel#1,barrel#3, barrel#4 and barrel#5, are tested. After application of mechanical shock to the test plates, angular movement of the mirrors bonded to barrel#1, barrel#3, barrel#4 and barrel#5 are recorded as 0 µrad, 322.3 µrad, 387.5 µrad and 58.2 µrad, respectively.

4.4 Design of Experiments

"Design of experiments (DOE) is a systematic approach to engineering problem-solving that applies principles and techniques at the data collection stage so as to ensure the generation of valid, defensible and supportable engineering conclusions" [44]. Main objectives of the experimenter in DOE are learning how to change a process average in the desired direction, learning how reduce process variation, learning how to make a process robust and learning which variables are important to control and which are not [45].

In this study, DOE is performed for one set of experimental data to identify which variables are important to control. DOE is done by Minitab® which is a statistics package. In order to carry out DOE to the experimental data acquired in the experiments, the factors causing angular movement of mirrors were grouped. Main factors causing different angular movement of mirrors were barrel type, adhesive type and environmental effects. Barrel type factor was composed of 5 levels which are barrel#1, barrel#2, barrel#3, barrel#4 and barrel#5. Adhesive type factor was also composed of five different levels since there were 5 different adhesives, MILBOND, MASTERBOND-2LO, MASTERBOND-2ND, OP-67-LS and ELC-1043, used in the experiments. On the other hand, environmental effects factor was considered as 2 levels, i.e, none and exists. Although there were mainly three environmental effects considered in the study, thermal shock, mechanical vibration and mechanical shock, it was considered as 2 level. This is due to the fact that there were no data for a test plate that was exposed to only mechanical shock or mechanical vibration. In the experimental study, the test plates were exposed firstly to thermal shock, then to mechanical vibration and finally to mechanical shock. So, a test plate exposed to mechanical shock had already exposed to thermal shock and mechanical vibration. In short, the system was considered as 3 factor sytem two of which was composed of 5 levels and one of which was composed of 2 levels. Then, 50 inputs were entered in Minitab® as shown in Table 4.3.

TABLE 4.3 Inputs Entered in Minitab®

BARREL TYPE	ADHESIVE TYPE	ENVIRONMENTAL EFFECTS	ANGULAR MOVEMENT(μrad)
BARREL#1	MILBOND	NONE	29.9
BARREL#1	MILBOND	EXISTS	87.3
BARREL#1	MASTERBOND-2LO	NONE	73.8
BARREL#1	MASTERBOND-2LO	EXISTS	167.9
BARREL#1	MASTERBOND-2ND	NONE	207.5
BARREL#1	MASTERBOND-2ND	EXISTS	417.3
BARREL#1	OP-67-LS	NONE	91.9
BARREL#1	OP-67-LS	EXISTS	335.1
BARREL#1	ELC-1043	NONE	29.1
BARREL#1	ELC-1043	EXISTS	67.9
BARREL#2	MILBOND	NONE	56.5
BARREL#2	MILBOND	EXISTS	95.3

TABLE 4.3 (continued)

BARREL#2	MASTERBOND-2LO	NONE	174.5
BARREL#2	MASTERBOND-2LO	EXISTS	205.2
BARREL#2	MASTERBOND-2ND	NONE	1020.1
BARREL#2	MASTERBOND-2ND	EXISTS	1811.9
BARREL#2	OP-67-LS	NONE	48.5
BARREL#2	OP-67-LS	EXISTS	130.6
BARREL#2	ELC-1043	NONE	58.2
BARREL#2	ELC-1043	EXISTS	5000
BARREL#3	MILBOND	NONE	104.9
BARREL#3	MILBOND	EXISTS	403.9
BARREL#3	MASTERBOND-2LO	NONE	1205.4
BARREL#3	MASTERBOND-2LO	EXISTS	1348.9
BARREL#3	MASTERBOND-2ND	NONE	990.2
BARREL#3	MASTERBOND-2ND	EXISTS	1945.7
BARREL#3	OP-67-LS	NONE	126.4
BARREL#3	OP-67-LS	EXISTS	485.3
BARREL#3	ELC-1043	NONE	343.1
BARREL#3	ELC-1043	EXISTS	1745.1
BARREL#4	MILBOND	NONE	384.2
BARREL#4	MILBOND	EXISTS	982.1
BARREL#4	MASTERBOND-2LO	NONE	314.6
BARREL#4	MASTERBOND-2LO	EXISTS	444.2
BARREL#4	MASTERBOND-2ND	NONE	360.7
BARREL#4	MASTERBOND-2ND	EXISTS	393.8
BARREL#4	OP-67-LS	NONE	1587.2
BARREL#4	OP-67-LS	EXISTS	1827.1
BARREL#4	ELC-1043	NONE	29.1
BARREL#4	ELC-1043	EXISTS	3198.3
BARREL#5	MILBOND	NONE	175.6
BARREL#5	MILBOND	EXISTS	298.8
BARREL#5	MASTERBOND-2LO	NONE	56.5
BARREL#5	MASTERBOND-2LO	EXISTS	114.1
BARREL#5	MASTERBOND-2ND	NONE	217.9
BARREL#5	MASTERBOND-2ND	EXISTS	909.1
BARREL#5	OP-67-LS	NONE	551.3
BARREL#5	OP-67-LS	EXISTS	1105.6
BARREL#5	ELC-1043	NONE	363.5
BARREL#5	ELC-1043	EXISTS	815.1

By using Minitab®; mean value, median, standart deviation and variance values of the collected data were calculated. Mean value, median, standard deviation and variance values of the data were 659, 339, 913 and 833929, respectively. Mean value is calculated by dividing the sum of derived data to the number of derived data. Median is the value placed in the middle when all the data are putted in order from smallest to the highest. Variance is the average of the squared differences from the mean whereas standard deviation is the square root of the variance. From the mean value and median of the collected data, it can be stated that data are positive skew since mean value is bigger than median (i.e. 659 > 339). Skewness describes asymmetry from the normal distribution in a set of data and positive skewness describes that there are data extremely higher than the mean value. Skewness of a data can also be determined from the histogram of the data series. Histogram of the data obtained in the experiments are seen in Figure 4.41.

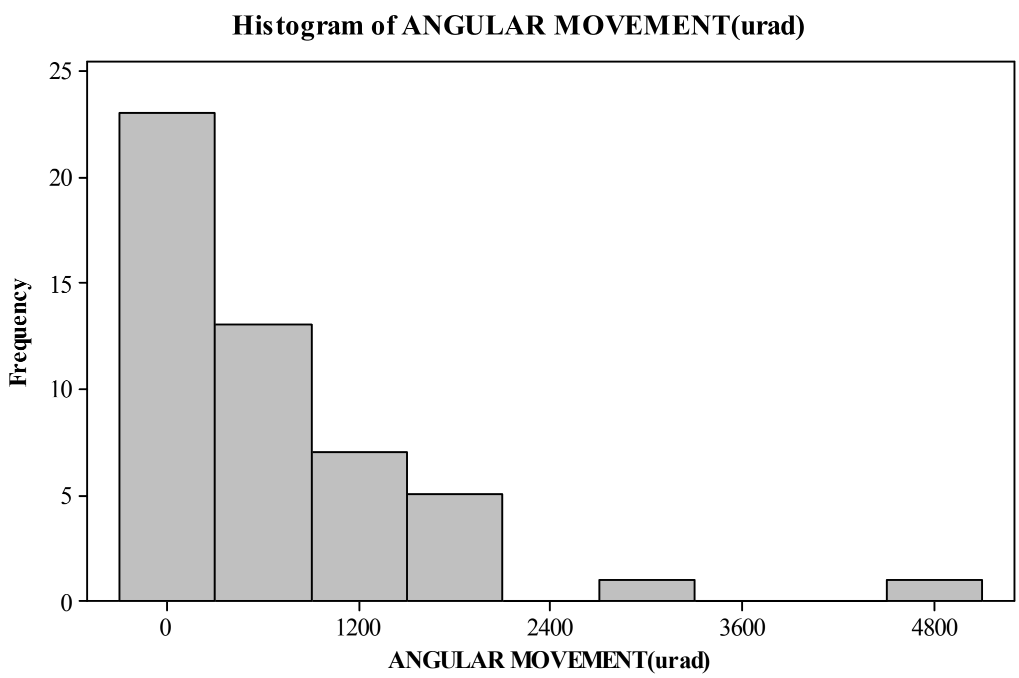


FIGURE 4.41 Histogram of the Experimental Data

In a system that has positive skewness, data extremely higher than the mean value can be removed. Removed data are named as outliers. There were two outliers in this study. One of them was angular movement of the mirror bonded to barrel#2 with ELC-1043 after environmental effects tests and the other one was the data taken from the mirror bonded to barrel#4 with ELC-1043 after environmental effects tests. After removing the outliers from the data set, main effect plots for angular movement were obtained as in Figure 4.42.

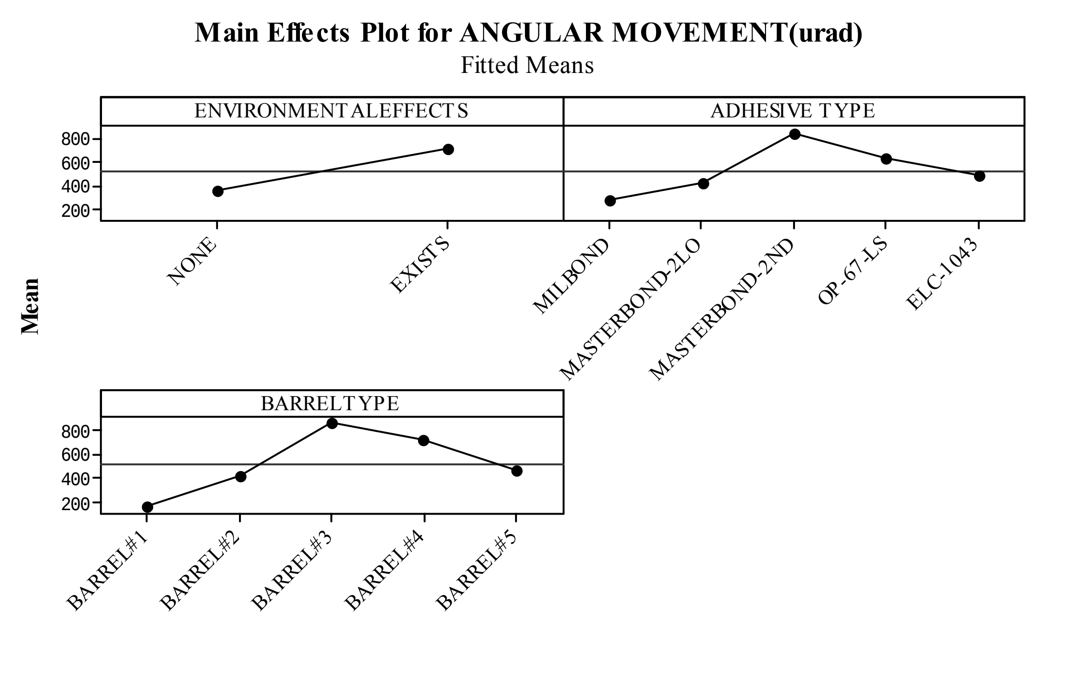


FIGURE 4.42 Main Effects Plot for Angular Movement of Mirrors

Straight lines in the figures represents the reference line (mean value) of the data. From Figure 4.42, it can be seen that environmental effects (thermal shock, mechanical vibration and mechanical shock) influenced angular movement of the mirrors. Also, it can be stated that mirrors bonded with OP-67-LS, ELC-1043 and MASTERBOND-2ND had more angular movement than the mirrors bonded with MILBOND and MASTERBOND-2LO. Moreover, it can also be indicated that mirrors bonded to barrel#3 and barrel#4 had more angular movement than the mirrors bonded to barrel#1, barrel#2 and barrel#4.

In order to show the relative importance of the effects, barrel type, adhesive type and environmental conditions, pie chart was obtained from Minitab®. In Figure 4.43, pie chart of the effects are seen.

