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EVALUATION OF EPOXY ADHESIVES FOR MUON MODULE ASSEMBLY

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INTRODUCTION

The SDC muon subsystem design is a monolithic design approach. The barrel subsystem includes 104 modules of various sizes. Each module, containing many detector tubes, is installed as a unit. The modules are to be pre–assembled, tested, and stored until the erection of the entire subsystem.

In this design, the detector tubes inside each module are supported by the external structure at the ends only. Inherent in this approach is the potential for deflection of the tubes and of the modules as a whole due to gravity. In order to maximize the stiffness of the modules, all elements of the module, including the drift tubes, are used as structural elements. Structural epoxy adhesives are used to connect the aluminum tubes and plates which make up this structure.

Testing frames consisting of a small part of a typical tube/plate structure were assembled and loaded until failure of the adhesive. Load values determined in testing here are translated into adhesive strength using finite element methods. This analysis is also confirmed by strain gauge and deflection measurements. The information gained in adhesive testing will help to refine the finite element models for estimating the deflection of modules and supermodules.

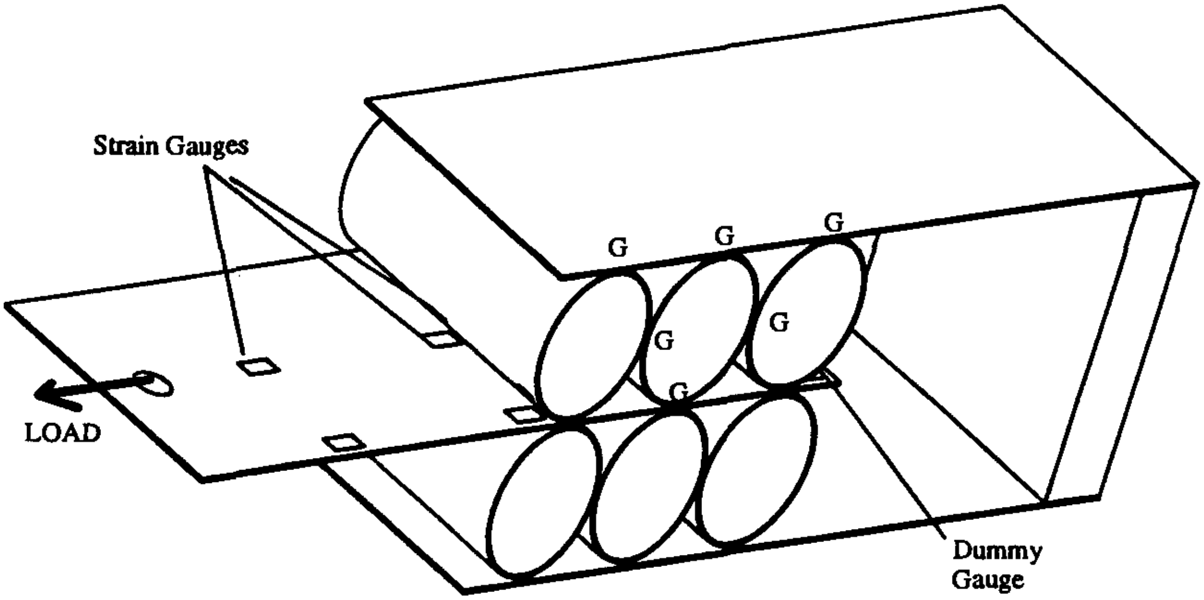
PROCEDURE

A series of eleven tests was conducted to determine the applicability of available adhesives. The tests were primarily designed to determine the strength of the adhesive in the joint configuration used in the modules and whether the bond would fail before the bulk of the adhesive. To this end, a frame was constructed that would mimic the stresses that would occur in the tubes and plates of a module. Figure 1 is an illustration of the testing frame showing top and side views.

