3M™ Scotch-Weld™ Structural Two-Part Epoxy Adhesive Performance vs. Mechanical Fasteners

Abstract

Many performance and economic drivers are causing customers to consider and use structural adhesives in replacing traditional joining methods—including weight and energy savings, labor cost reductions, aesthetics improvements, and the rise in the use of composites and other materials which are not amenable to traditional bonding methods. This paper provides background to assist in a successful transition from mechanical joining to adhesive joining.

Introduction

Traditional methods for joining parts include welding, riveting, the use of nuts and bolts and other mechanical fasteners. Design and production engineers are comfortable with these methods, and are now challenged due to new factors which make the limitations of these methods less acceptable. A key factor in many industries, especially the manufacture of self powered machines and equipment that rely on internal combustion engines or batteries for power, is the need to reduce weight to decrease fuel use, energy consumption and the concomitant emissions. This can be accomplished by the substitution of relatively heavy parts made of steel with lighter weight aluminum, composites, or plastics, by reducing the number of mechanical fasteners used, or by using thinner sheet metal. These changes challenge the traditional joining methods since dissimilar materials, plastics and composites simply cannot be welded; while thinner sheet metal parts will be more prone to distortion and tearing at the concentrated points where through-part fasteners (rivets, bolts) are placed. Metal distortion and tearing under heavy loads or due to fatigue can lead to lower part reliability, longevity and/or gapping between fasteners. Metals can also be damaged by traditional assembly processes, for example welding thin gage metal can cause heat distortion or burn through. An adhesive bonded joint provides a nice clean surface, which allows minimal surface preparation prior to final finishing. Finally, adhesives may be pre-applied in areas which are inaccessible to mechanical fastening during final assembly; and may allow novel designs which can further reduce weight, costs and labor.

Adhesives have developed to the point where they are suitable alternatives for these traditional joining methods for many applications including fabrication of metal panels such as doors and elevators, agricultural equipment, bus, truck and rail panel attachment, and others. To successfully make a change to adhesives, design and production engineers must consider a number of factors, as outlined below.

Adhesive Selection

A variety of structural adhesive chemistries are available in the market. These range from cyanoacrylate “instant” adhesives through one-part (heat cure) epoxy films. While all adhesives have their uses, they are not all suitable for weld/mechanical fastener replacement where structural strength is needed in a dynamic stress environment (e.g., resistance to impact and continual vibration). For these demanding applications, the number of suitable adhesive chemistries is limited.

There are three main chemistries which afford structural strength in bonding large areas (here, structural strength is defined as overlap shear strength in excess of 1000 psi when measured according to standard lap shear procedures). *Two-part urethanes* are formulated to cure upon mixing and generally cure fairly rapidly at room temperature even in thick bond lines (unlike one-part urethane sealants, which cure upon exposure to atmospheric or substrate moisture and cure slowly). Two-component urethanes can provide this strength and their flexibility allows them to provide relatively good impact resistance and peel strength when tightly adhered to substrates. However, their generally low modulus leads to relatively poor heat resistance. In addition, urethanes may also require metal priming to maintain adhesion to metal in challenging environmental conditions such as long-term water/humidity exposure.

Two component acrylics can be formulated to bond very strongly to metals without priming (and sometimes without removing processing or rust preventative oils from the metals). Acrylics have better high temperature performance than urethanes, but tend to be more brittle leading to lower peel strengths and poorer strength maintenance at low temperatures. Some acrylics try to overcome these limitations by clever formulation, such as the inclusion of elastomeric particles or epoxy resin. As a result, higher performing acrylics and acrylic hybrids may meet the needs in many applications where temperatures are not too extreme and their quick cure rates and ability to bond strongly to plastics are of particular benefit.

For the best vibration and environmental resistance *epoxy* adhesives are the chemistry of choice. However, there is a wide variation within epoxies in their ability to resist impact and vibration stress, environmental challenges and provide very high structural strength. Many people are familiar only with first generation epoxy adhesives which tend to be rigid and may have relatively poor environmental resistance. These epoxies, first introduced in the 1950’s, are similar to consumer epoxies sold at hardware stores or for hobbies. However, epoxy technology has overcome these limitations with continual improvement.

In the 1970’s epoxy adhesives with significantly greater flexibility were introduced. These adhesives provide greatly improved peel strength and improved impact/thermal stress/fatigue resistance. Flexible epoxies are now used in applications including honeycomb bonding for aircraft and flooring for rail, where they must provide a long and reliable service life even when challenged by repeated vibrations and thermal cycling.

In the 1980’s toughened epoxies came on the scene. Unlike flexible epoxies, which rely on a relatively low modulus to provide impact and fatigue resistance, toughened epoxies are formulated with a higher modulus matrix in which very small (micron sized) rubber particles are embedded. These particles absorb energy under stress, and can stop micro-cracks from propagating therefore providing ultimate impact and fatigue resistance. Toughened epoxies are now used for the most demanding applications such as bonding to cell towers, armament bonding, sporting good manufacture (composite mountain bike frames and golf club head to shaft bonding), etc.