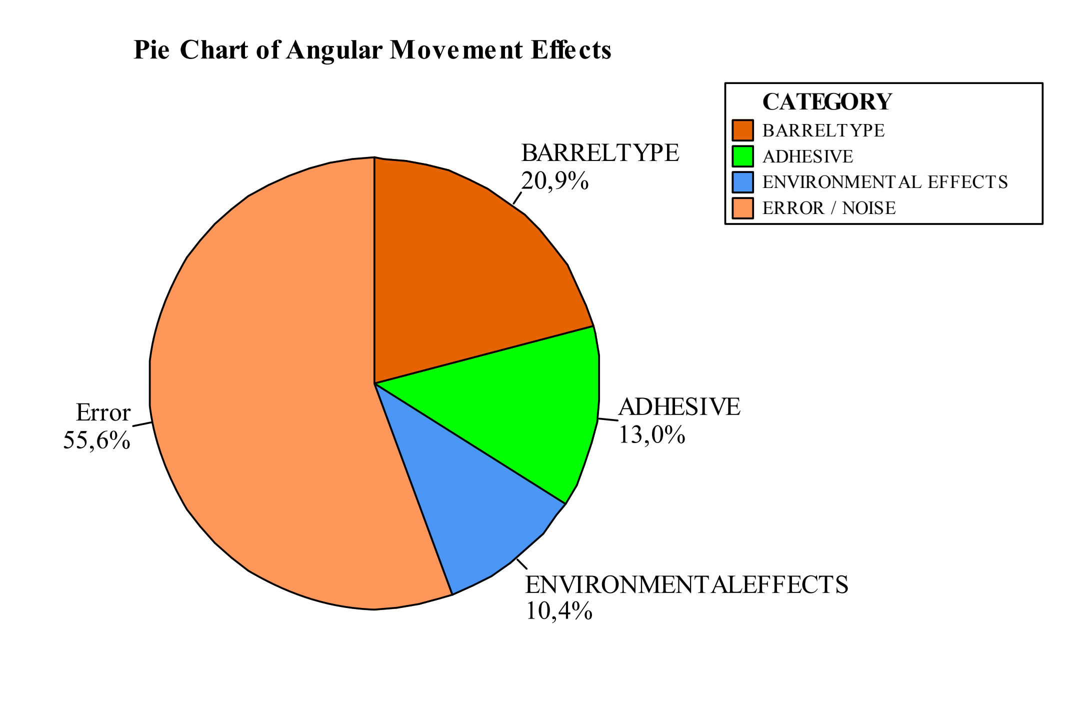


FIGURE 4.43 Pie Chart of Angular Movement Effects

Pie chart of angular movement effects represents that 20.9% of the angular movement was caused from barrel type. Also, 13% of the angular movement of the mirrors was caused by adhesive type whereas 10.4% was caused by environmental effects, thermal shock, mechanical vibration and mechanical shock. In other words, most important effect was barrel type among the effects examined in this study. However, from Figure 4.43 it is seen that there occured an error of 55.6%. Such percentage for an error in a statistical study shows that there were more effects causing angular movement of the mirrors. These effects were not considered in this study but these may be due to mechanical tolerances of the barrels, mechanical tolerances of the mirrors, adhesive application process, adhesive vacuum process, adhesive cure process and tolerances of autocollimator readings. Moreover, lack of repetition of the experimental study, experiments were performed for only once, caused such error.

CHAPTER 5

DISCUSSION and CONCLUSION

5.1 Summary and Conclusions

In this thesis, mounting methods of prisms and lenses and/or mirrors used in a laser system have been investigated. While mounting both prims and mirrors, bonding method has been preferred since this method has been more simple and cheaper than the other methods for mounting prisms and mirrors. However, optomechanical design, adhesive selection and application of the adhesive have been crucial for a good and reliable bonding of the prisms and the mirrors.

In order to provide good and reliable bonding of the prisms and the mirrors, proper optomechanical mounts has been designed, suitable adhesives has been selected and careful adhesive application processes has been done. While designing proper optomechanical mounts; easy bonding of the optical components, providing required bond area and not stressing the optical components have been considered. Also, adhesive selection has been done by considering the system requirements. So; structural, low-outgas, glass to metal bonding and wide temperature range operating adhesives have been selected. Moreover, it has been paid attention in bonding process that both optical surfaces and mechanical surfaces have been clean.

Mathematical correlations, derived by Paul R. YODER, Jr., have been used in order to determine the safety factor of bonding of different prisms to their optomechanical mounts. Safety factor values have been representing the bonding safety of the prisms for an acceleration level of 40g. In the study, bonding of 7 types of prisms used in a laser system, Beamsplitter Cube Assembly – Harting Dove Prisms – Porro Bend Prism – Porro Cut Prism – 37 mm and 41 mm Retro Reflector Prisms – Right Angle

Prism, with two different adhesives have been judged for 40g acceleration. Safety factor values of bonding prisms with two different adhesives are shown in Table 5.1.

TABLE 5.1 Safety Factor Values of Bonded Prisms with Different Adhesives

PRISM TYPE	SAFETY FACTOR FOR DIFFERENT ADHESIVES		
	3M EC-2216 A/B	MILBOND	MASTERBOND-2LO
BEAMSPLITTER CUBE ASSY.	100.7	105.8	49.3
HARTING DOVE	85.9	90.2	42.1
PORRO BEND	61	64.1	29.9
PORRO CUT	168.4	176.8	82.4
37mm RETRO REFLECTOR	44.9	47.2	22
41mm RETRO REFLECTOR	35.9	37.8	17.6
RIGHT-ANGLE	153	160.7	74.9

Safety factor values have been calculated by dividing optomechanical design bond area to required bond area of the correlations. It has been taken into account that mathematical correlations were derived for 3M EC-2216 A/B adhesive. So, safety factor values for this adhesive have been calculated. However, 3M EC-2216 A/B adhesive has not been used for bonding prisms because glass transition temperature (Tg) of this adhesive is between operating temperature range of the system (System operating temperature range : -40ºC to 70ºC and Tg of 3M EC-2216 A/B : 65ºC).

As a result, it has been concluded that optomechanical designs of prism mounts are reliable for an optical system operating at 40g acceleration if the adhesives are applied duly to the prisms. Also, it has been decided that bonding prisms with MILBOND provides the most resistant optomechanical system.

While determining the most stable and reliable design for bonding mirrors, 5 different adhesives suitable for the application has been selected and 5 different optomechanical mounts has been designed. In the designs of the optomechanical mounts, four mainly used methods for bonding mirrors and lenses have been taken into account. Considered bonding methods for bonding the mirrors used in the experiments have been “3 point edge bond in counterbore cell mount”, “3 point guided edge bond”, “3 point face bond” and “using an elastomer layer on the outer diameter of the lens". Also, symmetricity of the bonding has been considered in similar designs of "3 point edge bond in counterbore cell mount", "3 point guided edge bond", "3 point face bond". So, 3 positions for adhesive application have been placed 120º apart from each other in optomechanical mount designs.

In the experimental study, angular movement of the bonded mirrors to the designed mounts due to adhesive cure, thermal shock, mechanical vibration and mechanical shock have been measured. These measurements have been taken by autocollimator. Moreover, two different shakers and a furnace have been used to apply thermal shock, mechanical vibration and mechanical shock to the mirrors.

To monitor the effect of adhesive cure, firstly, mirrors are placed into their barrels and centered by mechanical shims. Then, measurements by autocollimator have been taken and adhesives have been applied to the mirrors. After application of the adhesives of the mirrors, they have been cured according to their cure schedules specified by the suppliers. Afterwards, angular measurements have been taken again with autocollimator. Difference between angular measurements before adhesive cure and after adhesive cure has indicated the effect of adhesive cure.

According to the angular measurements, it has been seen that least angular movement occurs on the mirrors bonded to barrel#1 with MILBOND and mirrors bonded to barrel#1 and barrel#4 with ELC-1043. However, it has been noted that least angular movement occurs on the mirrors bonded with MILBOND if the consistency of the adhesives on different mounts is considered. Also, according to the general trends of angular movement of the mirrors, barrel#1 design has been the least affected optomechanical design due to adhesive cure. Moreover, it has been determined that harmony of the optomechanical design with adhesive is more important than adhesive properties affecting the angular movement of the mirrors, i.e. shrinkage upon cure.

In observation of the effect of thermal shock, mirrors bonded to the barrels with different adhesives have been exposed to a thermal shock for a temperature range of -40ºC and 70ºC in a furnace. This thermal shock profile has been applied to the mirrors according to MIL-STD-810F standart in which the mirrors stay at -40ºC for 3 hours and then heated to 70ºC in 5 minutes and stays at 70ºC for 3 hours. This temperature loop has been followed for 3 times. After application of the thermal shock to the mirrors, angular measurements have been taken by autocollimator.

Angular measurements after thermal shock have indicated that mirrors bonded with MASTERBOND-2LO are affected less than the mirrors bonded with the other adhesives.

So as to determine the effect of mechanical vibration, mirrors bonded to their barrels have been mounted on two different shakers in turn (one of the shakers have been used to apply random vibration in X and Y directions and the other one have been used to apply random vibration in Z direction) and vibrated for 1 hour in X, Y and Z directions. Random vibration profile has been applied to the mirrors according to the data supplied from MIL-STD-810F. After exposure of the mirrors to mechanical vibrations, angular movement of them have been evaluated.

It has been concluded after exposure of the mirrors to mechanical vibrations that mirrors bonded with more viscous adhesives (MASTERBOND-2ND and OP-67-LS) to barrel#2 moves less than the mirrors bonded with other adhesives to barrel#2. However, it has also been concluded that mirrors bonded with less viscous adhesives (MILBOND, MASTERBOND-2LO and ELC-1043) to barrel#1 moves less than the mirrors bonded with other adhesives to barrel#1. But, according to the general response trend of the mirror bondings to mechanical vibrations, mirrors bonded with MILBOND have been affected less than the other mirrors. Moreover, it has been noted that mirror bonded to barrel#2 with ELC-1043 has failed in mechanical vibration test.

For the determination of the effect of mechanical shock, mirrors bonded to their barrels have been mounted on the same shakers used in mechanical vibration test. In this test, mirrors bonded to their barrels have been subjected to 40g acceleration for 6ms in X, Y and Z directions. After application of mechanical shock to the bonded mirrors, angular movement have been measured.

It has been concluded from the measurements that mirrors bonded with MILBOND, MASTERBOND-2ND, MASTERBOND-2LO and OP-67-LS were not much affected by the mechanical shock. However, mirrors bonded with ELC-1043 were affected by the mechanical shock. Moreover, it has been seen from the measurements that mirrors bonded to barrel#1 and barrel#2 were the least affected mirrors when general response trend of the bondings are considered.

In the experiments, it has been observed that one, based on one requirement, cannot directly choose the most reliable bonding method and adhesive combination. So, it has been decided to select the most reliable combination according to total angular movement of the mirrors. While calculating the total angular movement of the mirrors, adhesive cure effect has not been considered. Because, while forming the laser system, bonded mirros are used and then laser energy is adjusted. So, the effects; thermal shock, mechanical vibration, mechanical shock, that the adjusted laser system sustains has been considered. Total angular movement of the mirrors due to thermal shock, mechanical vibration and mechanical shock are shown for mirrors bonded with MILBOND, MASTERBOND-2LO, MASTERBOND-2ND, OP-67-LS and ELC-1043 in Figures 5.1, 5.2, 5.3, 5.4 and 5.5, respectively.

