EFFECT OF DIFFERENT ADHESIVES ON STRENGTH, ENERGY ABSORPTION AND DAMPING PROPERTIES OF BONDED ALUMINUM STRUCTURES FOR THE TRANSPORTATION INDUSTRIES

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ABSTRACT

The use of aluminum bonded structures is growing with the need for lighter cars and trucks and cheaper assembly techniques. Several adhesive manufacturers propose a broad range of structural adhesives from very strong and stiff epoxies to flexible urethane products. Despite the documentation available, the use of adhesive in the ground transportation especially for structural assemblies still requires knowledge reinforcement.

In this paper, three major types of adhesives, epoxies, acrylics/methacrylates and polyurethanes are first tested using standard samples to establish their properties. Several parameters related to the surface preparation, adhesive application, adhesive thickness are evaluated. Simple structural assemblies made of bonded aluminum extrusions and sheets are produced and tested combined with rivets for energy absorption under large deformations. Finally, dynamic analyzes are carried out to establish the impact of adhesives on vibration and noise attenuation.

Keywords: Aluminum structures, bonding, energy absorption, vibration damping.

INTRODUCTION

Over the last thirty years, adhesives have been increasingly applied for structural assembly. More recently, car manufacturers have used them in combination with spot welds and rivets to increase stiffness and impact energy absorption notably in chassis and body-in-white structural assemblies [1-4]. With the use of aluminum, riveting, MIG, TIG, laser and friction stir welding techniques have been preferred over resistance spot welding and bonding is playing a key role by reinforcing and distributing the stress over a larger surface. Indeed, because aluminum is softer than steel and in reason of thinner walls of many components it is even more important to
better spread the stress over a larger surface to optimize the strength and stiffness and reduce the weight. Some manufacturers of sport cars are testing or began to use adhesives as their main technique for chassis assembly. Other important reasons explaining the widespread utilization of adhesive in automobile and aircraft assembly include (1) the reduction of vibrations and noise, (2) the reduction of galvanic corrosion (e.g. steel and aluminum), (3) its capacity to join dissimilar materials (e.g. plastic and aluminum) and most importantly, (4) the assembly cost that is often lower compared to other techniques.

Although increasingly used for automobile and aircraft assembly, bonding techniques are still slowly emerging in assembly of commercial vehicles or has even failed in other industries. Among the main reasons are: (1) a lack of understanding of the techniques, (2) products poorly designed for bonding, (3) inadequate adhesives and surface preparation methods, (4) degradation of adhesives and lack of durability. The simple replacement of other joining techniques by bonding without adapting the design and making proper calculation and tests has little chance of success.

This paper is mainly intended to research, design and production engineers who want to better understand the use and benefits of adhesives for structural assembly of aluminum components. Its content involves (1) the characterization of different adhesives covering a wide range of structural assembly applications, (2) the study of the impact on energy absorption of assemblies using rivets and/or adhesives, (3) an investigation of the effect of adhesives on vibration reduction and (4) some design recommendations.

CHARACTERIZATION OF ADHESIVES

A wide range of products are available for structural assembly. It goes from very stiff epoxies to flexible polyurethanes, and includes acrylics and methacrylates and many other products. These products have specific mechanical properties (e.g. strength, stiffness, ...), durability and environment resistance and proposes specific methods for surface preparation, adhesive curing and thickness of joint. For engineers and designers the selection of proper adhesives and the design adaptation for its application require an extensive knowledge of all these aspects. For example, for a car space frame assembly, it is essential to adapt significantly the design of interfaces, consider the geometric errors in the components and assembly which will determine the gap for the adhesive, define how the surface will be prepared, and consider also the dynamic aspect, the stiffness and energy absorption during a collision.

The first source of information is obviously the manufacturer’s technical sheet. They generally include useful information such as operating temperature and humidity condition, environment resistance, preparation method and indication about the curing. They also give a general overview of the properties of the product, often including shear strength, as tested in laboratory using specifically controlled conditions sometimes more difficult to achieve in industries. Automotive and aerospace industries use extensive facilities especially for surface preparation and curing to achieve optimal performances.