Toughened epoxies do not sacrifice the environmental resistance properties inherent in the class of adhesives, and are generally the best choice for very demanding weld and mechanical fastening replacement.

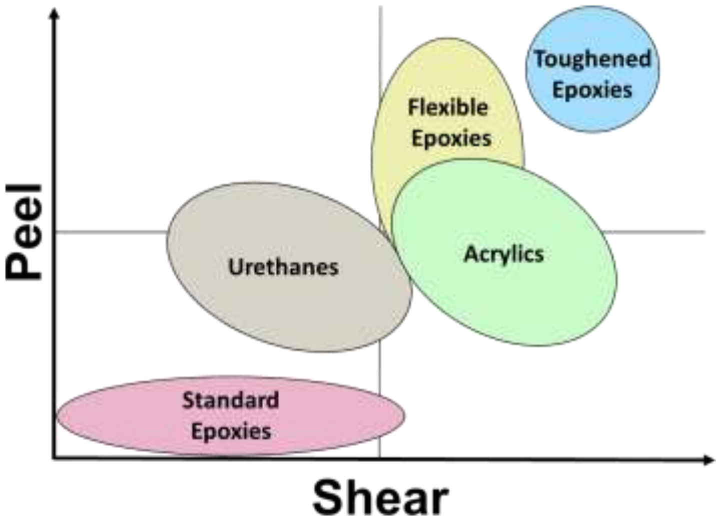

Figure 1. Relative relationship among two component structural adhesives comparing peel and shear performance.

Designing for Adhesively-Bonded Joints

Joint Configuration

Structural adhesives are strongest in shear and tensile modes (especially compression), and weaker in peel and cleavage where all the force on the bond is concentrated at the leading edge of separation. Therefore, it is useful to design joints where shear and tensile forces predominate, rather than designing joints where peel and cleavage forces are predominant. The illustration below shows a few examples of joint redesign for maximum adhesive strength. Sophisticated customers such as automotive and large equipment manufacturers will use computational modeling techniques to evaluate the stress on joints with various designs and optimize the final design.

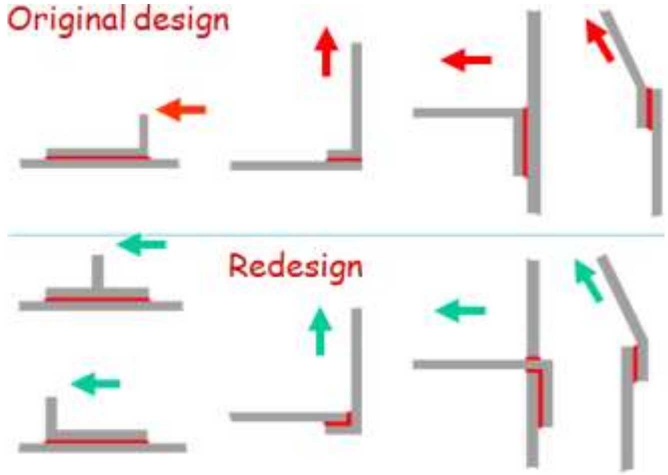

Figure 2. Some examples of joint redesign to put the adhesive bond in the preferred modes.

Surface Preparation

The parts to be bonded also must be clean. If there is a layer of weakly bound material on a surface (whether oxidation/rust, oil or dirt) the adhesive generally will not be able to reach the bulk metal and the result is joint failure. Adhesives may bond tightly enough to certain surfaces (such as mill scale on steel) to remove the surface from the underlying metal. Therefore, contaminants or weakly bound surface layers must be removed prior to bonding—generally by the use of solvent-based degreasers and abrasion to remove oxidation. One exception may be the use of certain acrylic adhesives including 3M™ Scotch-Weld™ Metal Bonder Acrylic Adhesive DP8407NS, which can absorb and bond through some metal processing and protecting oils. When using these adhesives, a trial comparing cleaned to uncleaned adhesive may indicate that the usual cleaning steps can be reduced or eliminated. Typically, a toughened epoxy like 3M™ Scotch-Weld™ Epoxy Adhesive DP420NS will provide the strongest bond on clean metal surfaces, and an acrylic adhesive like DP8407NS will provide the strongest bond on surfaces with a layer of oil or contaminates.