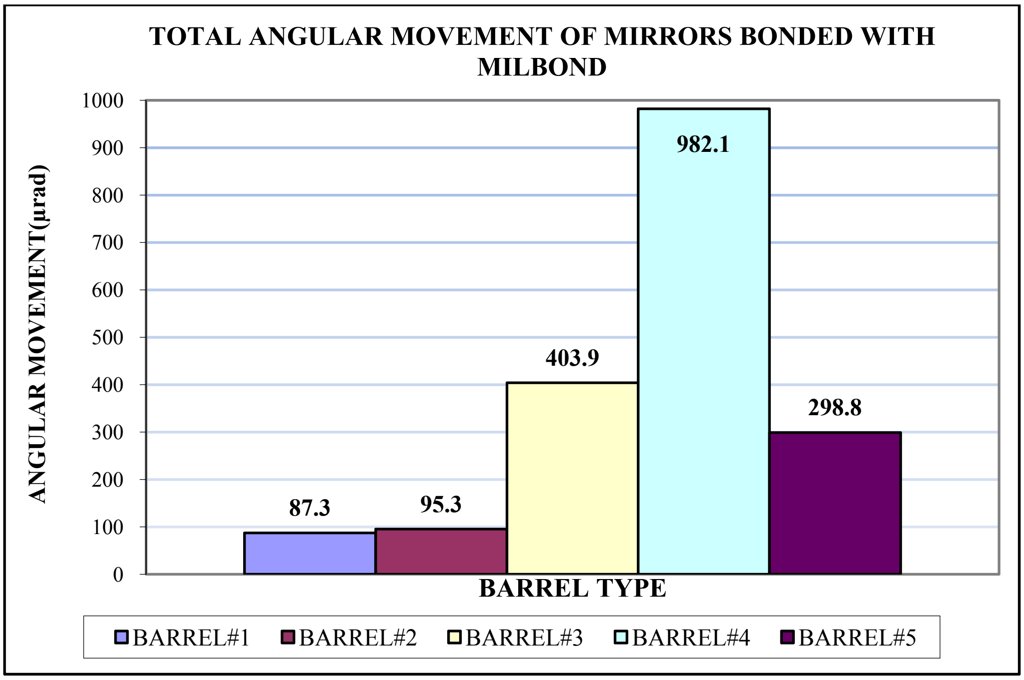


TABLE 5.1 Total Angular Movement of Mirrors Bonded with MILBOND

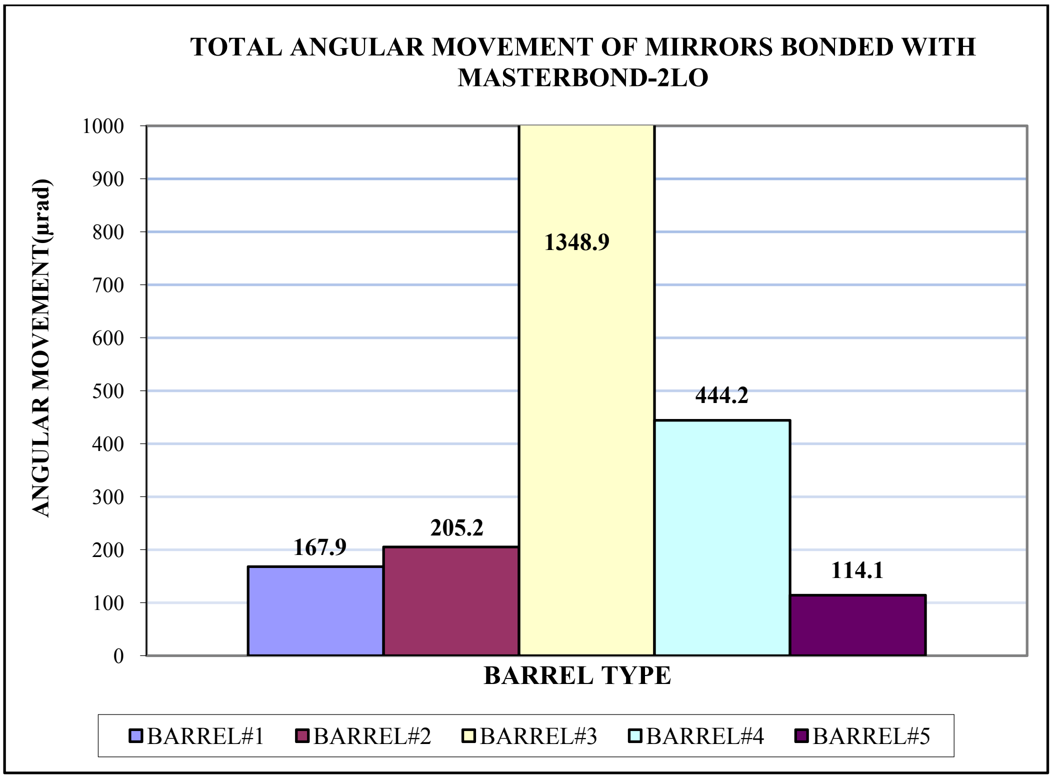


TABLE 5.2 Total Angular Movement of Mirrors Bonded with MASTERBOND-2LO

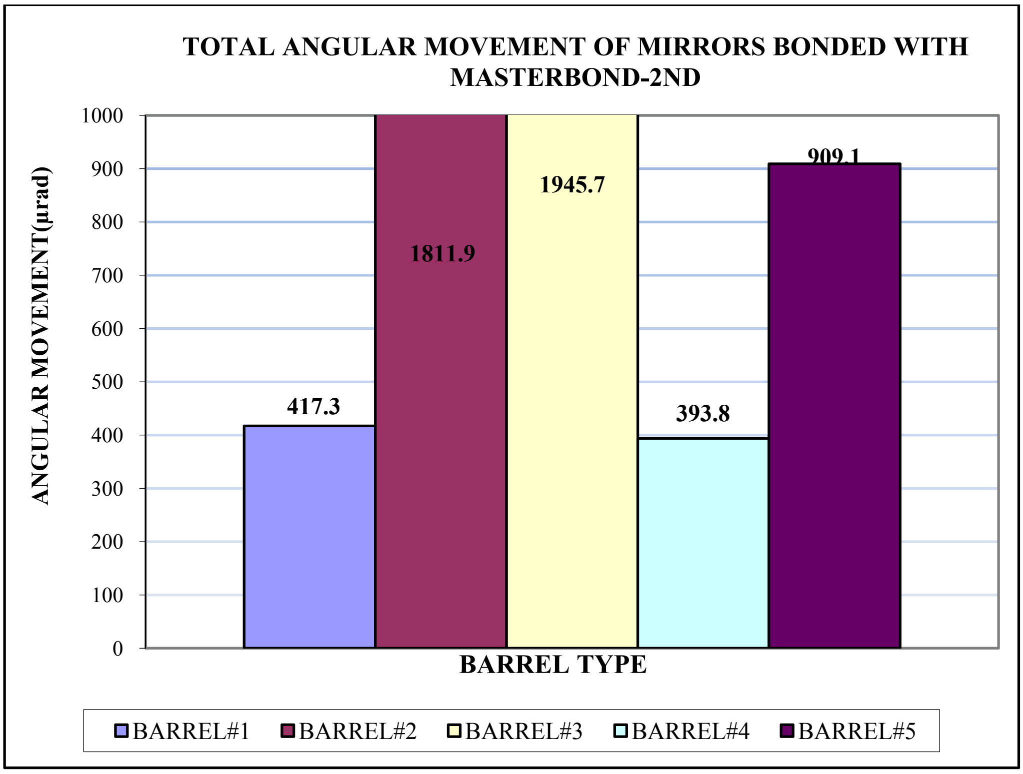


TABLE 5.3 Total Angular Movement of Mirrors Bonded with MASTERBOND-2ND

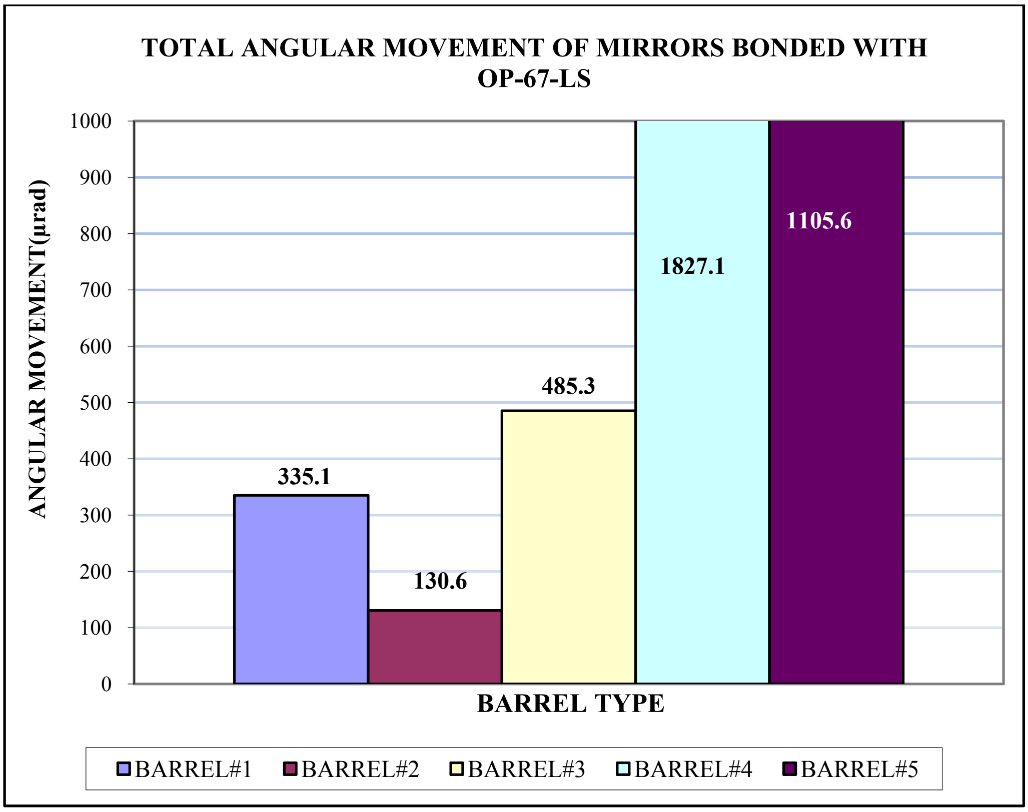


TABLE 5.4 Total Angular Movement of Mirrors Bonded with OP-67-LS

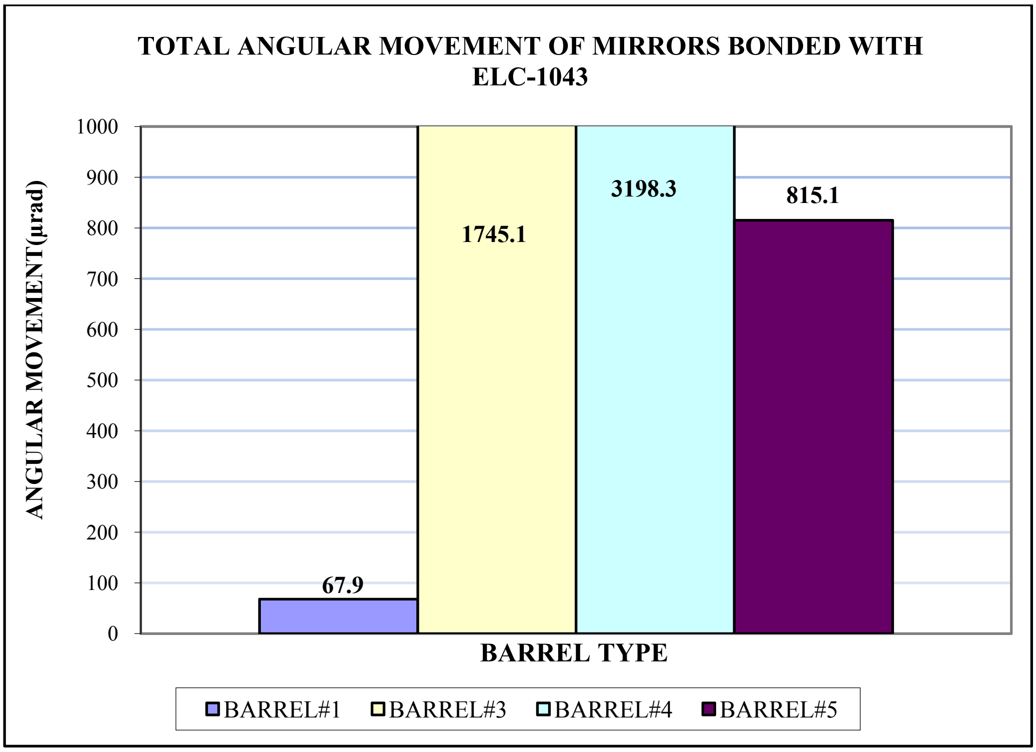


TABLE 5.5 Total Angular Movement of Mirrors Bonded with ELC-1043

Total angular movement results have shown that least angular movement has occured on the mirror bonded with ELC-1043 to barrel#1. However, ELC-1043 has not been trusted since a mirror bonded with this adhesive has failed in random vibration test. So, it has been decided to bond mirrors with MILBOND to either barrel#1 or barrel#2 in the laser systems to be designed.