Because of the wide range of conditions and applications found in industries, tests must be carried out. Standard ASTM tests are generally utilized to compare a pre selected set of adhesives and surface conditions. As shown in Figure 1 these include notably single [5] or
double lap shear test [6], the tensile strength test [7], the cleavage test [8] and the peel test [9]. Even if they are very useful to establish the performance of adhesives in specific conditions, the samples are of very simple geometry and tests are carried out under quasi static loading. In practice, complex geometries, irregular surface, geometric and positioning errors and dynamic loading are generally observed.

Fig. 1: Typical ASTM tests for adhesive characterization

Characterization of three types of adhesives

Table 1 presents the general characteristics of three types of adhesives popular in the transportation industry [3, 4,10]: epoxies, acrylics and polyurethanes. Although many other products are available, this study is limited to adhesives that cure at room temperature and humidity. Within each type of adhesive several formulations with different properties exist.

The epoxies have very high strength and are very stiff. However, their properties vary considerably with the adhesive film thickness. A very thin film (0.1 to 0.2mm) is required for optimal performances. Their use is recommended where consistent film thickness can be achieved for example with accurate mating surfaces or with sheet panels that are spot welded or riveted which also hold the parts together during setting. In reason of the thin film and their high strength, the amount of adhesive required is very small.

Polyurethanes are much more flexible but very significantly weaker. The film is generally much thicker (1 to 4mm) but their strength does not vary much with thickness. This adhesive is pertinent for application where components are not very accurate and where good isolation between components is required. A good example is for the assembly of truck box panels and bus sheet panels on structural members made of rolled or extruded aluminum. A gap of 1 or 2 mm can easily be tolerated by the adhesive. Because this type of adhesive is much weaker than epoxies, larger surfaces must be covered. A much larger volume of adhesive is also required.

Acrylics including methacrylates stand between epoxies and polyurethanes. They are less flexible but stronger than polyurethanes and more flexible and weaker than epoxies.

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### Table 1: Overall characteristics of adhesives (manufacturer and literature data)

<table>
<thead>
<tr>
<th></th>
<th>Epoxy 2 components</th>
<th>Acrylic (Methacrylate)</th>
<th>Polyurethane 1 component</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength (MPa)</td>
<td>12 - 35</td>
<td>20 - 30</td>
<td>2.5 – 15</td>
</tr>
<tr>
<td>R rigidity</td>
<td>rigid</td>
<td>average</td>
<td>flexible</td>
</tr>
<tr>
<td>Film thickness (mm)</td>
<td>0.1 - 0.5</td>
<td>0.1 – 0.5</td>
<td>0.1 – 5</td>
</tr>
<tr>
<td>Surface preparation</td>
<td>extensive</td>
<td>low</td>
<td>moderate</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>-50 to 120</td>
<td>-70 to 120</td>
<td>-100 to 80</td>
</tr>
<tr>
<td>Water resistance</td>
<td>excellent</td>
<td>good - excellent</td>
<td>excellent</td>
</tr>
<tr>
<td>Oil resistance</td>
<td>excellent</td>
<td>excellent</td>
<td>good</td>
</tr>
<tr>
<td>UV resistance</td>
<td>excellent</td>
<td>excellent</td>
<td>good</td>
</tr>
<tr>
<td>Impact resistance</td>
<td>good</td>
<td>good - excellent</td>
<td>excellent</td>
</tr>
<tr>
<td>Fatigue résistance</td>
<td>excellent</td>
<td>excellent</td>
<td>excellent</td>
</tr>
<tr>
<td>Shrinkage</td>
<td>very low</td>
<td>low</td>
<td>moderate</td>
</tr>
<tr>
<td>Peel resistance (N/cm)</td>
<td>low 20-40</td>
<td>moderate 100</td>
<td>good 50-60</td>
</tr>
</tbody>
</table>

Testing conditions. For all adhesives, the easiest and most industrially applicable but not necessarily the best method of surface preparation suggested by the adhesive manufacturer was generally used. The adhesive was applied manually within about ½ of the maximum deposition time recommended. For all ASTM tests, samples where made of 6061-T6 sheets and bars and during setting, held in specially made fixtures in order to assure constant film thickness and proper sample alignment.

