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Adhesives in Ordnance Applications

W. C. Tanner

Materials Research Section, Picatinny Arsenal, Dover, New Jersey

Introduction

Most engineers are familiar with the design properties of metals and many are now becoming familiar with the properties of plastics. However, the use of adhesive bonding as a technique for fastening members of a primary structure has only recently become apparent to a significant number of engineers. Unfortunately, many engineers who have used adhesives have done so as a last resort or as an attempt to salvage some poorly designed component of a structure.

Recent requirements for aerodynamically smooth structures with high strength-to-weight ratios for missiles and aircraft have led to increased use of adhesives. In many applications adhesive bonding is the most feasible method of meeting the design requirements.

For our purposes, adhesives may be divided into two categories, nonstructural and structural. The nonstructural adhesives may be thought of as those which are incapable of permanently supporting appreciable loads; frequently they are thermoplastic materials that remain somewhat rubbery or elastic. These are generally used in such applications as locating or fastening name and data plates, rubber bumpers, gaskets, or O rings and other accessory components or secondary members to each other or to various other substrates of a structure. The structural adhesives, on the other hand, are capable of developing high bond strengths and can be expected to resist relatively large stresses tending to separate bonded components. Failure of a structural adhesive bond may result in malfunction of the end item component.

Adhesives offer the designer the following advantages:

1. They provide relatively uniform distribution of stresses over the entire bonded area.

2. They simplify formation of aerodynamically smooth structures.

3. They facilitate construction of items with high strength-to-weight ratios.

4. They can readily join items of complex geometrical configuration.

5. They can join dissimilar materials.

6. They can effectively seal joints against fuels, gases, and environmental factors.

7. They can join dissimilar metals without fear of galvanic corrosion.

8. They can join thin sheets of materials.

9. They can provide certain special advantages such as: (*a*) electrical insulation of components, (*b*) ability to be formulated and to maintain electrical continuity, and (*c*) cost savings in production items.

The advantages characteristic of structures bonded with adhesives often correspond with design requirements for advanced ordnance items. This can be demonstrated by examining some of the properties or characteristics of some ordnance applications of adhesive-bonded assemblies. Some of the bonding applications are peculiar to ordnance items.

Discussion

It was mentioned that adhesives afford relatively uniform distribution of stresses throughout a joint. How does this occur? The adhesive bond may be considered as an infinite number of minute fasteners, each capable of resisting a certain amount of stress but each being so small that the load is distributed throughout the bonded area. Stress concentrations such as those occurring around rivets, bolts, or spot welds are eliminated and the designer can take advantage of the total strength of the metal. Notice that for such an application thinner sheets of metal can be used and considerable weight saved as a result.

Adhesives make it easy to form aerodynamically smooth structures. Ordinarily, welding, brazing, and flush riveting are used to produce such structures. These techniques, however, are much more

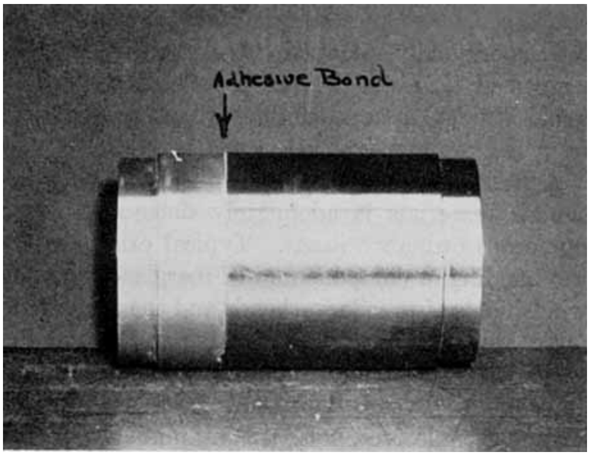

Fig. 1. A recovered warhead assembly.

expensive, require many more manhours to accomplish, and require thicker or heavier members. Figure 1 shows a portion of the primary structure of a warhead. The two metal cylindrical sections in the photograph have been joined with a single lap joint. This is an ordnance item that benefited from the advantages of adhesives discussed above. The design requirements for this item dictated that the exterior skin be aerodynamically smooth and that the joint remain intact after target impact and penetration. Originally, a combination of flush screws and adhesives was selected to secure this joint. A few prototype items were fabricated from steel and aluminum sections. The steel cylinder was the leading section in the direction of flight. Observation of a few tests and examination of the recovered test vehicles revealed the following information.