In Design of the Experiments part (Section 4.4), it has been observed that the effect of barrel type is 20.9%, adhesive type 13% and environmental effects 10.4% on the angular movement of the mirrors. On the other hand, 55.6% of error on angular movement of the mirrors has been occured. Such percentage for an error has showed that there were more effects causing angular movement of the mirrors. Moreover, lack of repetition of the experimental study, experiments were performed for only once, has caused such error.

In conclusion, reliability of the prism bonds under 40g acceleration and mirror bonds for thermal shock, mechanical vibration and mechanical shock has been confirmed.

5.2 Future Work

In this thesis, bonding of prisms and mirrors used in a laser system have been investigated.

While examining bonding of prisms, only mathematical correlations have been used for 40g acceleration. Also, those correlations have been used only for 2 different adhesives, i.e. MILBOND and MASTERBOND-2LO. Experiments may be done to determine whether the bonding of prisms with the specified bonding area and adhesive is sufficient or not. Moreover, different adhesives for bonding prisms may be chosen. On the other hand, it has been supposed that mechanical properties of the adhesives do not change due to vibrational effects. But, adhesives are elastomer materials and elastomer materials are known to be that their mechanical properties change with respect to vibration level of the environment. So, safety factor values for the adhesives and mechanical designs stated may be changed due to vibration level of the environment.

While investigating the effects of adhesive cure, thermal shock, mechanical vibration and mechanical shock on the angular movement of the mirrors bonded to 5 different barrels with 5 different adhesives, one sample from each test plate have been used. More tests may be done at least for the decided barrel design and mirror combination.

In the experimental study, angular movement of the mirrors at different temperatures has not been measured. However, angular movement of the mirrors at different temperatures is also an important fact, especially in military systems. Most importantly, an experimental set-up for measurement of angular deviation of bonded mirrors at different temperatures may be constituted. So, measurements may be taken at different temperatures and angular movement at the decided temperatures may be recorded by use of an autocollimator. Moreover, the experiments may be repeated more to decrease the percentage of the error in the design of the experiments part. Also, more effects on angular movement of the mirrors may be taken into account, i.e. mechanical tolerances of the barrels, mechanical tolerances of the mirrors, adhesive application process, adhesive vacuum process, adhesive cure process and tolerances of autocollimator readings, while repeating the experiments.

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APPENDIX A

DETAILED ENGINEERING DRAWING OF THE TEST PLATE

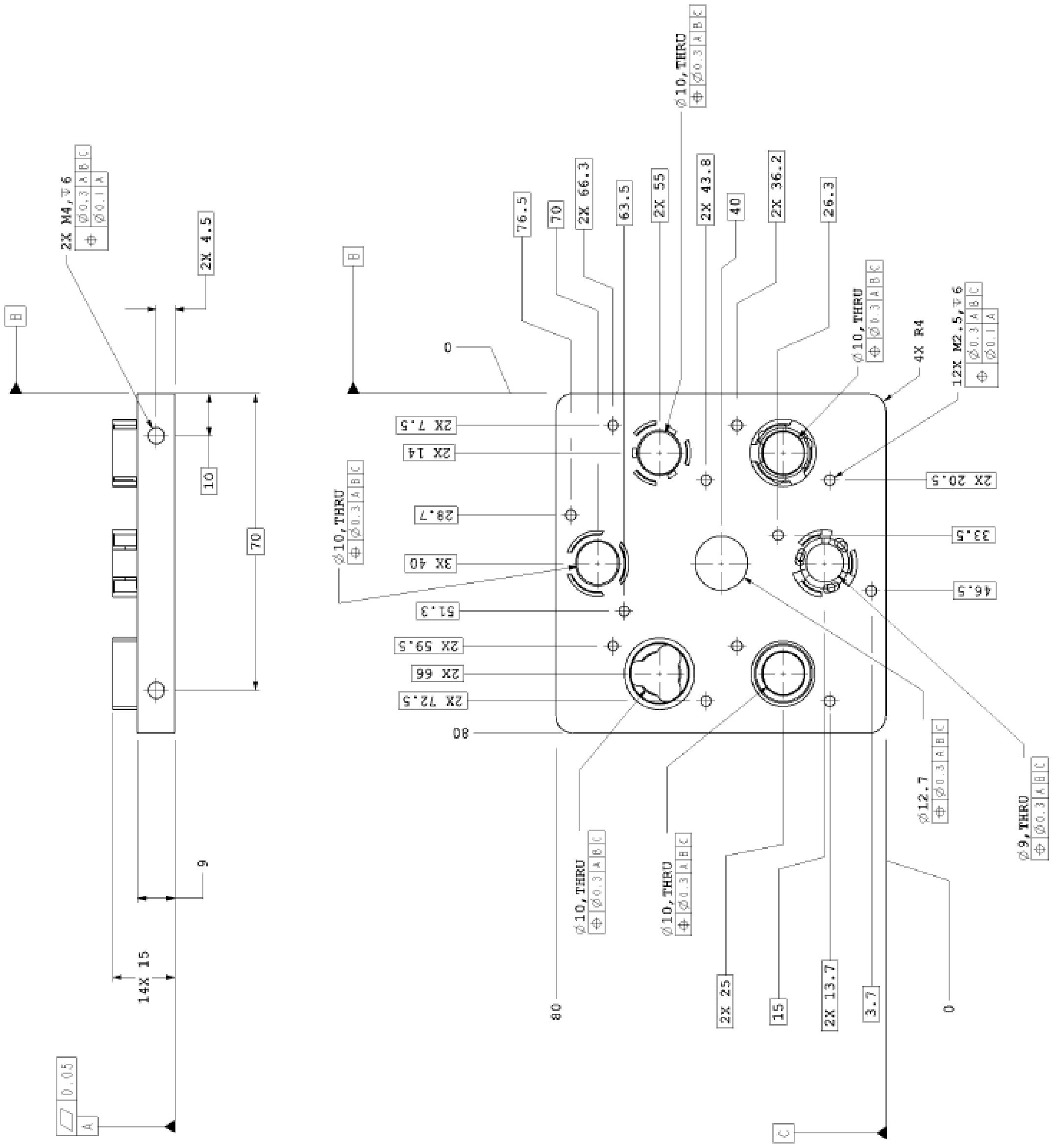

FIGURE A.1 DETAILED ENGINEERING DRAWING OF THE TEST PLATE

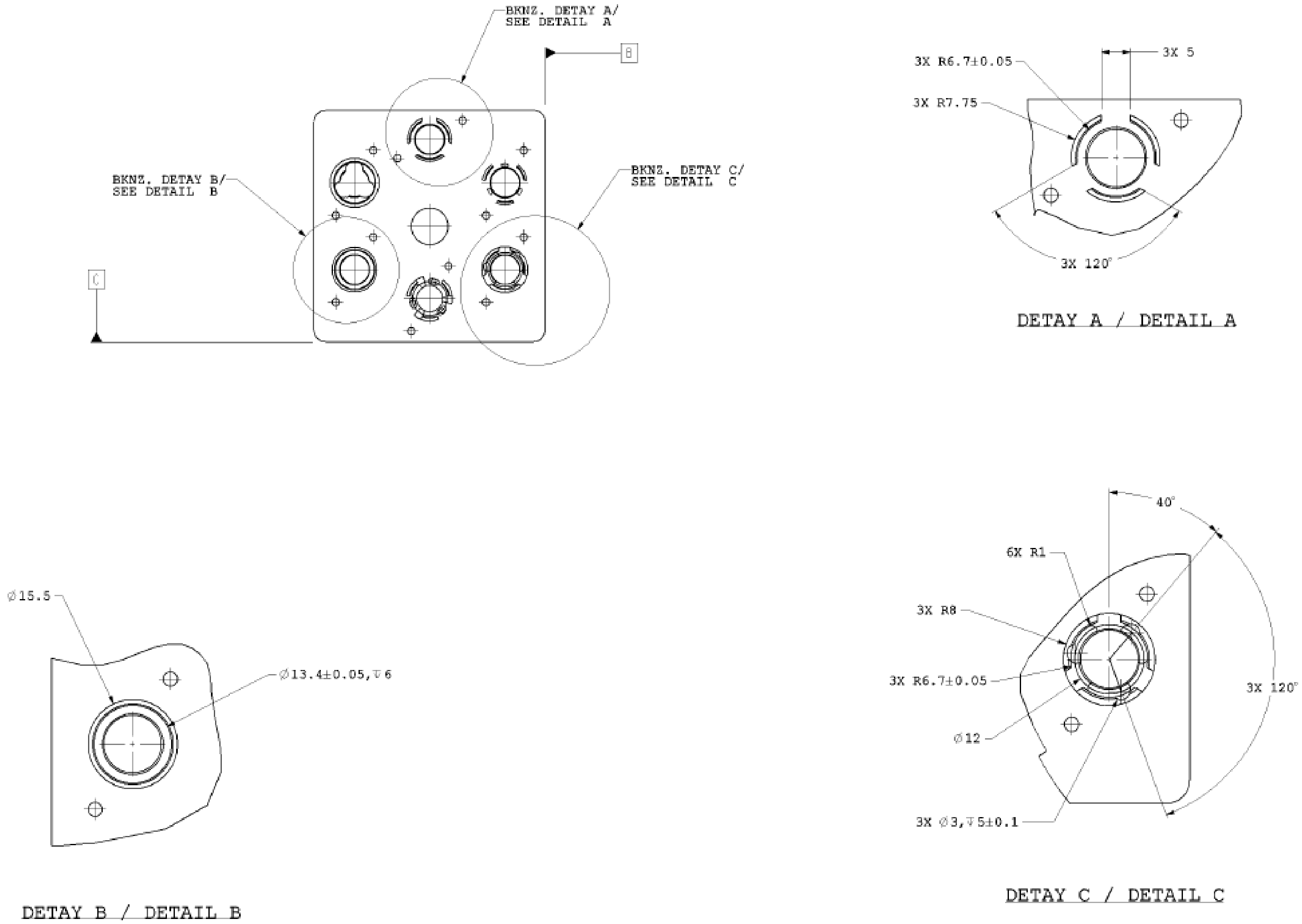

FIGURE A.1 (continued)

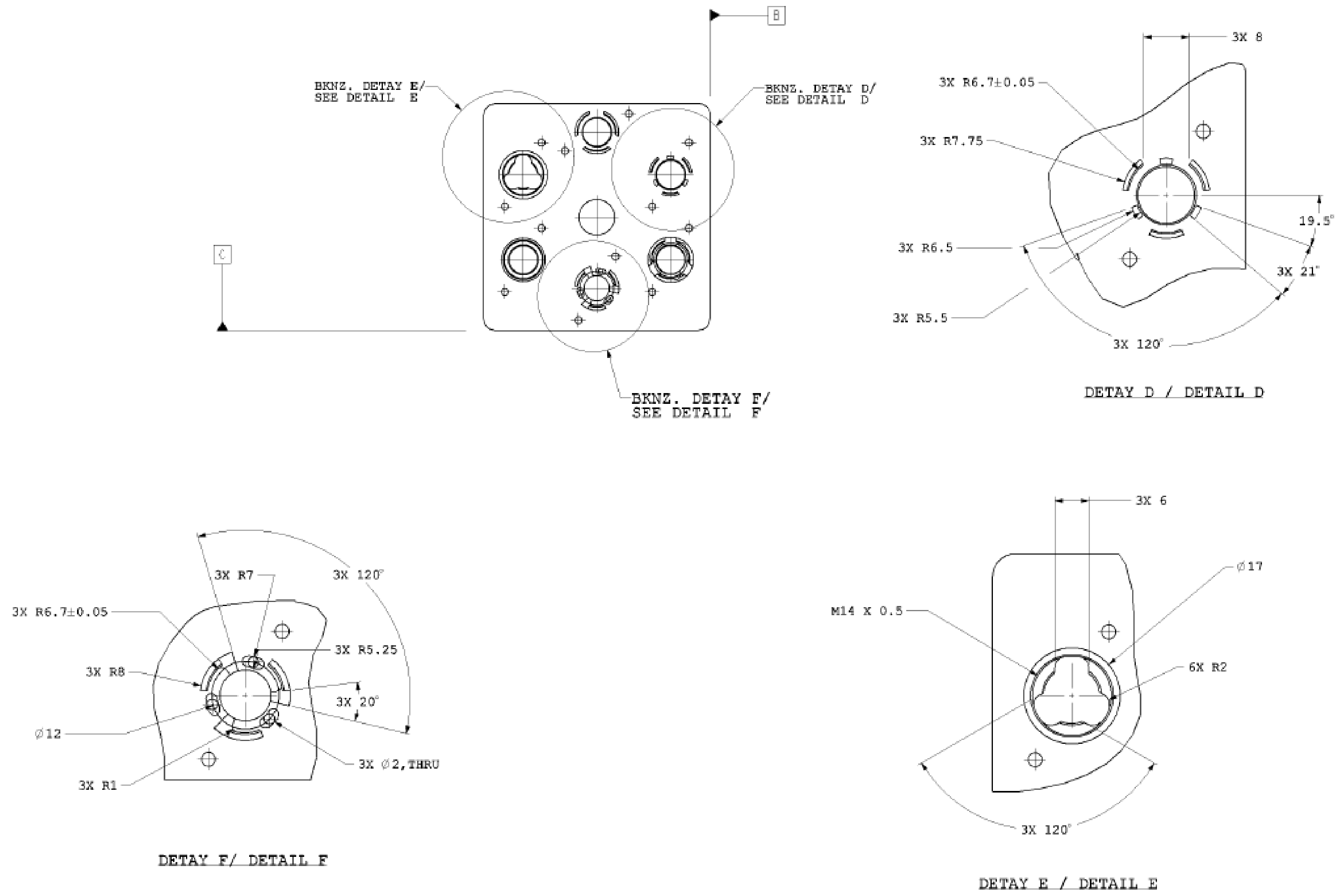

FIGURE A.1 (continued)