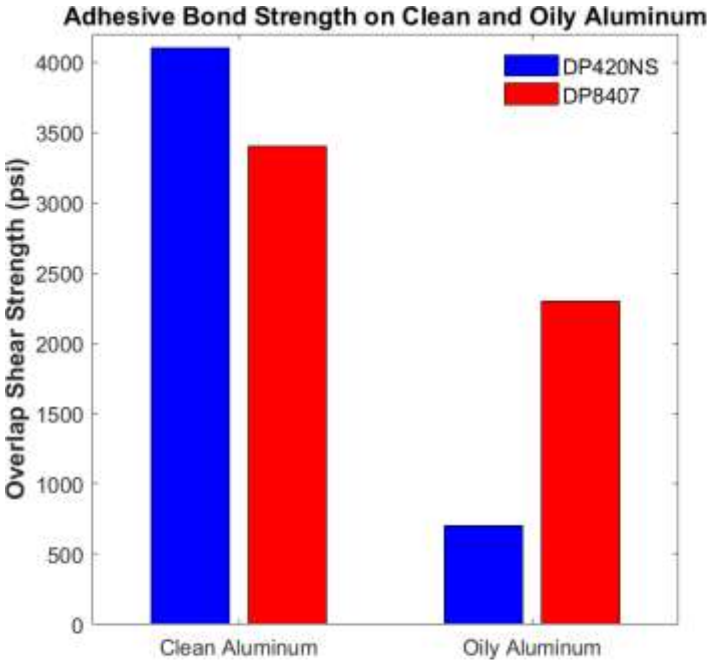

Figure 3. 3M™ Scotch-Weld™ Epoxy Adhesive DP420NS Black and 3M™ Scotch-Weld™ Metal Bonder Acrylic Adhesive DP8407NS on clean and oily aluminum.

Processing Considerations

Production methods also need to be factored into a final choice of a structural adhesive. There are three critical parameters of the adhesive which must be considered: work life (or the time between mixing the adhesive and closing the joint), time to handling strength (the time required for the adhesive to gel to a self-fixturing state allowing further processing) and final cure time (the time at which the adhesive has reached essentially ultimate cure). These times vary by the chemistry and specific formulation of the adhesive; as well as ambient or applied temperature. While the actual application process for structural adhesives is quite quick compared to welding, the structural adhesive itself will need a fixture period while sufficient strength develops to allow the adhesive joint to withstand further stresses during downstream piece processing. This may be as short as 15 minutes at room temperature, or as long as several hours. This time can be shortened by the application of heat (induction cure or heat lamps, guns or blankets for large parts; or ovens for smaller parts). This time can also be controlled by chemistry to provide a specific handling time. In addition, once a two-component adhesive is mixed it begins to cure or “gel up”. There is a finite amount of time between mixing, then, when two surfaces to be bonded must be mated. If the adhesive is in a mixed state for too long prior to mating the surfaces, the adhesive will not “wet out” the surface due to excessive gelling—that is, it will not be able to make full intimate contact with the surface and will greatly decrease ultimate bond strength.

Finally, two-part adhesives cure by chemical reaction; not by drying (as in contact adhesives) or by cooling (as in hot melts). Chemical reactions occur more quickly at higher temperatures than at lower temperatures. Thus, the temperature of the production facility and the substrates to be bonded should be considered when designing the production process. If the temperatures vary significantly (for example, winter to summer variation) either the production process may need to change or the adhesive used may need to change.

Joint Testing and Failure Modes

Design and production is validated by statistical application of destructive test methods that are designed to replicate the primary forces on actual joints. Such test methods are inexpensive and can be integrated with various environmental conditions. These methods can include lap shear, impact, peel and many other application specific methods.

The most common design test is lap shear testing with the substrates, surface preparation and bonding methods to be considered. ASTM D1002 provides a method which can generally be easily customized to generate test data validating a proposed design. (Due to the high strength of adhesive bonds on very high strength metal substrates, flat wise tensile tests may be more difficult and expensive to design and are often bypassed in favor of lap shear testing unless a fairly low failure load is anticipated based on the internal strength of a substrate (e.g. a plastic or laminated substrate)).

Lap shear testing is probably the most common way to evaluate the adhesion of various products to a variety of substrates. It is also amenable to testing the strength of mechanical fasteners and welds which can be prepared allowing sufficient overlap between the metal plates to place the fasteners. Comparative numbers can be obtained using standard methods and demonstrate the failure force of toughened epoxies versus rigid epoxies and mechanical fastening methods as well as welding (see fig. 4).

What standard overlap shear testing does not illustrate, however, is the impact resistance of the various designs. Other test methods can be devised to check impact/fatigue resistance; some are quite sophisticated and time-consuming (e.g. ASTM D3166); but often a simple test can provide a striking comparison. For example, a simple pendulum test machine can illustrate the relative ability of different bonding methods to absorb the force of impact (see fig. 5).

Another common method, used for flexible substrates, is a peel test. There are various types of peel testing, including: ASTM D3167 Floating Roller Peel and ASTM D1876- T-peel method.