For two-components epoxies, manufacturers recommend, in order of increasing efficiency, (1) cleaning with a good degreasing agent, (2) mechanical abrasion or (3) chemical etching. The method chosen for testing this adhesive will be to first degrease with methyl ethyl ketone (MEK), second chemical etching in an alkaline solution of 10% Sodium hydroxide (NaOH) at 60°C for 30sec and then rinse in running water for 2min and free air dry. The two components were fully mixed prior to application on the sample.

Polyurethanes are provided in a single component. It can be applied in bond line thickness up to 10mm and cure in 7 days, thinner layer will cure more rapidly. The surface preparation comprises first a cleaning of all surfaces with a glass cleaner, followed by the abrasion of the surfaces with a Scotchbrite™ pad before cleaning again with glass cleaner. Finally, an adherence promoter or activator is applied with a clean absorbent paper and let to dry for 15min.

For acrylics and methacrylates the surface preparation consists in cleaning all surfaces with MEK to remove grease and dirt and optionally to abrade the surface with Scotchbrite™ and cleaned again with MEK. Single component acrylics utilized an activator deposited to the surface before applying the adhesive in layers typically under 0.5mm thick. Two components methacrylates were mixed prior to application on the surface in thicker layers.

Results. Tables 2, 3 and 4 presents respectively the results obtained for double lapped shear strength, tensile and cleavage tests. Announced strength is provided by the manufacturer. The measured strength, adhesive thickness, flexibility and rupture mode in these tables are experimental observations made on at least two samples. In table 2, we can see that most tests
do not reach the announced strength which was probably obtained in optimal laboratory conditions using the best surface preparation and the optimal adhesive thickness.

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Surface preparation</th>
<th>Announced strength Mpa</th>
<th>Measured strength Mpa</th>
<th>Adh. thickness mm</th>
<th>Elongation mm</th>
<th>Rupture mode</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Epoxy    | 3M DP 420 MEK, NaOH 60°C, 30 sec | 25 | 21.6 | <.18 | 1.1 | Mixed | - The central plate was 2.5 mm thick  
- The adhesive bond line must be thin to avoid adhesive failure  
- Sensitive to the surface preparation |
| Methacrylate | Plexus MA 832 MEK | 16 - 19.6 | 10.8 - 11.3 | .254 | 1.15 | Cohesive | - Constant properties, even with little surface preparation  
- Always cohesive failure |
| Acrylic | Permabond TA 435 MEK, scotchbrite (SB), MEK | 20 – 25 | 17.8 | .127 | 4.7 | Cohesive | - Constant properties, even with little surface preparation  
- Always cohesive failure |
| Polyurethane | SikaFlex 252 GlassCleaner (GC), SB, GC, Aktivator (Akt.) 20 min | 2.5 | .99 | 1.5 | 6.6 | Cohesive | - Difficult to obtain cohesive failure with the minimal surface preparation recommended by the manufacturer |
| Polyurethane | SikaForce 7550 GC, SB, GC, Akt. 20 min | 6 | 3.4 - 3.7 | 1.5 | 3.8 - 12 | Cohesive | - With the recommended preparation method, total cohesive failure is rarely obtained  
- Constant cohesion failure  
- Air bubbles easily are trapped in the adhesive layer |

Table 2: Tests results of the double lap shear strength test (ASTM D 3528). Announced strengths from adhesive manufacturers are generally for AL2024-T3 and not AL6061-T6
Table 3: Results of the tension strength test (ASTM standard D 2095)

ENERGY ABSORPTION UNDER LARGE DEFORMATIONS

The intelligent design of lighter aluminum structures must also consider the absorption of energy during collisions. Because combined assembly modes are often used, this investigation will consider samples assembled using rivets, adhesive and combined rivets and adhesives. The adhesive utilized is the DP420 epoxy from 3M. First, ASTM double lap shear strength tests were carried out on samples assembled with (1) adhesive alone, (2) two 3.125x7.9mm aluminum rivets and (3) using both rivets and adhesive. For the samples assembled with rivets shown in Figure 2, these rivets were located 12.7mm apart and in the center of the bonding area of 9.53mm wide, i.e. 4.76mm from the edge.