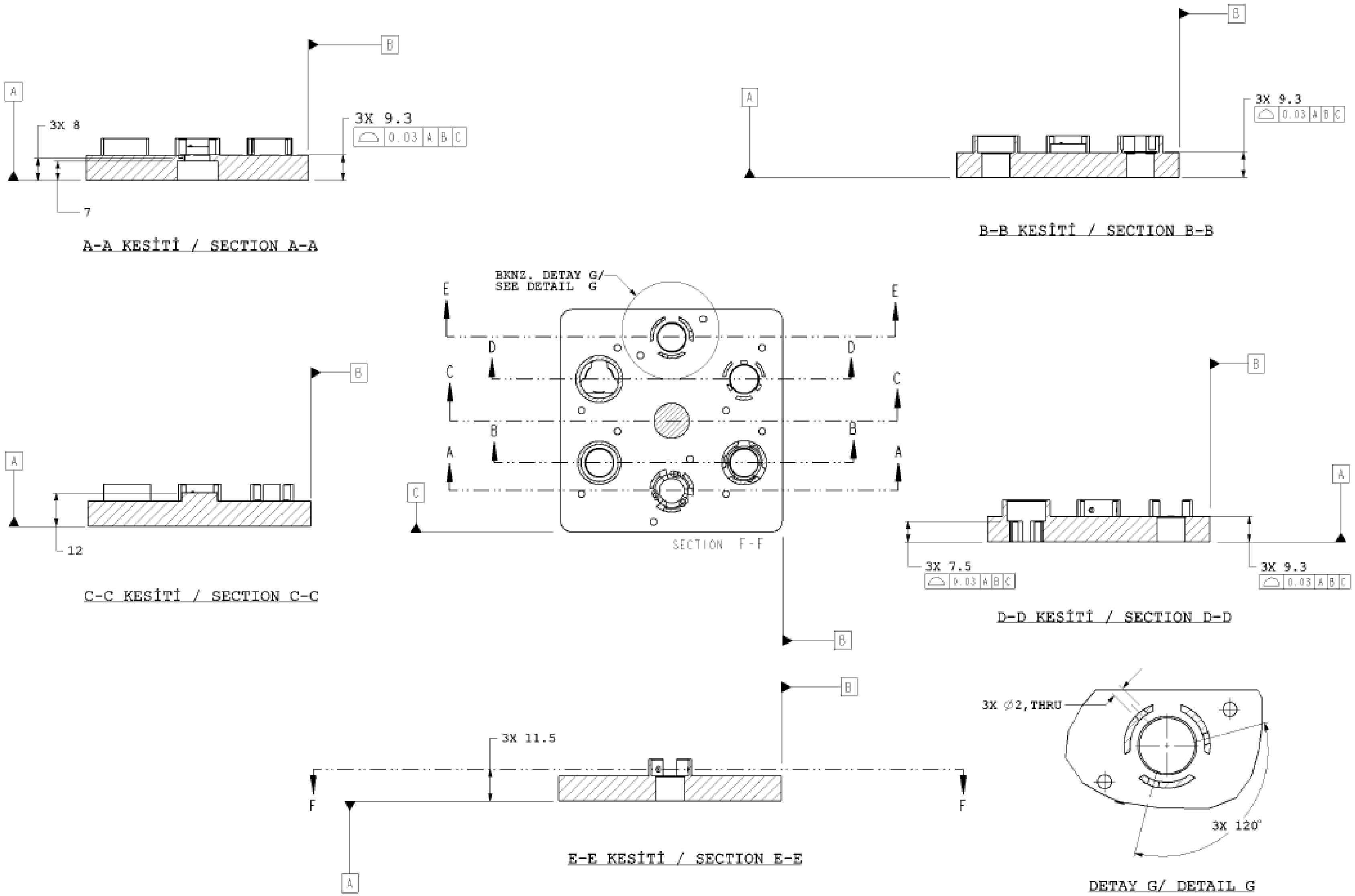

FIGURE A.1 (continued)

APPENDIX B

MILBOND DATA SHEET

INSTRUCTIONS FOR USE

MILBOND

GLASS-TO-METAL ADHESIVE SYSTEMS
MEETS MILITARY SPECIFICATION MIL-A-48611 (MU)

PREPARATION OF SURFACES TO BE BONDED

- **OPTICAL SURFACE**

  All contaminants, chemicals, pencil marks, etc., should be removed from the glass surface. Stubborn material can be removed by scouring with a paste of pumice or calcium carbonate and water. The residue should be removed with deionized or distilled water.
  The glass surface should then be thoroughly cleaned with acetone, using moistened (not wet), clean cheesecloth or lens tissue. Cotton tipped applicators should be not be used.
  The glass surface must be dry before either primer or bonding material is applied.

- **METAL SURFACE**

  Except in special cases, the metal bonding surface must be free from corrosion products, burrs, surface impregnants, anodic, passivation, oxide and other surface treatments as well as other surface contaminants. Imperfections should be removed by careful rubbing with a medium or fine abrasive paper or cloth, while being careful not to destroy the physical dimensions and flatness of the surface. The surface should then be wiped with cheesecloth or lens tissue moistened with acetone. Cotton-tipped applicators should not be used. The surface should be allowed to dry completely before the primer or bonding material is applied.

PREPARATION OF PRIMER

The base resin and curing agent should be vigorously stirred or better yet agitated for one hour to disperse any solids. One part BY VOLUME of the curing agent should be added to an equal volume of the base, and the two components thoroughly mixed. The mixture should be allowed to stand for one-half hour before it is used. During this time it should be capped.

Any unused primer should be discarded no longer than eighty hours after mixing (four hours for best results).

APPLICATION OF PRIMER

The primer should be applied as described below to an area which is at least as large as the cured bond area shown on the engineering drawing. The primer should be applied within two hours after cleaning and the primed surface should be bonded within 30 days after application.

If practical, the optical and metal parts to be primed should be warmed from three to six degrees centigrade above ambient temperature to drive off absorbed moisture on their surfaces.

Shake or stir primer to a homogeneous mixture and apply one uniform coat to the surfaces of the metal and glass parts. Do this either by spraying with an air brush (using dry air or dry inert gas), or by brushing (using a camel's hair brush). There must be no pudding or drips, and the primer must have a smooth, uniform color. The primer thickness should be 0.3 to 1.0 mil as determined by measurement with a micrometer or similar instrument, or by color comparison with standard specimens on the same substrate with known primer thickness.

CURING THE PRIMER

Curing the primer at room temperature (21°C(70°F)) for twenty four hours.

PREPARATION OF ADHESIVE

Stir each part (A and B) thoroughly in its original container to achieve a homogeneous mixture. Weigh out, on a one-to-one BY WEIGHT basis, and mix parts A and B. Take care to minimize the inclusion of entrapped air in the mixed adhesive. The pot life of the mixed adhesive is one hour.

APPLICATION AND ASSEMBLEY OF ADHESIVE

Within 30 days of the application of the primer, the parts should be assembled by one of the two methods described below.

METHOD 1. FOR METAL PARTS WITH NO ADHESIVE INJECTION HOLES

Lightly wipe the primed surfaces with lens tissue or cheesecloth moistened with alcohol to remove any foreign material.

If practical , warm the optical and metal parts to three to six degrees centigrade above ambient temperature to drive off absorbed moisture. Apply sufficient adhesive to both parts with a spatula, glass rod, syringe or other suitable applicator to provided full bonding to the size of bond area shown on the applicable engineering drawing.

Assemble parts in the bond fixture using the spacer material provided to maintain the bond line thickness. The bond line thickness should be between .014 and .016 inches. Metal spacers should not be used. At the option of the user, the spacers employed with this material may be permanently embedded in the bond line. Clean or wipe away excess adhesive prior to cure with cotton tipped applicators moistened as required with methyl-ethyl-ketone or acetone.

METHOD 2. FOR METAL PARTS WHICH HAVE ADHESIVE INJECTION HOLES

A bond fixture should be constructed to provide mechanical positioning of the components to be bonded to an accuracy shown in the applicable drawing. Sufficient support should be provided to protect components of the boned assembly from scratches or damage during the bonding and curing cycle. The fixture should be constructed so as to maintain intimate contact between the metal, glass and adhesive during the curing cycle. Lightly wipe the primed surfaces with lens tissue or cheesecloth moistened with alcohol to remove any foreign material.

Assemble the optical and metal components in the bond fixture using the spacer material provided to maintain the proper bond line thickness. The bond line thickness should be between .014 and .016 inches.

If practical, the assembly should be warned to three to six degree centigrade above ambient temperature just before injection to drive absorbed moisture. Fill a clean syringe with freshly prepared adhesive and inject the adhesive to fill the bond line to the size indicated on the applicable engineering drawing. Inject the adhesive within two hours of cleaning the primed surfaces with alcohol. Avoid the introduction of air into the adhesive since air will cause the bond area to expand during cure and will leave void areas in the bond. Unless otherwise specified, spacers used with this method must be removed. Clean or wipe away excess adhesive with cotton tipped applicators moistened with methyl-ethyl-ketone or acetone.

CURING THE ADHESIVE

The adhesive should be cured for three hours at 71 degrees C. (160 degrees F)

STORAGE

The components in unopened containers, have a shelf life of 12 months when stored in a cool, dry place. (do not refrigerate)

SAFETY

Some persons may be sensitive to one or more the chemicals comprising the formulation. For them, the use of finger cots or chemical gloves are recommended. Adequate ventilation should be provided, and wherever possible, work should be done under a hood.

Milbond contains chemicals that may present a health and fire hazard. Refer to the Material Safety Data sheets for proper handling and storage procedures.

SUMMERS OPTICAL
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Approximate Curing Times

Mix Ratio	Room Temperature 25°C (77°F)	Oven Temperature 71°C (160°F)
Epoxy 1:1 (by weight)	7 days	3 hours
Primer 1:1 (by volume)	1 hour (to touch) 24 hours (to dry)	Not Recommended

Specifications

Pot Life @ 25°C.........................Primer- 8 Hours
Epoxy- 30 Min.

Coverage at .015inch (.38mm)..................1322 sq inches

Tensile Shear @ 25°C..........................2,099 psi
- After 60 min @ 70°C.......................992 psi
- After 60 min @ -50°C......................2,561 psi
- After 10 min @ 70°C(100% R.H.)............1,892 psi
(test to failure at .015inch bond layer thickness, all failures cohesive, thinner bond layers yield higher results.)

