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Joining I: Mechanical/Adhesive

Richard J. Switz

1. INTRODUCTION

The fact that it is sometimes cost effective to spend as much as $20,000 to save a pound of weight in spacecraft systems [1] makes beryllium a very good candidate for reducing overall system weight. Even with the availability of the forthcoming Space Transport System (shuttle), weight savings will continue to be a very important parameter in spacecraft design. To achieve the full potential of beryllium, it is necessary to develop efficient methods for making structural joints, since the structural subsystem usually offers the widest choice of weight-saving possibilities. The joining methods considered here use either mechanical devices or adhesives and have proven application in unmanned spacecraft. TACSAT I, shown in Fig. 1, is representative of such a spacecraft; it is 3 m in diameter, 7.6 m tall, and weighs 726 kg. Three forms of beryllium are considered in its design: block, sheet, and extrusions. The joining considerations and methodology are different for each.

The following discussion emphasizes design and manufacturing techniques rather than approaches to structural analysis. For the most part, tools needed for analyzing beryllium structural joints are no different from those used with lightweight structures made from other materials. Textbooks such as those by Bruhn[2] and Roark[3] supply adequate analytical methods, and no further discussion on that aspect of the problem is continued in this chapter. However, little information is available in the literature on design and manufacturing steps that have been used successfully in production quantities for joining beryllium to itself or to other materials.

Richard J. Switz • Hughes Aircraft Company, El Segundo, California 90245

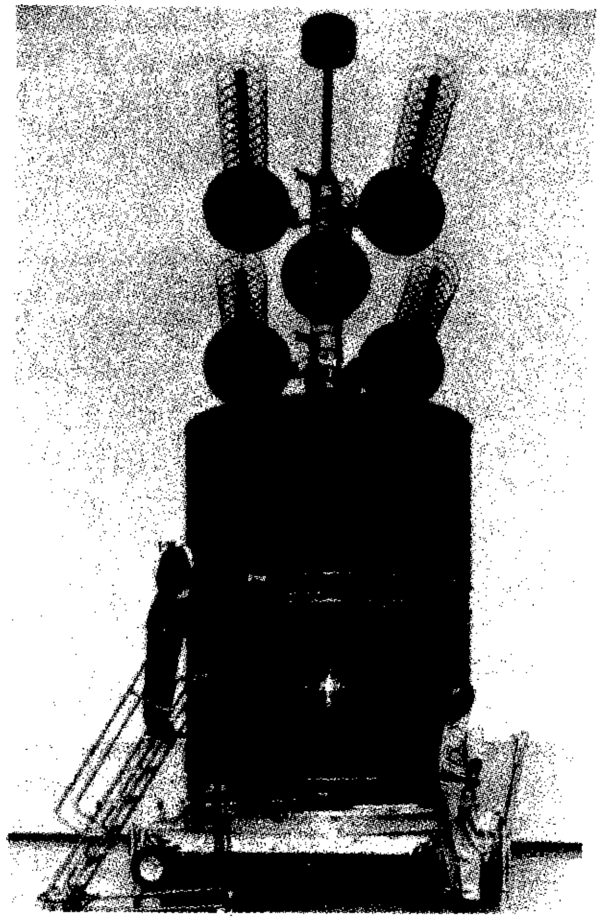

Fig. 1. TACSAT I communication satellite.

2. GENERAL CONSIDERATIONS

A first consideration in designing a joint is whether it will ever require disassembly. If it will, threaded fasteners are required; clamping methods are not recommended. If the juncture can be permanent, other approaches are chosen utilizing structural adhesives and/or mechanical fasteners such as rivets.

Knowledge of temperature extremes during the structural lifetime is also important; it frequently establishes limits on material choices. For example, room temperature curing epoxies are unreliable after being exposed to temperatures in excess of 150°C. Temperature information also furnishes guidance in choosing materials that must fay with beryllium in order to minimize joint stresses caused by differences in thermal coefficients of expansion. Beryllium–aluminum is usually a poor materials combination for that reason.

An additional factor not to be overlooked is that the direction, duration, and magnitude of the forces applied must be well defined and understood by the designers so that they do not create an overly conservative product and largely negate the weight saving for which beryllium was chosen in the first place.

3. JOINTS MADE WITH MECHANICAL FASTENERS

Mechanical fasteners generally fall into two categories—bolts and rivets. Regardless of which is used, a hole must first be created in the beryllium. Producing holes that are free from cracks and delaminations is far more difficult with beryllium than with other materials.