Fig. 2: Double lap shear strength samples with rivets
The results of shear tests are shown in Table 5. Because there is an initial gap of 0.1 mm in diameter between the holes and the rivets and because the rivets and plates deform prior to failure, rivets fail after 2.3mm of global elongation with an equivalent shear strength of 12.7 MPa over the contact face or 5195.3N. The epoxy fails after only 1.1mm of elongation and a force of 8778.2N thus much before the rivets. With combined rivets and adhesive, part of the bonded surface is replaced by the rivets. This and the different of elongation before failure explains why the adhesive plus rivets is somewhat weaker than adhesive alone. For a better design, we should eventually select an adhesive with slightly higher elasticity. A positive impact of adding rivets to adhesive is that rivets can hold firmly the components together during adhesive setting.

Finally 6 samples of tubular structure made of two “U” bent sheet components have been assembled in combinations similar to the samples of Table 4. These tubular assemblies are illustrated in Figure 3. Where applicable, four 3.97x9.53mm aluminum rivets have been used per tube.

Table 4: Results of cleavage strength test (ASTM standard D 1062)

<table>
<thead>
<tr>
<th>Adhesive</th>
<th>Surface preparation</th>
<th>Measured force N</th>
<th>Adh. thickness mm</th>
<th>Rupture mode</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy</td>
<td>Araldite 2012 MEK, NaOH 60°, 30 sec</td>
<td>7003.3</td>
<td>.152</td>
<td>0.5-0.7</td>
<td>mainly cohesive</td>
</tr>
<tr>
<td></td>
<td>3M DP 420 MEK, NaOH 60°, 30 sec</td>
<td>10227.5</td>
<td>.152</td>
<td>0.9-1.0</td>
<td>Cohesive</td>
</tr>
<tr>
<td></td>
<td>Plexus MA 832 MEK</td>
<td>4201.3</td>
<td>.318</td>
<td>0.6</td>
<td>Cohesive</td>
</tr>
<tr>
<td></td>
<td>Loctite H8000 MEK</td>
<td>5070.6</td>
<td>.203</td>
<td>0.6</td>
<td>Cohesive</td>
</tr>
<tr>
<td></td>
<td>LORD 406 MEK, SB, MEK</td>
<td>4870.0</td>
<td>.304</td>
<td>0.5</td>
<td>Cohesive</td>
</tr>
<tr>
<td></td>
<td>Perma-bond TA 435 MEK, SB, MEK</td>
<td>1335.8</td>
<td>.165</td>
<td>0.3</td>
<td>Mainly adhesive</td>
</tr>
<tr>
<td></td>
<td>Sika Flex 252 GC, SB, GC, Akt. 20 min</td>
<td>268.5</td>
<td>2.67</td>
<td>3.4-4.1</td>
<td>Cohesive</td>
</tr>
<tr>
<td></td>
<td>Sika Force 7550 GC, SB, GC, Akt. 20 min</td>
<td>866.6</td>
<td>2.91</td>
<td>1.6-1.7</td>
<td>Cohesive</td>
</tr>
</tbody>
</table>
Crushing of the tube is realized on a 75tons servo-controlled hydraulic press. The force to displacement curve and more specifically the area under the curve will give the energy absorbed by the tube. One set of three tubes including a bonded tube, a riveted tube and a combined bonded and riveted tube, has been crushed in the vertical position as illustrated in Figures 3b and 4a. The second set of three tubes has been crushed in horizontal position as shown in Figure 4b. This latter figure illustrates also the crushing of the tubes in both orientations.

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Fig. 4: Crushing results (a) progressive crushing of a riveted tube oriented vertically (b) riveted tube lying horizontally prior to crushing, (c) riveted tube after some vertical force which sheared all 4 rivets without deforming the U bent component, (d) riveted and bonded tube after crushing.