The Testing Frame

The testing frames were built in the configuration of the modules, as layers of tubes separated by plates. The frames were made of two layers of three aluminum tubes separated by one aluminum plate. Two other plates enclosed the assembly as shown in Figure 1. Each tube was 75 mm diameter and 150 mm in length with a 1.6 mm wall thickness. The plates were 150 mm wide, 450 mm in length and 1.6 mm thick. The tubes and plates were joined together by the adhesive being evaluated. Figure 1 indicates where the bonds were positioned.

After the adhesive had cured to full hardness, the frame was placed in a Tinius–Olsen tension testing machine and pulled to failure. Failure would be: a) rupture of the bulk adhesive, b) rupture of the bond between the adhesive and the aluminum tubes or plates, and c) plastic yielding of the aluminum plates or tubes, such that the adhesive would not fail.



G – Typical locations of glue joints at all contact points between tubes and plates and tubes to tubes.

Figure 1. Frame for Testing Adhesive.

As illustrated in Figure 1, the tubes were arranged in two layers of three tubes each, one layer directly above the other. One plate separated the layers of tubes. The other two plates, joined at one end by a sturdy spacing block, surrounded the six tubes and middle plate. A tension bar protruded from the middle of the spacing block, providing a centered point to apply a force. The middle plate had a hole centered in its width to allow a hook to engage the plate and to provide an oppositely directed force. In this configuration, the applied forces would tend to pull the middle plate out from in between the layers of tubes.

The distance between the hook hole and the first row of tubes was sufficient to allow for the assumption of uniform stress along the length of the adhesive junction between the plate and tubes. Because the application of the force was slow and gradual, the stress state was essentially static and any stress concentration due to the hook hole could be ignored. By the same token, the stresses in the outer plates could be assumed uniform at the other end of the frame because the spacing block applied steady force uniformly to both of the outer plates.

Strain Gauges

In the first and second tests, bonded resistance strain gauges were applied to the middle plate and to one of the tubes. The strain gauges were applied to the plate in five places as shown in Figure 1. Two pairs of strain gauges were applied to the top and bottom sides of the plate. The members of each pair were applied directly opposite one another. One pair of gauges was applied along the center–line in the long dimension and the other along one edge, both near the adhesive line of the first tube. A fifth strain gauge was applied at the free end of the middle plate to serve as a dummy as it would not be under stress. Three strain gauges were also applied to the first tube in one of the layers. Two gauges were placed on the outside of the tube such that they aligned with the gauges on the middle plate, and one gauge was placed inside the tube opposite the edge–placed gauge on the outside. With this arrangement of strain gauges, it would be possible to cancel the effects of any bending stress in the frame and consider only the pure tensile stress applied by the Tinius–Olsen tension testing machine. In addition, stresses in the tubes could be evaluated and compared to expected values.

In addition to the strain gauges, the frame was equipped with a displacement transducer to measure the movement of the middle plate with respect to the outer plates.

The Adhesives

Four epoxy adhesives were used in the testing. The four had different characteristics for working and curing time. Two were products of the 3M Company and two were Epibond products, produced by Ciba–Geigy. The 3M products were Scotch Weld 2216, and DP 460. The Ciba–Geigy products, Epibond 1526 and 1555, and one 3M product, DP 460, became the main adhesives tested. The working times varied from 20 minutes for E 1526 to one hour for DP 460 and E 1555. The curing times also varied from 4–5 hours for DP 460, to 24 hours for E 1526, to 5–7 days for E 1555.

The room temperature viscosities of the adhesives varied. E 1555 was significantly more viscous than DP 460. The DP 460 would be more likely to run after applied, having the consistency of cool honey. The E 1555 could be accurately described as stiff, although the adhesive would flow slowly on a vertical surface.

The Scotch Weld 2216 was used on the first test only and DP 460 was used in three of the last six tests. The E 1526 was used in the second and third test frames and the E 1555 used in all other tests. All the adhesives were two part epoxies.