1. The joint failed upon target impact.
2. The leading steel cylindrical section often split upon target impact.
3. The trailing aluminum cylindrical section was forced into the hollow forward section.
4. The screws had either been sheared or stripped of thread in some of the tests.
5. The metal failed between some of the screw holes.

Consideration of the above observations suggested that the adhesive had probably failed as a result of large peeling forces set up as the trailing aluminum cylinder was forced into the leading section. This failure was probably caused by the geometry of the joint. The screws seemed to be superfluous and the screw holes weakened the metal in the joint area.

A critical reconsideration of the geometry of joint was conducted. Calculations were made to determine the order of magnitude of the primary forces to be exerted at the joint and the time over which these forces would act. Final calculations revealed that the adhesive in the joint would be exposed to shearing forces of about 2000 psi over a time interval of 85 μsec. Laboratory tests had established that aluminum-to-steel bonds using the candidate adhesive had shear strengths of 2200, 2720, and 2460 psi at −65, 73, and 160°F., respectively. These results were derived by static or conventional shear tests using single lap specimens.

It has been demonstrated in our laboratory that adhesive bond strengths are sensitive to rates of loading. Our tests indicate that where the times of load application differ by several orders of magnitude, adhesive bond strengths differ. The bond strengths at high rates of loading are usually higher than those measured at low rates. An average shear strength of 5350 psi was obtained using steel adherends bonded with the candidate adhesive when the average time of bond destruction was 4700 μsec. Although these high rate data were obtained with steel-to-steel lap joints, it was assumed that the same general trend would hold for aluminum and titanium adherends which would be considered for this end-item application. This sensitivity of bond strength to rate of load application is attributed to the viscoelastic properties of the adhesive when metal adherends are used. Further, the bond failures were predominantly cohesive. In our preliminary investigation, using the candidate adhesive, we found adhesion to the steel, aluminum, and titanium to be comparable.

On the basis of the shear test results it was decided that the adhesive alone should be sufficient for this joint, provided peel or cleavage stresses were reduced or eliminated. The joint was redesigned to reduce peeling and cleavage stresses which occurred upon target impact. Figure 2 shows the redesigned joint. Notice that the leading cylinder has a tapered or scarfed edge and the trailing cylinder has an undercut to accept this tapered edge. When bonded, this scarf arrangement effectively locks the end of the lap joint and reduces the large peeling and cleavage forces which occurred at this point when a butt arrangement was used. Subsequent tests of items utilizing only adhesives and the joint geometry shown have been successful.

Figure 1 is actually a photograph of a recovered

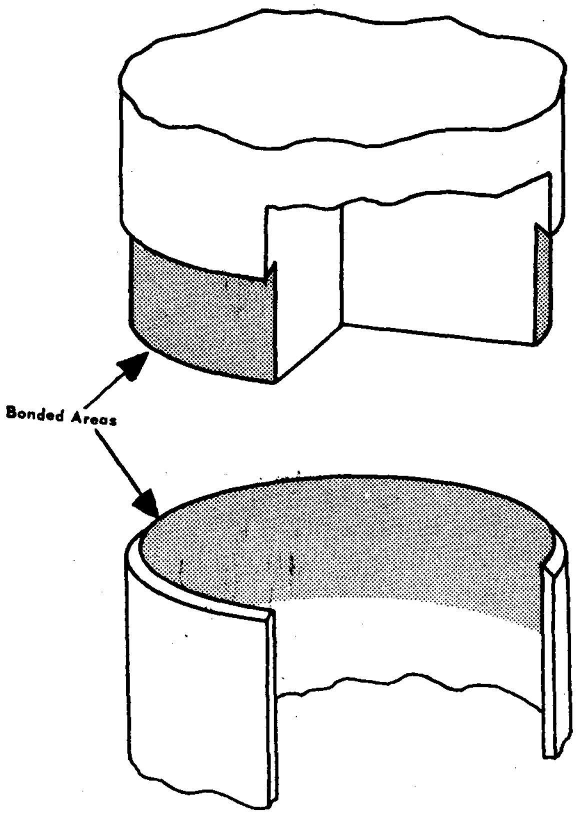

Fig. 2. Illustrated geometry of a structural adhesive bond.

section of a vehicle that successfully penetrated the target. In this item the forward section is made of titanium. A room-temperature-curing polyamide-bisphenol A epoxy adhesive was used to bond the titanium to the aluminum.