Modulus of Elasticity @
-50°C..85,900 psi
+20°C..23,000 psi
+70°C..1,070 psi
(2inch long specimens were used, 5 specimens per test, and the crosshead speed was .2"/min)

Mechanical Shock @
-40°C..250-400G
+20°C..250-400G
+70°C..250-400G
(Shock pulses were approximately half sinewave; 1.5 millisecond duration.)

Linear Coefficient Of Expansion
From (+20°C) - (-54°C)....................6.2×10^{-5}/°C
From (+20°C) - (+70°C)....................7.2×10^{-5}/°C
(2inch long (50mm) substrates were used, 2 substrates per test.)

Outgassing TML (Total Mass Loss)..............0.98%

CVCM (ASTM E595)...............................0.03%
(Collected Volatile Condensable Material)

Thermal Conductivity..........................300-350 x 10^{-5} cal/(sec)(sq.cm)(°C)(

Specific Heat @
40°C...3 cal/(gm)(°C)
60°C...35 cal/(gm)(°C)
80°C...48 cal/(gm)(°C)

Specific Gravities
Primer Resin..................................1.21
Primer Curing Agent............................[illegible]

APPENDIX C

MASTERBOND-2LO DATA SHEET

Technical Data Sheet

MASTER BOND POLYMER SYSTEM EP21TDC-2LO

Two Component, Low Outgassing Epoxy Resin Compound Featuring Flexibility and Thermal Conductivity For High Performance Bonding, Sealing, Coating, And Encapsulation. Cryogenically Serviceable

Product Description

Master Bond Polymer System EP21TDC-2LO is a low outgassing two component highly flexible, thermally conductive epoxy resin compound for high performance bonding sealing, coating, and encapsulation. It is formulated to cure fully at ambient temperature or more quickly at elevated temperature with a convenient one to three mix ratio by weight. The cured compound exhibits high elongation and excellent toughness. As very little exotherm is developed during cure the Master Bond EP21TDC-2LO is suitable for potting and encapsulating thick as well as thin sectioned configurations. This epoxy resin compound exhibits superior tensile shear and peel strength for bonding and sealing applications. It adheres well to many different substrates including metals, glass, ceramics, rubber and plastics. The hardened composition is an excellent electrical insulator with outstanding resistance to chemicals including water, acids, bases and salts. The service temperature range is from 4°K to 250°F making it suitable for many cryogenic applications. Master Bond EP21TDC-2LO is widely used in the electronic, electrical, optical, fiberoptic, aerospace and other industries where low outgassing, flexibility, and thermal conductivity are desirable.

Product Advantages

- Convenient mixing: non critical one to three weight ratio
- Easy application: product spreads evenly and smoothly
- Versatile cure schedules: ambient temperature cures or fast elevated temperature cures as required
- High peel strength and elongation, excellent thermal shock and chemical resistance
- Superior bonding properties on similar and dissimilar substrates, superb impact resistance
- Excellent durability, high thermal conductivity combined with good electrical insulation properties.
- 100% reactive, no solvents, dilutes or volatiles emitted during cure or in service
- Cryogenically serviceable; temperature range 4°K-250°F.
- Meets NASA low outgassing specifications.

Product Properties

- Mixing ratio, weight or volume, parts A to B 1/3
- Viscosity of mixed adhesive, 75°F, cps .... paste
- Working life after mixing, 75°F, 100 gm mass, minutes .... >90
- Cure schedule ambient temperatures, 75°F hrs........ 48-72 hours
- Cure schedule ambient temperatures, 150°F hrs........ 3-4 hours
- Tensile strength, psi, 75°F pli 1070
- Elongation, 75°F .... >50
- Tensile shear strength, aluminum/aluminum, 75°F, psi .... >980
- T-peel strength, 75°F pli .... >15
- Hardness, shore D 36
- Water absorption (tap water) submersion @ 25C for 14 days .... < 1%
- Volume resistivity, 75°F ohm cm .... $>10^{12}$
- Thermal conductivity, BTU * in/ft^2 * hr * °F 9
- Thermal expansion coefficient, in/in x10^{-6}°C 90-100
- Service temperature range, ... 4K to 250°F
- Shelf Life, unopened containers @ RT 75°F........ 6 months

Preparation of Compound for Casting or Bonding

Master Bond Polymer System EP21TDC-2LO is prepared for use by thoroughly mixing part A with part B in a one-to-three mix ratio by weight. Mixing should be done slowly to avoid entrapping air, stir until uniform. The working life of a 100 gm batch is in the order of 90 minutes. It can be substantially lengthened by using shallower mixing vessels or mixing smaller size batches. For bonding and sealing uses, matching surfaces should be carefully cleaned, degreased and dried to maximize bond strength. When bonding to metal surfaces, chemical etching should be employed when the bonded joints are to exhibit optimal environmental durability. Non-porous surfaces should be roughened with sandpaper or emery paper and solvent cleaned using acetone or xylene.

Compound Application and Assembly

Master Bond Polymer System EP21TDC-2LO can be conveniently cast or applied with a spatula, knife, trowel, etc. When bonding, enough (mixed) adhesive should be applied to obtain a final adhesive bond line thickness of 4-6 mils. This can be accomplished by coating each surface with an adhesive film of 2-3 mils thick. Porous surfaces may require somewhat more adhesive to fill the voids than non-porous ones. Thicker glue lines do not increase the strength of a joint but do not necessarily give inferior results as the EP21TDC-2LO compound does not contain any volatiles. The parts to be bonded should then be pressed together with just enough pressure to obtain and maintain intimate contact during cure.

Cure

Master Bond Polymer System EP21TDC-2LO can be cured at room temperature or at elevated temperatures as desired. At room temperature Master Bond Polymer System EP21TDC-2LO will cure in 2-3 days. Faster Cures can be realized at elevated temperatures, e.g. 3-4 hours at 150°F. Remove excess material promptly with a spatula before it hardens. Then wipe with rag and solvent such as isopropyl alcohol, toluene or acetone. Thinner sections of epoxy take longer to cure than thicker ones.

Handling and Storage

All epoxy resins should be used with good ventilation and skin contact should be minimized. The EP21TDC-2LO compound employs a low toxicity hardener. To remove resin or hardener from skin, use solvent, then wash with mild soap and water. If material enters the eyes, flood with water and consult a physician. Optimum storage is at or below 75°F in closed containers. No special storage conditions are necessary. Containers should however be kept closed when not in use to avoid contamination. Cleanup of spills and equipment can be achieved using acetone or xylene employing proper precautions of ventilation and flammability.

Master Bond Inc.

Adhesives, Sealants & Coatings • 154 Hobart Street • Hackensack, N.J. 07601-3922 • Tel: 201-343-8983

Internet Address: http://www.masterbond.com

APPENDIX D

MASTERBOND-2ND DATA SHEET

Technical Data Sheet

MASTER BOND POLYMER SYSTEM EP21TDC-2

Highly Flexible, Two Component Epoxy System With Good Peel Strength for High Performance Bonding, Sealing, Coating and Encapsulation. Serviceable at Cryogenic Temperatures.

Product Description

Master Bond Polymer System EP21TDC-2 is a two component highly flexible epoxy resin compound for high performance bonding sealing, coating and encapsulation. It is formulated to cure fully at ambient temperature or more quickly at elevated temperature with a convenient, non-critical one to three mix ratio by weight. The cured compound has remarkably high peel strength of more than 30 pli along with an elongation of over 150%. EP21TDC-2 develops very little exotherm while curing, making it well suited for potting or encapsulating in thicker sections. It bonds well to many substrates including metals, glass, ceramics, and a wide array of rubbers and plastics. The cured epoxy is an excellent electrical and thermal insulator with outstanding resistance to chemicals such as water, oils, hydraulic fluids, bases and salts. Master Bond EP21TDC-2 is widely used in the electronic, electrical, computer, optical, metalworking, appliance, automobile and aerospace industries where excellent flexibility and related properties are desired. EP21TDC-2 has excellent thermal cycling properties along with outstanding resistance to thermal and mechanical shock and vibration. In addition, EP21TDC-2 has wide applicability as both a adhesive and sealant in cryogenic environments. Its service temperature range is 4°K to 250°F. A lower viscosity version called EP21TDC-2LV as well as a "non-drip" version called EP21TDC-2ND are also available. All three versions of EP21TDC-2 are 100% reactive and contain no solvents or volatiles.

Product Advantages

- Convenient mixing: non critical one to three weight ratio
- Easy application: product spreads evenly and smoothly
- Versatile cure schedules: ambient temperature cures or fast elevated temperature cures as required
- High peel strength and elongation, excellent mechanical and thermal shock resistance
- Bonds well to a wide array of materials.
- Good abrasion resistance.
- Outstanding electrical insulation properties
- Serviceable at cryogenic temperatures down to 4°K.

Product Properties

- Mixing ratio, by weight, parts A to B 1:3
- Viscosity of mixed adhesive, 75° F, cps 70,000-80,000
- Working life after mixing, 75°F
  100 gm mass, minutes .... >90
  200 gm mass, minutes .... >75
- Cure schedule
  75°F, hours 48-72
  200°F, hours 2-3
- Tensile strength, psi, 75°F 1150
- Elongation %, 75°F .... >150
- Tensile shear strength, aluminum/aluminum, 75°F, psi .... >1000
- T-peel strength, 75°F, pli 35
- Hardness, Shore D 35
- Volume resistivity, 75° F ohm-cm .... $>10^{13}$
- Taber Abrasion (CS 17 wheel, 1000 gms, 1000REV)
  Wt loss, mg 1.6
  Wt loss, % 0.01
- Water absorption (tap water) submersion @ 25C for 14 days .... < 1%
- Service temperature range .... 4°K to +250°F
- Shelf life at 75°F, in unopened containers .... 1 year
- Parts A and B are available in pints, quarts, gallons and 5 gallon kits.

Compound Preparation

Master Bond Polymer System EP21TDC-2 is prepared for use by thoroughly mixing part A with part B. in a one-to-three mix ratio by weight. Mixing should be done slowly to avoid entrapping air. Simply mix the required amounts of parts A and B by weight and stir thoroughly. The working life of a 100 gm batch is more than 90 minutes and that of a 200gm mass is more than 75 minutes. It can be lengthened by using shallower mixing vessels or mixing smaller size batches. For bonding and sealing uses, matching surfaces should be carefully cleaned, degreased and dried to obtain maximum bond strengths. When bonding to metal surfaces, if possible chemical etching should be employed when the bonded joints are to exhibit optimal environmental durability. Ideally, all substrates should be roughened with sandpaper, emery paper or mechanically abraded for optimum adhesion.

Compound Application and Assembly

Master Bond Polymer System EP21TDC-2 can be applied with a spatula, knife or similar implement. For bonding, enough adhesive should be applied to obtain a final adhesive bond line thickness of 3-6 mils. This can be accomplished by coating one surface with the adhesive. Porous surfaces may require somewhat more adhesive to fill the voids than non-porous ones. Thicker glue lines do not increase the strength of a joint but do not necessarily give inferior results as the EP21TDC-2 compound does not contain any volatiles. The parts to be bonded should then be pressed together with just enough pressure to obtain and maintain intimate contact during cure. Epoxies have excellent gap filling properties.

Cure

Master Bond Polymer System EP21TDC-2 can be cured at room temperature or at elevated temperatures as desired. At room temperature Master Bond Polymer System EP21TDC-2 cures in 48 to 72 hours. Faster cures can be realized at elevated temperatures, e.g. 2-3 hour at 200°F or 3-4 hours at 150°F. Remove excess material promptly before it hardens with a spatula. Then wipe with rag and solvent such as acetone or toluene. The thinner the layer of epoxy the slower the rate of cure. For potting applications, it may be necessary to vacuum degas to remove air bubbles.

Handling and Storage

All epoxy resins should be used with good ventilation and appropriate measures should be taken to minimize skin contact. EP21TDC-2 employs a low toxicity hardener. To remove resin or hardener from skin, use mild solvents, then wash with soap and water. If material enters the eyes, flood with water and consult a physician. Optimum storage is at or below 75°F in closed containers. No special storage conditions are necessary. Containers should however be kept closed when not in use to avoid contamination. Cleanup of spills and equipment is readily achieved with acetone or toluene employing proper precautions of ventilation and flammability.