The adhesives were mixed and applied by various means. The application effort was to apply a narrow bead of adhesive to the tube, keeping the size of the bead around 3 to 4mm in diameter. On the first two frames, the adhesive was applied with a narrow stick. This method was slow and messy but the beads were reasonably uniform and of the right general size. In an effort to be more uniform in the narrow application of the adhesive bead, the third frame was assembled by first mixing a sufficient amount of adhesive and loading the mixture into a large syringe. The syringe allowed easier and more uniform dispensing of the mixture. The last nine frames were assembled using the adhesive manufacturer's mixing and dispensing nozzle. The nozzle provided a smooth mixing action of the two–part epoxy adhesive as it flowed down the nozzle, and allowed for bead size control by snipping the tip of the nozzle to suit the job. This made the application of the adhesive more uniform.

Tube and Plate Preparation

The best adhesive bond can be expected when the surfaces are cleaned to be free from dirt, oils, and oxide layers. The first frame was assembled to the worst case condition. The tubes and plates were not cleaned with solvent nor were they abraded to roughen the surface and remove any penetrating contaminants. This frame had strain gages attached. Subsequent frames were thoroughly abraded and washed with solvents, either isopropyl alcohol, acetone or 100% ethyl alcohol. The abrasion on the first six frames was done using fine (400 grit) abrasive paper and the rinsing was done just before assembly.

The abrasion on the later frames was done using an abrasive impregnated nylon pad called Bear–Tex. Some of the frames in the latter half of the testing series had an alodyned surface and were not abraded. Others were only mildly abraded.

Assembly Process

The assembly of the frame was done on a sturdy table. To ensure the frame remained square during the assembly and curing, machinist's 90 degree angle blocks and parallels were used for orientation of the pieces. Lead plates were used to hold the tubes and plates in position as well as to provide vertical loading while the adhesive cured. The loading helped to press out excess adhesive leaving a thin bonding layer between the tubes and plates of the frame.

The Tension Test

The tension testing consisted to two parts, a) static loading for evaluating the stress state of the testing frame, and b) loading the frame with increasing force until failure, including a pause to evaluate whether the adhesive was creeping. The static loading was done using a dead weight of 180 N and took place on the first and second tests only. The strain gages were utilized in the static loading in the first two tests, and in only the second test during the loading to failure portion of the testing. All tests included a pause to observe the creep behavior of the adhesive under load at 2200 N. In tests three through eleven, only the loading to failure portion of the test was performed and no strain gages were utilized.

The Tinius–Olsen machine grips the tension bar in jaws. Care was taken to produce a load in the axial direction only, and to eliminate any lateral loading. The load was reasonably axial, however, a small component of lateral loading did exist in some of the tests.

RESULTS AND DISCUSSION

The results of the twelve tests are summarized in Table 1, below. The table includes the type of adhesive, tube type and preparation, the behavior of the adhesive at a sustained load of 2200 N, the maximum load achieved and failure mode.

In the test 1, the tubes and plates were bonded together but the tubes were not bonded to one another. This test used the 3M Scotch Weld 2216 epoxy. This adhesive did not cure to a hardened state. The adhesive retained a rather rubbery, resilient nature when probed with a sharp instrument. It may have been improperly mixed or, if shelf life of epoxy adhesives is a factor, it could have been too old.

The static (180 N) loading test was conducted and strain gauge and deflection readings taken. These were found to be consistent through several load/unload cycles. This frame was then pulled to failure in the Tinius–Olsen machine. The failure occurred at less than 2200 N force and the type of failure was failure of the bond between the tubes and the outer plate. This type of failure is not unexpected since the first frame was the worst case scenario with no tube or plate cleaning performed prior to assembly.

The second and all subsequent testing frames were assembled by bonding the tubes to one another and to the plates. This, together with harder–cured adhesives, appears to have significantly increased both the load bearing ability and the stiffness of the testing frame.