Using adhesives in this design made possible a stronger joint, a higher strength-to-weight ratio, simplicity in design, and economy in manufacture and assembly. Also it should be mentioned that if, as originally planned, steel had been used instead of titanium the use of an adhesive would avoid the galvanic corrosion which could result from an aluminum-to-steel couple.

Adhesive bonding as a technique for joining dissimilar materials is adequately demonstrated in numerous ordnance items. Typical examples are the bonding of components in Fiberglas-laminated windshields of missile warheads and the bonding of optical systems to various sighting and aiming devices. An excellent demonstration of the versatility of adhesives is their use in bonding such materials as explosives, gold, and uranium. Bonding to these materials has been the object of several investigations in our laboratories. As a result Picatinny has one of the most comprehensive compilations of technical data on adhesive bonding of explosives available in the United States.

Successful adhesive systems and bonding procedures have been found and are currently used for bonding with such explosives as Cyclotol 75/25, polystyrene-bonded RDX (PB-RDX), compositions 9404 and 9406, HMX-Exon, and others. Explosives have been effectively bonded to aluminum, cold-rolled steel, stainless steel, cadmium-plated steel, titanium, uranium-238, beryllium, nickel, and zinc. Figures 3, 4, and 5 illustrate the adhesive bond strengths developed between titanium and certain explosive compositions. In most cases, the low tensile strengths shown reflect failure of the inherently weak explosive compositions rather than failure of the adhesive bonds. Sometimes, the adhesives dissolved or penetrated the explosive compositions at the adhesive-explosive interface causing weak boundary layers. In addition to the difficulties caused by the weakness of the explosive

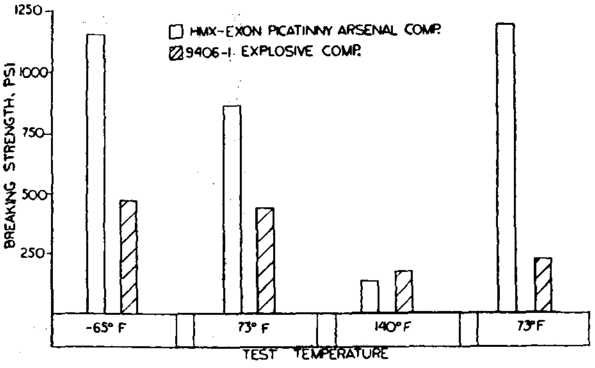

Fig. 3. Bond strengths developed between composition 9406-1 and Exon-HMX with a urethane adhesive; right-hand block, after storage at 160°F. for 7 days.

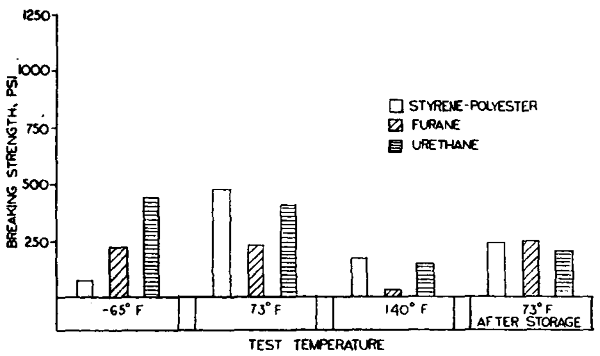

Fig. 4. Bond strengths developed by different adhesives between composition 9406-1 and titanium; right-hand block, at 160°F. for 7 days.