Fig. 5: Crushing results in vertical and horizontal positions
The crushing results are shown in Figure 5. In vertical position the area under the force to displacement curve expresses the amount of energy absorbed by the tubes. In vertical position, the bonded and bonded+riveted tubes sustain a maximum force at the beginning of deformations. Rivets of the riveted tube failed partly at the beginning and also after 60 mm. Although relatively similar before 60mm, the energy absorbed after 60mm is must higher for the bonded and riveted tube where part of the bounding and half of the rivets last over the entire stroke. In horizontal position, all four rivets of the riveted tube sheared after only 5mm of press motion. The bonded tube sustained again a higher force but failed on one side avec 4 mm and on the other side after about 13 mm. The bonded and riveted tube is by far the best by absorbing more than twice the energy of the bonded tube and many times the energy of the riveted tube. Again, part of the bond and most rivets sustain the entire stroke. The crushing process illustrates very well all the stressing modes occurring over the stroke on the bond joint. For example in horizontal position, shearing is the first mode and cleavage appears in second as the lateral lips bend. Although very illustrative, this example shows all the complexity and the need to better understand and optimize structural designs especially where thin wall and buckling occurs, i.e. in most vehicle structures.

VIBRATION AND NOISE REDUCTION

One advantage of using adhesives is their capacity to increase stiffness and attenuate noise and vibrations. As reported in [2] stiffness in car space frame can be increased by 15 to 30% providing higher modal frequencies of somewhat lower magnitude. Two phenomena can be observed. First, by joining larger surfaces, the adhesive increases the stiffness of assemblies especially where thin walls are involved. This also increases the modal frequencies of the assemblies. Generally higher frequencies also mean lower vibration magnitudes and audible sound levels. Secondly, other researchers have investigated the additional damping due to the adhesive (i.e. absorbed energy in the bond line) when vibrations occur [11]. Using FE simulations, it was observed that modal frequencies and amplitudes change very little as the adhesive properties are modified (see also [12]). The most important effect seems to come from the joining area and the increase of stiffness. To better understand the effect of adhesive on vibration attenuation, a first series of impact tests have been carried out on the assembled tube of the previous section (before they were crushed!). The apparatus is illustrated in Figure 6. A PCI 353MM77 accelerometer located inside the tube on the bottom face was used for receptance. The impact force was monitored using a B&K8200 accelerometer installed on the hammer. A small impact force was applied on the top surface at the opposite of the receptance accelerometer. Both signals are received by a HP3560A dynamic analyzer and downloaded to a computer for further data processing. Finally,
the tubes were supported by rubber bands inside the top corner in order to have negligible effect on the dynamic response. Several impacts have been tested and only repeatable signals are illustrated in Figure 7 for the riveted, bonded and combined riveted and bonded tubes. The time and spectral responses of the riveted tube shows two harmonics around 500 Hz which generate beats. The magnitudes at low frequencies are much higher. The adhesive used in bonded and bonded+riveted tubes reduces considerably the peaks at low frequencies but generate some smaller high frequency harmonics.

![Graphs showing time and frequency responses of riveted, bonded, and bonded and riveted tubes](image)

**Fig. 7**: Dynamic results with an impact hammer

**CONCLUSION AND RECOMMENDATIONS**

The performance of the adhesives proposed in the paper could in many cases be improved by used of more sophisticated surface preparation, automated application of adhesive or use an optimal thickness for example. However, these results also provide the forces and weaknesses of different adhesives as applied on AA6061-T6 using conditions that will usually take place in industry. The different mechanisms tested (shear, tensile, cleavage) appear in most
applications. Peeling results tested in a previous project and not reported in this paper should be avoided when designing components and assemblies.

An intelligent design of structural assemblies sometime needs to consider larger deformations or impact resistance. Again adhesives especially as combined with other assembly methods can improve significantly the absorption of energy. A good structure should consider the deformation and adjust the design to maximize the effect of adhesives.

Finally, adhesives are useful to increase stiffness and reduce vibrations especially at low frequencies. In the range of properties of the adhesives tested previously, their effect on vibration reduction comes mainly from the surface area covered and the increase of stiffness and not much from the adhesive properties. However, as for other design requirements, it is important to avoid weak bonding areas which could under vibrations, break progressively.

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REFERENCES


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