Table 1: Results of Adhesive testing using tube and plate frame.					
Test	Adhesive	Tube & Prep *	2200 N creep	Max Load (N)	Fail. Mode
1	3M 2216	1, u, n	NA	< 2200	bond
2	E 1526	1, a, I	no	6111	bulk
3	E 1526	1, a, I	no	4696	bulk
4	E 1555	1, a, A	no	4696	bond
5	E 1555	1, a, I	no	5150	bulk
6	E 1555	1, a, I	no	8386	bulk
7	E 1555	1, b, E	min	6730	bulk
8	DP 460	1, b, E	min	8043	bulk
9	E 1555	2, u, E	no	4647	bond
10	DP 460	2, u, E	no	4593	bond
11	DP 460	2, b, E	no	8110	bulk

* KEY: tube type, preparation, solvent. Type; 1 = plain, 2 = alodyned. Prep; u = unabraded, a = 400 grit abrasive paper, b = bear-tex abrasive nylon pad. Solvent; n = none, I = isopropyl alcohol, A = acetone, E=100% ethyl alcohol.

The testing frame 2 was assembled with Epibond 1526 adhesive and the parts were all abraded and rinsed with isopropyl alcohol. The E 1526 cured to a much harder and stiffer form than the first adhesive. The static test again showed consistent strain readings in the plate. The failure test was performed with the strain gauges active and a series of readings were taken at various load values. All strain and deflection results were linear with load. The failure mode was one of brittle fracture of the bulk adhesive at the middle plate. The adhesive-to-metal bond remained intact.

There was a small, but noticeable, lateral component of force in the frame during the test due to difficulty in finding the perfect alignment of forces. The fracture of the adhesive layer occurred in that portion of the frame that was under a lateral force that tended to pull the tubes away from the middle plate. In addition, the middle plate had strain gauges attached that were protected with a polymer "gauge-coat." After the fracture occurred, visual inspection showed that no bonding occurred in the areas of the gauge-coat. This, in effect, created local stress concentrations (at each of two strain gauge sites in the area) that could have contributed to early failure of the bulk adhesive.

Testing frames 3 and 4 were assembled using the same techniques but different adhesives and different solvent rinses. Frame 3 was assembled using Epibond 1526 after rinsing with isopropyl alcohol, while frame 4 was assembled using Epibond 1555 following an acetone rinse. The lower values of the maximum loads (compared to frame 2) may indicate that the assembly technique was poorly carried out. The bond failure of frame 4 may indicate that the solvent either was used ineffectively or that acetone leaves a residue that affects the bonding of the adhesive.

Frames 5 and 6 were also assembled under very similar circumstances. Following the low load results of tests 3 and 4, all subsequent assembly was more carefully done. Squareness and cleanliness of the surfaces were especially emphasized. The higher values of the tests indicates that either or both may be important factors in achieving the best performance from the adhesives. The very high load sustained by testing frame 6 indicates that the adhesive is capable of very high strength.

During the loading of the sixth frame, the observation was made that some part of the frame was yielding. It was determined the yielding was occurring at the hook hole of the middle plate. Although the hole was armored with a stainless steel grommet to reduce the stress concentration, the hole became enlarged under the loading showing permanent plastic deformation of the 1.6 mm aluminum plate while the adhesive remained intact.

The test was prematurely stopped when the tension hook, made of wrought steel about 6 mm in diameter broke in brittle failure. A new hook was built of 9.5 mm mild steel. In the second attempt to load the sixth frame to failure, the new hook yielded and the test had to be halted again while the new hook could be hardened by solution heat treatment and quenching. This done, the sixth frame finally failed. The failure was a bond failure, part of which may be due to the impact load the frame endured when it fell to the floor after the first hook broke.

Tests 7 and 8 compared Epibond 1555 with a similar product by 3M, DP 460. Both frames were constructed of plain tubes abraded with Bear–Tex, the abrasive impregnated nylon pad. Small evidence of creep was observed on each specimen and both showed bond failure. Both frames showed a very small amount of creep during the pause at 2200 N.