3.1. Drilling Holes

Holes are usually drilled in beryllium with a machine having a servo system to limit the feed and speed of the cutting surface during the operation. Settings for the equipment are developed by the shop for each machine, since they all have different characteristics. Although no attempt will be made here to specify exact servo settings, values given in Table 1 relating spindle speed to drill sizes can be used as a starting point for calibrating the servo system. These values can also be used as maximum conditions for machines without the feedback controls.

Figure 2 shows a setup being used to drill holes in a beryllium channel 1.5 mm thick. Drill bushings are used to guide the drill, and the operation is performed without coolant fluids. Note the ever-present vacuum system used to collect beryllium chips, which otherwise could create a toxicity problem. Small granular flakes produced during drilling are indicators of good machining; the operation does not produce metal curls, as happens when steel is drilled.

Table 1. Spindle Speeds versus Drill Size for Drilling Beryllium

Drill size (mm)	Speed (rpm)
Up to 3.2	140
3.2–4	127
4–4.8	112
4.8–5.6	108
5.6–6.3	102
Over 6.3	102

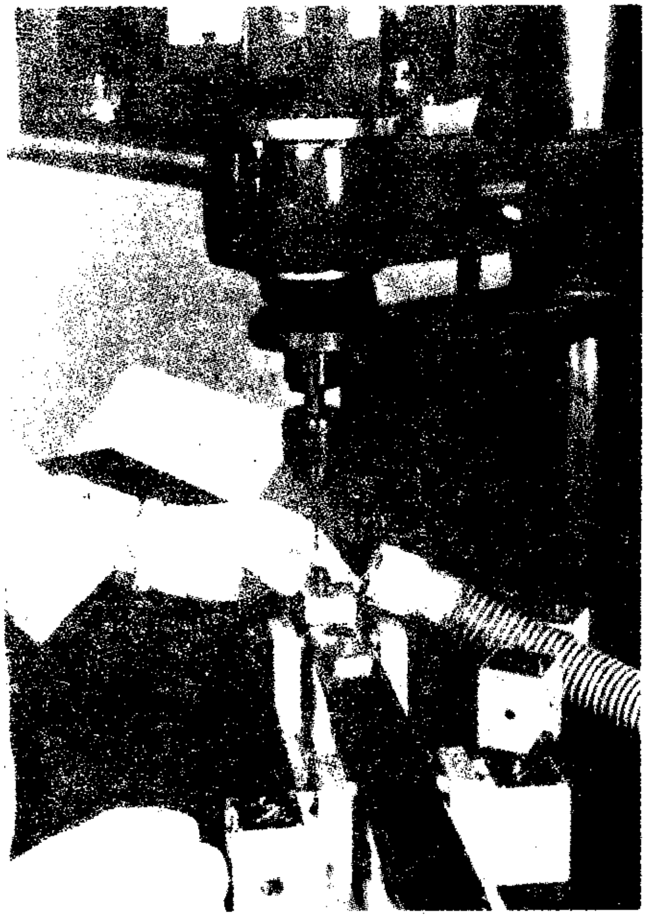

Fig. 2. Setup for drilling holes in beryllium.

Fig. 3. Drill tool for drilling beryllium.

The cutting tool itself is very important—it must be sharp and have the proper cutting surface. Carbide tools having cutting surfaces as shown in Fig. 3 can be used with good results, provided that proper control is maintained to certify their calibration and records are maintained on the number of holes drilled since it was last sharpened. Satisfactory work can also be obtained with twist drills, although the burr configuration in Fig. 3 is generally preferred.

Maintaining strong quality surveillance in the drilling area is crucial; records must be kept of machine settings and drill condition. Considering the value of beryllium, visual inspection of the tool's cutting surfaces with 10× magnification after each hole is not unreasonable. There should be no evidence of dullness or chipping of the cutters. Further, replacing the drill after 100 holes is good practice. Although they can be resharpened, the cost saving compared to replacement is minimal. Finally, each drill should be qualified by drilling three to five holes in a test part prior to introduction into tool inventory.