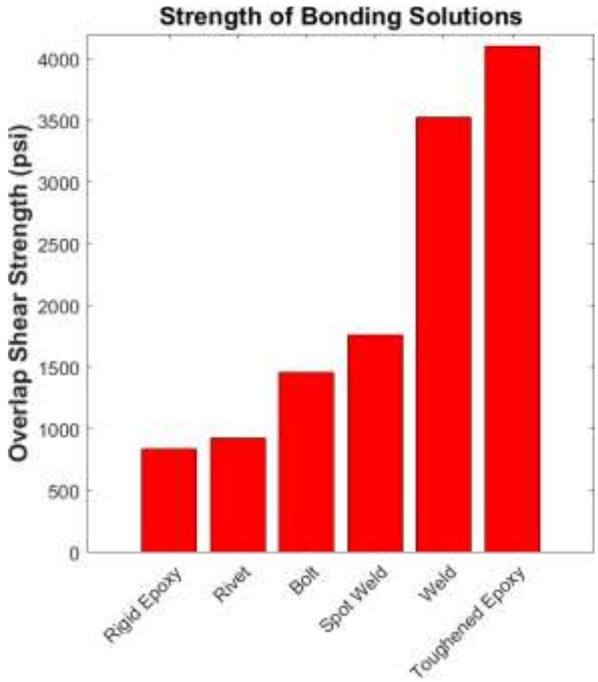

Figure 4. Toughened epoxy resins can meet or exceed the ultimate shear failure force of traditional joining methods.

Structural adhesive bonding enables the production of lightweight materials by eliminating the need for bolts, rivets, and other parts typically required for mechanical fastening. Lightweighting is of particular importance in the aerospace and automotive industry, where weight reduction directly impacts performance and efficiency.

Figure 5. Toughened epoxy bond vs. spot welded bond, T6061 aluminum, pendulum impact test (3 lb weight on a 20” swing arm) http://www.youtube.com/watch?v=CPR28olqf5Y

When substrates are bonded with adhesives, the adhesive can be applied to cover the entire joint. This eliminates any concentration of force (as will occur when rivets or bolts are used along a joint). The spreading of stress along the joint can reduce metal distortion under strain, as well as improve ultimate failure force. If a joint will be repeatedly stressed, the spreading of stress along the joint line can provide better fatigue resistance and part longevity. This effect can be demonstrated using a tensile force test machine to examine adhesively-bonded vs. mechanically fastened joints (see fig. 6). Another advantage indirectly demonstrated here is that the thinner sheets of steel may be adhesively bonded without metal distortion (due to stress concentration with rivets, bolts and spot welds). Adhesive will allow the stress to be spread equally across a larger area of thinner metal. Thus, thinner metal can be used to reduce weight without sacrificing strength or fatigue resistance.

Figure 6. Failure of T6061 aluminum (0.063” thick) bolted together and the rivets upon tensile force application vs. adhesively-bonded aluminum.

Welding along an entire joint will produce a strong joint; however, welding itself may have other undesirable effects (including high labor and energy costs and distortion/weakening of the metal due to the heat of welding). Welding and mechanical fasteners may also require more finishing to meet aesthetic requirements for the finished part. Testing indicates that the ultimate failure force for high end structural adhesives can even meet that of full seam welding, without the consequent metal distortion or weakening due to heat. In the testing shown in figure 4 above, the welded specimen failed at the edge of the weld, presumably due to heat weakening of the aluminum in that area. Comparison to a non-welded piece of aluminum indicated the metal had been weakened by more than 40% in tensile strength.

A further comparison of specific strength of bonded joint shows the advantage adhesives have in not only strength, but also in minimizing weight.

	Rigid Epoxy	Rivet	Bolt	Spot Weld	Weld	Toughened Epoxy
Strength of Joint (psi)	840	920	1460	1700	3500	3770
Relative Weight (final wt./initial wt.)	1.03	1.05	2.02	1.00	1.06	1.03
Specific Strength (strength/relative weight)	820	880	720	1760	3330	3660

Summary

As discussed above, various driving forces are leading numerous companies that have relied upon standard joining methods such as welding, brazing, rivets and bolts in the past; to consider the use of high performing toughened structural adhesives. Such adhesives can provide significant advantages in terms of overall cost and weight reduction, as well as the ability to join dissimilar substrates and the ability to create joints with good stress distribution and concomitantly good fatigue and force resistance. Toughened adhesives can also improve aesthetics and eliminate labor-intensive finishing costs such as sanding off slag from spot welding. Choosing the right adhesive is paramount and engineers should work closely with their material supplier to select the right product. In addition, some joint redesign and production processing adjustments may greatly affect ultimate project success. However, as can be demonstrated empirically, when used properly structural adhesives can meet or exceed the performance of traditional joining methods such as welding, rivets and bolts.

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