Tests 9 and 10 were performed on un–abraded alodyned tubes. These tests were carried out to evaluate the bonding surface provided by alodyning. Alodyning will be present on tubes in the muon detector, but is a requirement for the inside surfaces only. Eliminating the abrading step would be desirable from the standpoint of assembly time. Both frames failed by debonding, however loads were very close to one another.

In test 11, using DP 460, the alodyned surface of the tubes was slightly abraded with the Bear–Tex pad. The pad could be used to remove all the alodyning, which would be equivalent to an abraded plain tube. An effort was made to abrade the tubes such that the alodyning was well roughened, but not entirely removed. The test showed significant yielding at 7390 N which was determined later to have been yielding of the middle plate at the hook hole. The yielding was observed in two small pauses in loading followed by the major yielding. When loading resumed, the frame failed completely at 8110 N.

FINITE ELEMENT ANALYSIS

<u>Methods</u>

In order to estimate the stresses in the adhesive bonds of the testing frame, a finite element model of the frame was built using Ansys®. As shown in Figures 3 and 4, this model includes elements for the tubes, plates and epoxy bonds. With the model loaded by an axial load of 4550 N, the adhesive elements were isolated and the maximum values of tensile stress normal to the joints and the von Mises stress in the epoxy were found. The corresponding stresses in the various frames at failure were then found by scaling. The deflection of the middle plate and the tensile stresses in the frame at the strain gauge locations were also found for comparison with the test results.