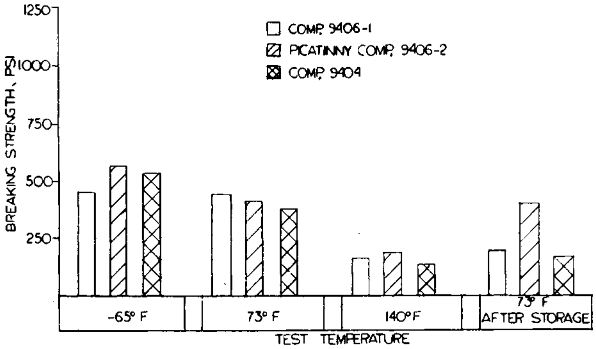

Fig. 5. Bond strengths of explosive compositions 9406-1, PA-9406-2, and 9404 bonded to titanium with a urethane adhesive; right-hand block, at 160°F. for 7 days.

compositions, many problems were encountered in bonding to explosives. Foremost among these is the incompatibility of certain adhesives with explosives, which will be discussed later.

The problem of bonding uranium to itself and other materials is greatly complicated by the reactivity of the uranium. Removing or preventing the formation of weak boundary layers before and after adhesive bonding is of paramount importance if effective bonds are to be obtained. Uranium develops a brittle, weak oxide layer when exposed to air or to the presence of certain chemicals. A procedure was developed in our laboratory of wet sanding the uranium under a liquid adhesive film. This effectively minimized oxidation of the cleaned surfaces and trapped the fine uranium particles, preventing possible pyrophoric reactions. Improved bond strengths were obtained following this procedure. However, when the uranium, abraded and bonded as described above, was stored at 160°F. for seven days, the bond strengths fell to only a fraction of the original values.

Initial tensile strengths obtained between steel and uranium bonded with a polysulfide-epoxy adhesive were approximately 1200 psi. However, after storage of the specimens under various conditions, bond strengths of less than 100 psi resulted. Close observation of the storage specimens after rupture revealed that the oxide layer from the unbonded sides of the uranium had spread under the adhesive layer. This continued oxidation is analogous to the spread of corrosion of steel under a ruptured chromium-plated surface. An obvious solution was to abrade all faces of the uranium and leave the protective layer of cured adhesive on the unbonded surfaces. Table I gives tensile bond strengths developed with different adhesives and the strength retained by some of the adhesive bonds after storage under certain conditions.

Joining thin sheets of materials without distortion and developing high strength-to-weight ratios are demonstrated in Figure 6, which shows a helically wound pressure vessel. Thin strips of metal and adhesives are combined to produce items with high strength-to-weight ratios. Items with strength-to-weight ratios of over one million have been developed by this technique. Similar structures made of glass filaments and adhesives have given strength-to-weight ratios of over 1,600,000. In addition to their high strength-to-weight ratio, structures such as these result in considerable savings of time, material, and labor.

Only a few ordnance items have been used to

TABLE I

Tensile Strengths Obtained when Bonding to Uranium[a]

Adhesive	No. of sides cleaned and coated	Cure time and temp.	Tensile strength, psi
Polysulfide-modified epoxy	2	7 days at 73°F.	1640
Polysulfide-modified epoxy	2	7 days at 160°F.	100
Polysulfide-modified epoxy	2	4 months at 73°F.	300
Polysulfide-modified epoxy	2	7 days at 160°F. in He atm.	300
Styrene-unsaturated polyester	2	7 days at 73°F.	0
Cyanoacrylate	2	7 days at 160°F.	0
Polyurethane	2	7 days at 160°F.	950
Polyamide-epoxy	2	7 days at 160°F.	1075
Polyurethane	6	2 weeks at 160°F.	515
Polyurethane	6	4 weeks at 160°F.	1200
Polyurethane	6	1 year at 25 to 90°F.	1000
Polyamide-epoxy	6	2 weeks at 160°F.	1200
Polyamide-epoxy	6	4 weeks at 160°F.	1200
Polyamide-epoxy	6	1 year at 25 to 90°F.	1700

[a] Note: test temperature, 73°F.

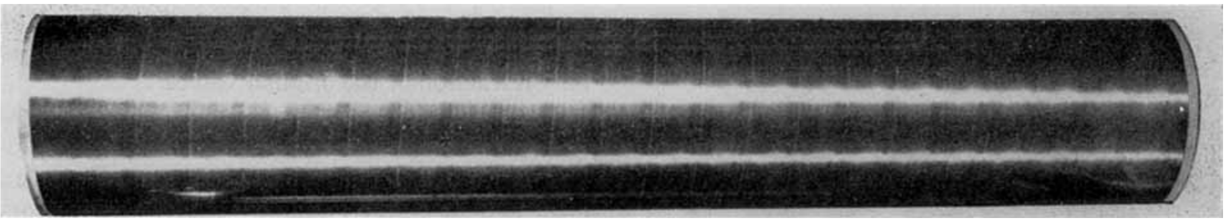

Fig. 6. Helically wound pressure vessel.

demonstrate the usefulness of structural adhesives. Many nonstructural applications of adhesives in ordnance items could also be cited to attest to the appropriateness of adhesives in modern industrial design.