Master Bond Inc.
Adhesives, Sealants & Coatings • 154 Hobart Street • Hackensack, NJ 07601-3922 • Tel: 201-343-8983
Internet Address: http://www.masterbond.com

APPENDIX E

DYMAX OP-67-LS DATA SHEET

DYMAX®

OPTICAL ADHESIVES

OP-67-LS Product Data Sheet

Low-Shrink™ OP-67-LS
Precision Positioning Optical Adhesive

APPLICATIONS

- Optic/Lens Alignment
- VCSEL Positioning
- Prism Placement

FEATURES

- UV/Visible Light Cure
- Complete Cure in Seconds
- Minimal Shrinkage During Cure
- Low CTE for Stability Through Thermal Excursions
- Low VOC

OTHER FEATURES

- Low Moisture Absorption
- Adhesion to Various Substrates Including Acrylic and Other Plastics
- Low Outgassing

DYMAX Low-Shrink™ OP-67-LS cures upon exposure to light and is designed for rapid positioning of optical components. Low-Shrink™ is a patented technology designed to minimize movement of high-accuracy optical components during cure and throughout service life. DYMAX Low-Shrink™ materials contain no nonreactive solvents and cure upon exposure to light. Their ability to cure in seconds enables faster processing, greater output, and lower processing costs. When cured with DYMAX light-curing spot lamps, focused-beam lamps, or flood lamps, they deliver optimum speed and performance for optical assembly. DYMAX lamps offer the optimum balance of UV and visible light for the fastest, deepest cures. This product is in full compliance with the RoHS Directives 2002/95/EC and 2003/11/EC.

UNCURED PROPERTIES *

Property	Value	Test Method
Solvent Content	No Nonreactive Solvents	N/A
Chemical Class	Acrylated Urethane	N/A
Appearance	White Paste	N/A
Soluble in	Organic Solvents	N/A
Density, g/ml	1.14 g/ml	ASTM D1875
Viscosity, cP (20 rpm)	135,000 (nominal)	ASTM D2556

ADHESION

Substrate	Recommendation
Ceramic	✓
Glass	✓
Metal	✓
Plastic	✓

✓ Recommended o Limited Applications

st Requires Surface Treatment (e.g. plasma, corona treatment, etc.)

CURED MECHANICAL PROPERTIES *

Property	Value	Test Method
Durometer Hardness	D80	ASTM D2240
Tensile at Break, MPa [psi]	28 [4,000]	ASTM D638
Elongation at Break, %	6.5	ASTM D638
Modulus of Elasticity, MPa [psi]	570 [83,000]	ASTM D638

OTHER CURED PROPERTIES *

Property	Value	Test Method
Refractive Index (20° C)	N/A	ASTM D542
Boiling Water Absorption, % (2 h)	2.9	ASTM D570
Water Absorption, % (25°C, 24 h)	2.3	ASTM D570
Linear Shrinkage, %	0.2	ASTM D2566

* Not Specifications

N/A Not Applicable

CURING GUIDELINES

Fixture time is defined as the time to develop a shear strength of 0.1 N/mm² [10 psi] between glass slides. Actual cure time typically is 3 to 5 times fixture time.

DYMAX Curing System (Intensity)	Fixture Time or Belt Speed[B]
2000-EC (50 mW/cm²)[A]	<1 s
5000-EC (200 mW/cm²)[A]	<1 s
BlueWave® 75 (5.0 W/cm²)[A]	<0.2 s
BlueWave® 200 (10 W/cm²)[A]	>0.2 s
UVCS Conveyor with one 5000-EC (200 mW/cm²)[C]	>8.2 m/min [>27 ft/min]
UVCS Conveyor with Fusion F300S (2.5 W/cm²)[C]	>8.2 m/min [>27 ft/min]

A Intensity was measured over the UVA range (320-395 nm) using a DYMAX ACCU-CAL™ 50 Radiometer.

B Curing through light-blocking substrates may require longer cure times if they obstruct wavelengths used for light curing (320-400 nm for UV light curing, 320-450 nm for UV/Visible light curing). These fixture times/belt speeds are typical for curing thin films through 100% light-transmitting substrates.

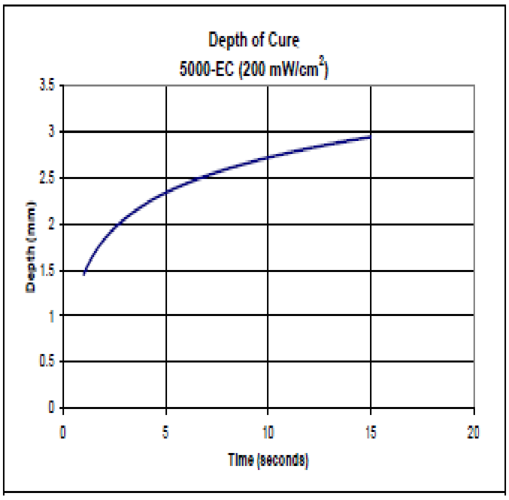
C At 53 mm [2.1 in] focal distance. Maximum speed of conveyor is 8.2 m/min [27 ft/min]. Intensity was measured over the UVA range (320-395 nm) using the DYMAX ACCU-CAL™ 100 Radiometer.

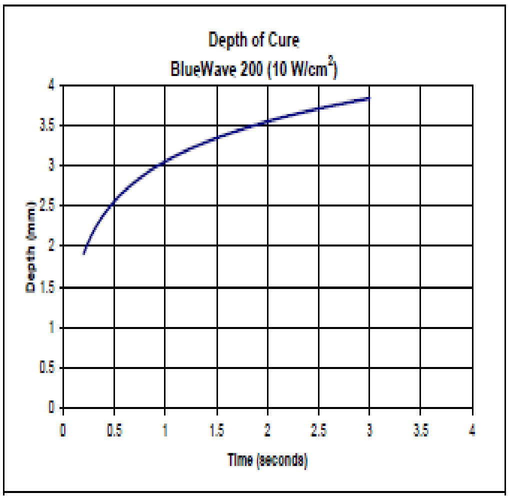
Full cure is best determined empirically by curing at different times and intensities, and measuring the corresponding change in cured properties such as tackiness, adhesion, hardness, etc. Full cure is defined as the point at which more light exposure no longer improves cured properties. Higher intensities or longer cures (up to 5x) generally will not degrade DYMAX light-curable materials.

DYMAX recommends that customers employ a safety factor by curing longer and/or at higher intensities than required for full cure. Although DYMAX Applications Engineering can provide technical support and assist with process development, each customer ultimately must determine and qualify the appropriate curing parameters required for their unique application.

DEPTH OF CURE

The graphs below show the increase in depth of cure as a function of exposure time with two different lamps at different intensities. A 9.5 mm [0.37 in] diameter specimen was cured in a polypropylene mold and cooled to room temperature. It was then released from the mold and the cure depth was measured.





OPTIMIZING PERFORMANCE AND HANDLING

1. This product cures with exposure to UV and visible light. Exposure to ambient and artificial light should be kept to a minimum before curing. Dispensing components including needles and fluid lines should be 100% light blocking, not just UV blocking.
2. All surfaces in contact with the material should be clean and free from flux residue, grease, mold release, or other contaminants prior to dispensing the material.
3. Cure speed is dependent upon many variables, including lamp intensity, distance from the light source, required depth of cure, thickness, and percent light transmission of components between the material and light source.
4. Oxygen in the atmosphere may inhibit surface cure. Surfaces exposed to air may require high-intensity (>100 mW/cm^2) UV light to produce a dry surface cure. Flooding the curing area with an inert gas, such as nitrogen, can also reduce the effects of oxygen inhibition.
5. Parts should be allowed to cool after cure before testing and subjecting to any loads or electrical testing.
6. In rare cases, stress cracking may occur in assembled parts. Three options may be explored to eliminate this problem. One option is to heat anneal the parts to remove molded-in stresses. A second option is to open any gap between mating parts to reduce stress caused by an interference fit. The third option is to minimize the amount of time the liquid material remains in contact with the substrate(s) prior to curing.
7. Light curing generally produces some heat. If necessary, cooling fans can be placed in the curing area to reduce the heating effect on components.
8. At the point of curing, an air exhaust system is recommended to dissipate any heat and vapors formed during the curing process.

DISPENSING THE MATERIAL

This material may be dispensed with a variety of manual and automatic applicators or other equipment as required. Questions relating to dispensing and curing systems for specific applications should be referred to DYMAX Applications Engineering.

CLEAN UP

Uncured material may be removed from dispensing components and parts with organic solvents. Cured material will be impervious to many solvents and difficult to remove. Clean up of cured material may require mechanical methods of removal.

PERFORMANCE AFTER TEMPERATURE EXPOSURE

DYMAX light-curable materials typically have a lower thermal limit of -54°C [-65°F] and an upper limit of 150°C [300°F]. Many DYMAX products can withstand temperatures outside of this range for short periods of time. Please contact DYMAX Applications Engineering for assistance.

STORAGE AND SHELF LIFE

Store the material in a cool, dark place when not in use. Do not expose to light. This product may polymerize upon prolonged exposure to ambient and artificial light. Keep covered when not in use. This material has a minimum six-month shelf life from date of shipment, unless otherwise specified, when stored between 10°C [50°F] and 32°C [90°F] in the original, unopened container.

GENERAL INFORMATION

This product is intended for industrial use only. Keep out of the reach of children. Avoid breathing vapors. Avoid contact with skin, eyes, and clothing. Wear impervious gloves. Repeated or continuous skin contact with uncured material may cause irritation. Remove material from skin with soap and water. Never use organic solvents to remove material from skin and eyes. For more information on the safe handling of this material, please refer to the Material Safety Data Sheet before use.

RECOMMENDED DYMAX LITERATURE

LIT010A	Guide to Selecting and Using UV Light-Curing Systems
LIT077	Chemical Safety
LIT133	UV Light-Curing System Safety Considerations
LIT159	ACCU-CAL™ 50 Radiometer
LIT206	Flood and Focused-Beam UV Light-Curing Systems
LIT208	UV Light-Curable Lens Bonding and Fiber Optic Adhesives
LIT218	BlueWave® 200 UV Light-Curing Spot Lamp

Literature is available through our website, www.dymax.com, or by calling any DYMAX location.

APPENDIX F

ELECTRO-LITE ELC-1043 DATA SHEET

ELECTRO-LITE UV ADHESIVES
Technical Data Sheet
ELC-1043
Low Shrink Bonding and Potting Adhesive

Description:

The ELC-1043 is a high viscosity UV Curing adhesive for bonding all transparent plastic substrates and optical devices. The ELC-1043 is excellent for glass to metal bonding such as lense mounting and other sensitive applications where low shrinkage is required. The ELC-1043 cures rapidly, in 15-20 seconds or less, when exposed to ultraviolet light from medium pressure mercury or LED UV spot systems. Cured performance shows excellent adhesion to glass, metals and most types of plastic substrates with a high temperature service performance of 225C with high solvent resistance and low shrinkage applications in optical, electronics and electronics. The ELC-1043 is formulated to solve "dark curing" applications by its ability to heat cure at 180-250F in 30 minutes or less.

Features:

- **High Viscosity for small drop shape requirements or beading devices**
- **Cures In 20 Seconds With Medium Intensity UV Light**
- **Excellent Adhesion To Glass, Metals and Plastics**
- **100% Solids Formulation For VOC Compliance**
- **Excellent Toughness And Durability**
- **Good Temperature And Solvent Resistance**

Physical Properties

Typical Uncured Properties:

Viscosity-	100,000 cps at 2 rpm, spindle #6
Specific Gravity	1.08 (20/20C)
Color	clear, water white in thin sections
Flashpoint	greater than 200F (COC method)
Toxicity	low to moderate, see MSDS
Clean Up Solvents	IPA, MEK

Solvents-none **Component Parts**-one **Fillers**- none

Typical Cured Properties: **(bulk properties ASTM D882)**

Shore D Hardness	65
Thermal Service Range	-40C to 225C
Dielectric strength	>500 v/mil
Dielectric constant ASTM D150	5.697@ 100Hz
Refractive index N_D	1.5017
Elongation @ break	90%
Tensile strength @ break	2,000 psi
Water absorption, ASTM D570	7.6 % **(2 hrs in boiling water)**

Cure Schedule:

Cure speed is dependent upon the UV light source, thickness of material, distance from the light, and UV transmission of substrates through which the UV light must pass to reach the adhesive. Optimum curing @ 365 nm.