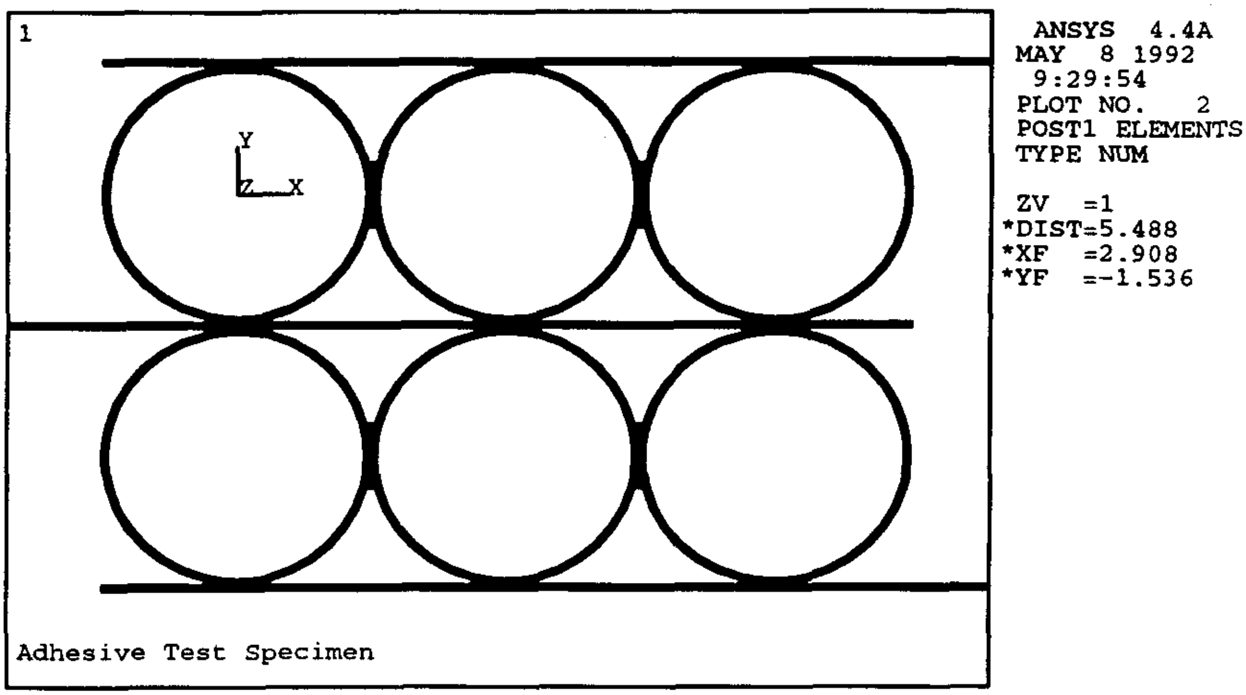


Figure 2. Finite Element Model of the Testing Frame

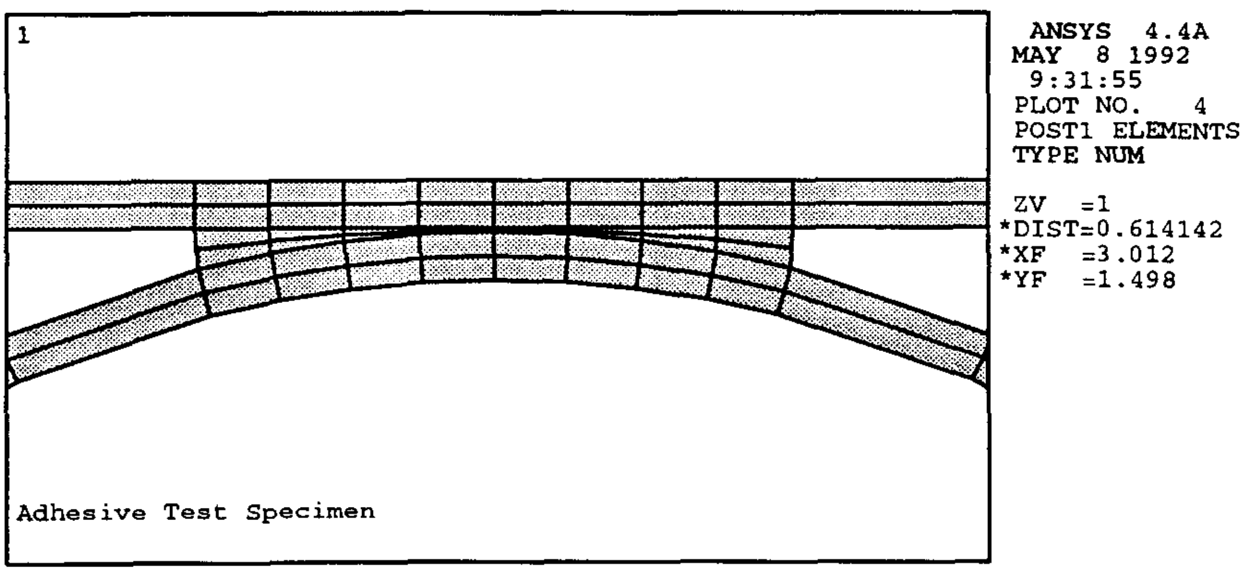


Figure 3: Close up of Finite Element Model Showing Elements for the Adhesive Bond.

Results and Discussion

Determination of the strength of adhesive bonds in a general manner is complicated by the dependence of both the stresses in the adhesive and the material properties of the adhesive on the geometry of the joint. For example, data from ANSI standard tests is only strictly applicable to simple lap joints with thin (150 – 200 μm) bonds. As most of the joints in the muon modules consist of a 90 mm diameter tube touching a flat plate, ANSI test results may not give valid data. However, as finite element models of the modules will contain elements representing the bonds, the failure stresses in the bonds found in the tests described here will give a reasonable basis for estimating factors of safety for the modules.