As a fastening method, adhesive bonding has limitations. Just as the advantages of adhesives have been touched upon, so should their disadvantages and current limitations be pointed out. We say "current limitations" because rapid advances are being made in adhesives technology and it is not being overly optimistic to expect a breakthrough that will greatly minimize or eliminate some of the present difficulties. Hence it behooves the design engineer to stay abreast of developments.

Heat and certain other environmental conditions can greatly reduce the strengths of adhesives, which may result in cohesive failure within the adhesive bond or adhesive failure at the adhesive-adherend interface. The low service temperature of which current structural adhesives are capable appears to be their most significant limitation for many ordnance applications. Care must be taken to select, or in areas of doubtful performance to evaluate, adhesives which will withstand the conditions anticipated throughout the useful life of the item.

Corrosiveness and reactivity of adhesives in contact with or close to certain materials must be evaluated or checked during adhesive selection. For instance, the corrosion of uranium-238 by peroxide catalysts and possibly other components of polyester resins prevents their use in bonding uranium. Polysulfides behave similarly in the presence of uranium. Epoxy resins cured with aliphatic polyamines reduce the stability of certain explosives and propellants. When adhesives cannot be used in proximity to explosives or propellants, the two are said to be incompatible. Incompatibility encompasses the effect of the adhesive on the stability and reactivity of the explosive as well as the detrimental effects of the explosive or propellant on the adhesive. Since adhesives used in ordnance items are often close to propellants or explosives, the compatibility problem is a serious one.

Another limitation of adhesive bonding is that there is currently no satisfactory method of determining the quality of an adhesive bond without destructive testing. For instance, an adhesive bond capable of withstanding a 10,000-psi tensile load looks no different from one capable of withstanding only a 1000-psi tensile load. Accordingly, rigorous process control during bonding plus proof testing or sample joint testing must be used to maintain reliable production of uniform quality bonded joints as well as to prevent failure in the bonded assemblies.

Adhesive bonding is generally considered a permanent fastening technique. Hence adhesives cannot readily be used to fasten covers or panels over areas that must be periodically inspected.

In conclusion it should be emphasized that the primary theme here is to acquaint the ordnance design engineer and other design engineers as well with the advantages of adhesives when used properly in the design and assembly of structural components. The best approach to achieving good performance in bonded joints is to: (*1*) design the joint properly for the specific application, (*2*) select the proper adhesive and bonding technique, and (*3*) maintain rigid process control.

Synopsis

The advantages to be derived from the use of structural adhesives are discussed. Specific developments are cited to illustrate the effectiveness of adhesives in ordnance materiel. Problems peculiar to ordnance applications are discussed. The strengths of adhesive bonds as determined by "static" and "dynamic" conditions are compared, and the importance of proper joint geometry is illustrated.

Résumé

Les avantages issus de l'utilisation d'adhésifs structurels sont soumis à discussion. Des développements spécifiques sont cités pour illustrer l'efficacité des adhésifs dans le matérial militaire. Les problèmes particuliers de leurs applications militaires sont décrits. On compare la résistance des liens adhésifs dans des conditions "statiques" et "dynamiques" et on illustre l'importance de joints à géométrie bien définie.

Zusammenfassung

Die Vorteile einer Anwendung von Strukturklebestoffen werden diskutiert. Spezifische Entwicklungen werden angeführt, welche die Brauchbarkeit von Klebstoffen bei Artilleriematerialien zeigen. Die spezifischen Probleme der Verwendung von Klebstoffen für Artilleriezwecke werden diskutiert. Die Festigkeit von Klebeverbindungen bei "statischen" und "dynamischen" Bedingungen wird verglichen und die Wichtigkeit einer geeigneten geometrischen Ausführung der Verbindung gezeigt.