Storage:

Store out of sunlight and in original container. Maintain at 45 to 65 degrees F for a maximum shelf life. Avoid exposing material to moisture or Nitrogen environments

Packaging:

p/n 82545	30ml syringe unfilled

1 Liter bottles, 12 oz and 32 oz SEMCO cartridges are also available. For pricing and p/n please contact Electro-Lite Sales @ 203-743-6733, extension 304 or 305.

Important:

The information in this brochure is based on data obtained by our own research and is considered accurate. However, no warranty is expressed or implied regarding the accuracy of these data, the results to be obtained from the use thereof, or that any such use will not infringe any patent. This information is furnished upon the condition that the person receiving it shall make his own tests to determine the suitability thereof for his particular purpose.

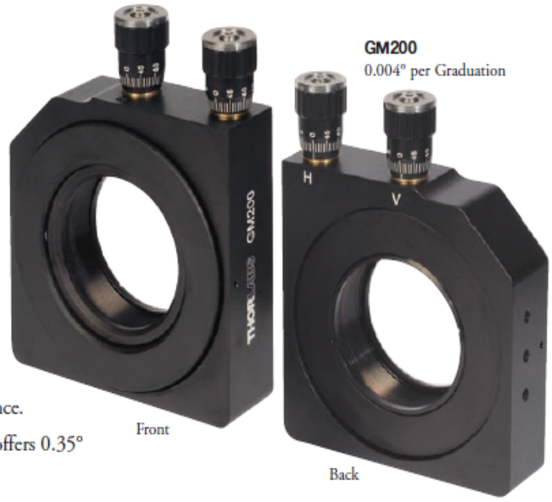
6 Trowbridge Drive
Bethel CT 06801
Phone: 203-743-4059 - Fax: 203-743-6733
www.electro-lite.com

APPENDIX G

THORLABS GM100 GIMBAL DATA SHEET

Gimbal Mirror Mounts

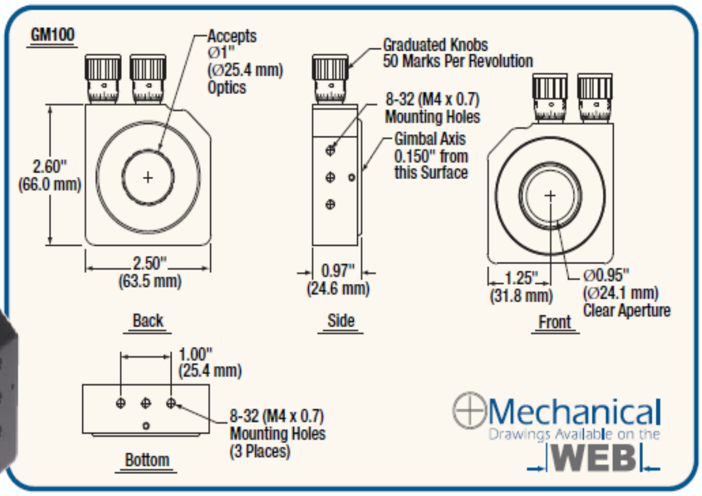
- Designed for Intra-Cavity Use
- Angular Range of ±2.5° (GM100) or ±2.0° (GM200)
- True Gimbal Design
- Graduated Adjuster Knobs (50 Divisions per Revolution)
- Hardened Steel Drive Mechanism Provides Long-Term Stability



Thorlabs' Gimbal Mounts, designed for intra-cavity use, incorporate a true gimbal design that locates the optical surface directly on the axis of rotation. This design provides pure rotational motion without angular or positional crosstalk.

The gimbal mounts have two adjustment knobs located on the top surface, making them easy to reach, even when integrated in an optical system. They provide excellent angular positioning performance.

The GM100, which is designed to house Ø1" (Ø25.4 mm) optics, offers 0.35° of angular displacement per revolution, while the GM200, which is meant for Ø2" (Ø50.8 mm) optics, offers 0.2° per revolution. In either case, the maximum optic thickness allowed is 0.63" (16.0 mm).



Please refer to our website for complete models and drawings.

APPENDIX H

VERIFICATION OF AUTOCOLLIMATOR READINGS

TABLE H.1 VERIFICATION OF AUTOCOLLIMATOR READINGS

	AUTOCOLLIMATOR READINGS (Minute of Arc)					
	x	y	NOMINAL VALUE	NOMINAL VALUE(degree)	NORMALIZED VALUE	NORMALIZED VALUE(degree)
REFERANCE #0	0	0	0.000	0.000		
MEASUREMENT #1	4.1	0.4	4.119	0.069	4.119	0.069
REFERANCE #1	0	0	0.000	0.000		
MEASUREMENT #2	4.2	0.2	4.205	0.070	4.205	0.070
REFERANCE #2	0	0	0.000	0.000		
MEASUREMENT #3	4.2	0.2	4.205	0.070	4.205	0.070
REFERANCE #3	0	0	0.000	0.000		
MEASUREMENT #4	4.2	0.2	4.205	0.070	4.205	0.070
REFERANCE #4	0.1	0	0.100	0.002		
MEASUREMENT #5	4.1	0.2	4.105	0.068	4.005	0.067
REFERANCE #5	0.1	0	0.100	0.002		
MEASUREMENT #6	4.2	0.2	4.205	0.070	4.105	0.068
REFERANCE #6	0.1	0	0.100	0.002		
MEASUREMENT #7	4.1	0.2	4.105	0.068	4.005	0.067
REFERANCE #7	0	0	0.000	0.000		
MEASUREMENT #8	4.2	0.2	4.205	0.070	4.205	0.070
REFERANCE #8	0.1	0	0.100	0.002		
MEASUREMENT #9	4.1	0.2	4.105	0.068	4.005	0.067
REFERANCE #9	0.1	0	0.100	0.002		
MEASUREMENT #10	4.2	0.2	4.205	0.070	4.105	0.068
REFERANCE #10	0	0	0.000	0.000		

APPENDIX I

ANGULAR MOVEMENT OF THE MIRRORS DUE TO ADHESIVE CURE

TABLE I.1 ANGULAR MOVEMENT OF THE MIRRORS DUE TO ADHESIVE CURE

		BARREL #1	BARREL #2	BARREL #3	BARREL #4	BARREL #5
MILBOND	X(µrad)/Absolute	29.09	29.09	58.18	261.80	174.53
	Y(µrad)/Absolute	0.00	48.48	87.27	281.19	19.39
	rms(µrad)	29.09	56.54	104.88	384.20	175.61
MASTERBOND-2ND	X(µrad)/Absolute	164.84	824.19	48.48	213.32	77.57
	Y(µrad)/Absolute	126.05	601.17	989.03	290.89	203.62
	rms(µrad)	207.51	1020.14	990.21	360.72	217.90
MASTERBOND-2LO	X(µrad)/Absolute	29.09	0.00	174.53	174.53	48.48
	Y(µrad)/Absolute	67.87	174.53	1192.65	261.80	29.09
	rms(µrad)	73.85	174.53	1205.35	314.65	56.54
OP67-LS	X(µrad)/Absolute	29.09	0.00	126.05	145.45	223.02
	Y(µrad)/Absolute	87.27	48.48	9.69	1580.50	504.21
	rms(µrad)	91.99	48.48	126.43	1587.18	551.33
ELC-1043	X(µrad)/Absolute	0.00	0.00	232.71	29.09	252.10
	Y(µrad)/Absolute	29.09	58.18	252.10	0.00	261.80
	rms(µrad)	29.09	58.18	343.09	29.09	363.45

APPENDIX J

ANGULAR MOVEMENT OF THE MIRRORS DUE TO THERMAL SHOCK

TABLE J.1 ANGULAR MOVEMENT OF THE MIRRORS DUE TO THERMAL SHOCK

		BARREL#1	BARREL#2	BARREL#3	BARREL#4	BARREL#5
MILBOND	X(μrad)/Absolute	48.48	0.00	58.18	494.51	58.18
	Y(μrad)/Absolute	0.00	9.69	203.62	96.96	29.09
	rms(μrad)	48.48	9.69	211.77	503.93	65.05
MASTERBOND-2ND	X(μrad)/Absolute	58.18	572.08	9.69	9.69	290.89
	Y(μrad)/Absolute	164.84	533.29	901.76	9.69	193.93
	rms(μrad)	174.81	782.1	901.81	13.71	349.61
MASTERBOND-2LO	X(μrad)/Absolute	29.09	0.00	58.18	67.87	19.39
	Y(μrad)/Absolute	58.18	0.00	0.00	0.00	29.09
	rms(μrad)	65.05	0.00	58.18	67.87	34.96
OP67-LS	X(μrad)/Absolute	58.18	0.00	184.23	29.09	310.28
	Y(μrad)/Absolute	29.09	38.79	67.87	116.36	252.1
	rms(μrad)	65.05	38.79	196.34	119.94	399.79
ELC-1043	X(μrad)/Absolute	29.09	58.18	349.07	814.49	58.18
	Y(μrad)/Absolute	0.00	29.09	804.79	2259.25	116.36
	rms(μrad)	29.09	65.05	877.24	2401.58	130.09

APPENDIX K

ANGULAR MOVEMENT OF THE MIRRORS DUE TO RANDOM VIBRATION

TABLE K.1 ANGULAR MOVEMENT OF THE MIRRORS DUE TO RANDOM VIBRATION

		BARREL#1	BARREL#2	BARREL#3	BARREL#4	BARREL#5
MILBOND	X(µrad)/Absolute	9.69	0.00	0.00	29.09	0.00
	Y(µrad)/Absolute	0.00	19.39	58.18	19.39	29.09
	rms(µrad)	9.69	19.39	58.18	34.96	29.09
MASTERBOND-2ND	X(µrad)/Absolute	29.09	0.00	9.69	0.00	261.8
	Y(µrad)/Absolute	19.39	9.69	38.79	19.39	29.09
	rms(µrad)	34.96	9.69	39.98	19.39	263.41
MASTERBOND-2LO	X(µrad)/Absolute	19.39	9.69	48.48	9.69	9.69
	Y(µrad)/Absolute	0.00	29.09	58.18	38.79	29.09
	rms(µrad)	19.39	30.66	75.73	39.98	30.66
OP67-LS	X(µrad)/Absolute	116.36	9.69	38.79	77.57	87.27
	Y(µrad)/Absolute	29.09	19.39	126.05	19.39	38.79
	rms(µrad)	119.94	21.68	131.88	79.96	95.49
ELC-4007	X(µrad)/Absolute	0.00	7291.64	193.93	232.71	29.09
	Y(µrad)/Absolute	9.69	2443.48	58.18	300.59	261.8
	rms(µrad)	9.69	7690.16	202.47	380.14	263.41

APPENDIX L

ANGULAR MOVEMENT OF THE MIRRORS DUE TO MECHANICAL SHOCK

TABLE L.1 ANGULAR MOVEMENT OF THE MIRRORS DUE TO MECHANICAL SHOCK

		BARREL#1	BARREL#2	BARREL#3	BARREL#4	BARREL#5
MILBOND	X(μrad)/Absolute	0.00	0.00	29.09	58.18	29.09
	Y(μrad)/Absolute	0.00	9.69	0.00	9.69	0.00
	rms(μrad)	0.00	9.69	29.09	58.98	29.09
MASTERBOND-2ND	X(μrad)/Absolute	0.00	0.00	9.69	0.00	77.57
	Y(μrad)/Absolute	0.00	0.00	9.69	0.00	9.69
	rms(μrad)	0.00	0.00	13.71	0.00	78.17
MASTERBOND-2LO	X(μrad)/Absolute	9.69	0.00	9.69	19.39	0.00
	Y(μrad)/Absolute	0.00	0.00	0.00	9.69	0.00
	rms(μrad)	9.69	0.00	9.69	21.68	0.00
OP67-LS	X(μrad)/Absolute	58.18	9.69	9.69	38.79	58.18
	Y(μrad)/Absolute	0.00	19.39	29.09	9.69	9.69
	rms(μrad)	58.18	21.68	30.66	39.98	58.98
ELC-4007	X(μrad)/Absolute	0.00	FAIL	87.27	203.62	0.00
	Y(μrad)/Absolute	0.00	FAIL	310.28	329.68	58.18
	rms(μrad)	0.00	FAIL	322.32	387.49	58.18