Adhesive joints can fail by either adhesive failure at the bond line or by cohesive failure in the bulk of the adhesive or the substrate. In the above described tests, no failures were seen in the metal substrate and bond failures were only seen if the surfaces were poorly prepared. The cohesive failures in the epoxy occur in two ways: peeling failures due to a tensile stress normal to the joint and shear failure parallel to the joint surface. The latter mode is best described by the von Mises stress in the epoxy. The failure stresses corresponding to the failure loads given in Table 1 are shown in Table 2. Results are given only for tests which resulted in cohesive failure. For tests 9 and 10, the presence of the alodyned surface caused bonding failure with a tensile bond strength of about 20 MPa for both E 1555 and DP 460 epoxies, i.e. the alodyned surface reduces the load carrying capacity of the joints by approximately 43%

The strain gauge data agreed with the finite element model within 20% for the gauges on the tubes and on the plates close to the tubes. The gauges on the plates at points well removed from the tubes and the hook hole gave results within 3% of the model. The latter result reflects the expected uniform stress at this location. The other data is acceptable confirmation of the model given the high stress gradients at the gauge locations. The gauge measures the average strain over its active area (1.6 x 1.6 mm) and will, thus not show the considerably higher peak stress present. The measured deflection of the middle plate was within 5% of the value from the FEA model.

Table 2: Failure Stresses in Epoxy Bonds

Test	Adhesive	Tensile Strength (MPa)	von Mises Strength (MPa)
2	E 1526	20.5	19.5
3	E 1526	20.5	19.5
5	E 1555	35.4	33.7
6	E 1555	36.6	34.9
7	E 1555	29.3	28.0
8	DP 460	35.1	33.5
11	DP 460	35.4	33.7

CONCLUSIONS

These tests show a wide spread in the performance of three adhesives under very similar conditions. The EpiBond 1525 and EpiBond 1555, products of Ciba–Geigy, and DP 460, produced by the 3M Company, were the primary adhesives tested. 3M Scotch Weld 2216 may be a viable product as well but the particular mixture performed poorly, probably due to poor control of the mixing ratio or to the sample used having exceeded its shelf life. Precise control of adhesive mixing is essential if good performance is to be obtained.

The major finding is that epoxy adhesive bonds are capable of sustaining high stresses both in the peeling and shear failure modes. Data from FEA models of muon modules indicates that the epoxy strengths found in these tests will correspond to static factors of safety of about 8. In particular, E–1555 and DP 460 appear to be the best performers. E–1526 also performs acceptably given that it has a much faster curing rate.

The greatest differences between the E 1555 and DP 460 are the curing times, 5–7 days and 4 hours, respectively, and the viscosity. The E 1555 was significantly stiffer in the uncured form, flowed less and presumably would be easier to apply in cases where adjacent tubes had space between them. DP 460 is less viscous and would flow easily from the applicator. DP 460 is rated to have a 1 hour working time, as does E 1555, but it was noted that the initial runny nature of the DP 460 changed to a stiffer consistency well before 1/2 hour. Motion of bonded parts becomes difficult in 1/2 hour using DP460, where E 1555 maintains workability longer. Both adhesives develop considerable strength within 3–4 hours and bonded parts could be handled at this time without damage.

All surfaces to be bonded must be cleaned by both abrasion and washing with alcohol before bonding. Although alodyning the metal surface reduces the bond strength, the alodyned surface is easily removed by light abrasion. The resulting surface seems to give excellent adhesion with the tested epoxies. Given that alodyning will protect the tube surface during storage and transportation and that it is easier to clean the alodyned surface than a bare aluminum surface, it is recommended that all tubes be alodyned.

Comments

In addition to bond strength and shear strength, other parameters that would make a particular adhesive desirable include; viscosity, adequate working time, curing time, and ease of application. The adhesive must be viscous enough to stay in position on the tube regardless of the orientation of the tube, i.e. it shouldn't be too runny. Furthermore, high viscosity will assist in positive positioning of the mid–body of the tubes when placed in the module during assembly. Working time must be long enough that the tube can easily be positioned in the module without developing so much "set" as to inhibit good flow of the adhesive or good bonding. Curing time to full strength under the temperatures and conditions found in the assembly building should be such that assembly of the modules can continue without undue delay. The adhesive should be applied with an automated dispensing system.