3.2. Electrical-Discharge Machining

Electrical-discharge machining (EDM) methods can also be used to create holes, although the process is not so flexible in handling small quantity jobs as is drilling. If EDM is used, the metal removal rate for finished holes should not exceed 0.032 cm^3/hr to produce good structural holes. The advantages of EDM over drilling are that it offers the possibility of creating many holes simultaneously and can produce hole shapes other than circular; the quality of the hole is not necessarily any better. Unlike drilling methods, the EDM process uses fluids during the operation, and care must be taken to choose materials free from halogens, which might otherwise create a corrosion problem by their interaction with beryllium.

Regardless of the method used for creating the hole, clearance for bolt and rivet shanks must be included in the hole diameter; minimum radial clearances for bolts and rivets is 0.025 mm, but for the rivet, this allowance is after the rivet has been expanded. The objective is to minimize radial forces introduced by the fastener shank, which otherwise could cause premature failure because of the extra preload.

3.3. Inspection

As mentioned, good structural holes must be free from radial cracks and delaminations within the plane of the material. To remove any local damage after drilling, the part must be chemically etched with either of the two solutions identified in Table 2 to remove 0.05 mm from all surfaces. It

Table 2. Chemical Etch Solutions for Beryllium—All Forms

Solution	Material	Volume (%)
A[a]	Deionized water	10 ±1
	Chromic acid (dry)[b]	—
	Phosphoric acid	75 ±3
	Sulfuric acid	15 ±1
B	Nitric acid	25 ±2
	Hydrofluoric acid	0.25 to 1.0
	Deionized water	Balance

[a]Discard solution when chloride ion concentration reaches 20 ppm. Air agitation not recommended.
[b]3.8 ±0.11 g/liter.

should then be subjected to dye penetrant examination using materials and methods specified in MIL-I-6866, Type B, to verify that the hole is indeed free from damage.

Figure 4 shows a beryllium housing made from hot-pressed block that is 25.4 cm in diameter and approximately 30.5 cm long. It consists of two components, a rotor and a stator, and serves to despin the large cantilev-

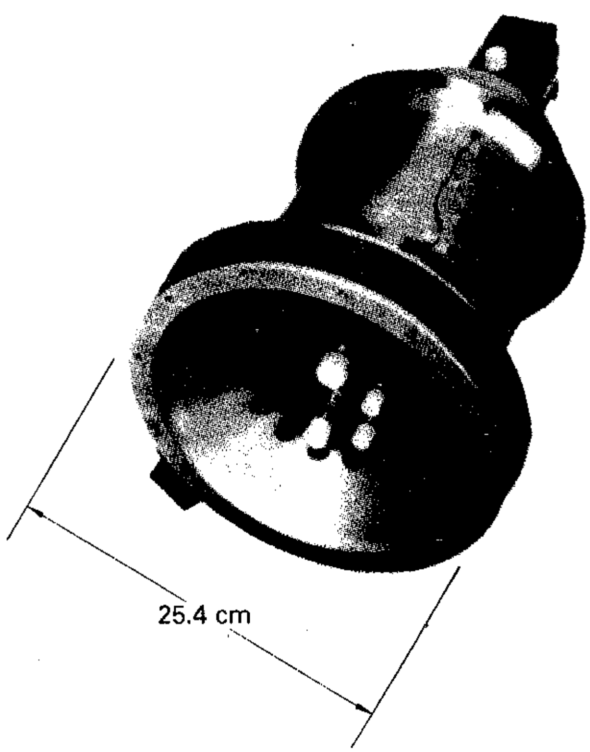

Fig. 4. Beryllium structural housing.

ered antenna assembly shown in Fig. 1 from the spinning main body of the spacecraft. Thus the housing is very much a part of the spacecraft primary structure and must react large bending and compressive forces.

Both threaded and through holes are used in the housing to accept titanium bolts. The thermal coefficients of expansion for beryllium and titanium are well matched for the temperature ranges expected.

3.4. Tapping

Holes requiring threads are tapped by conventional methods using a torque-controlled machine. Hand tapping methods are possible if proper alignment jigs are used to maintain perpendicularity, but torque-controlled machines produce more satisfactory results, especially for thicker materials where the thread depth is much greater.

Stress-relieving a tapped hole in nonwrought materials is done with a thermal treatment in accordance with the schedule shown in Fig. 5. This method has advantages over acid etch techniques in that the thread configuration is not altered. After stress relief, the form, dimensions, tolerances, and contour of thread should conform to MIL-S-7742. The rounded root configuration of Figure III of Federal Screw Thread Standards for Federal Services Handbook H 28, Part I, is mandatory.

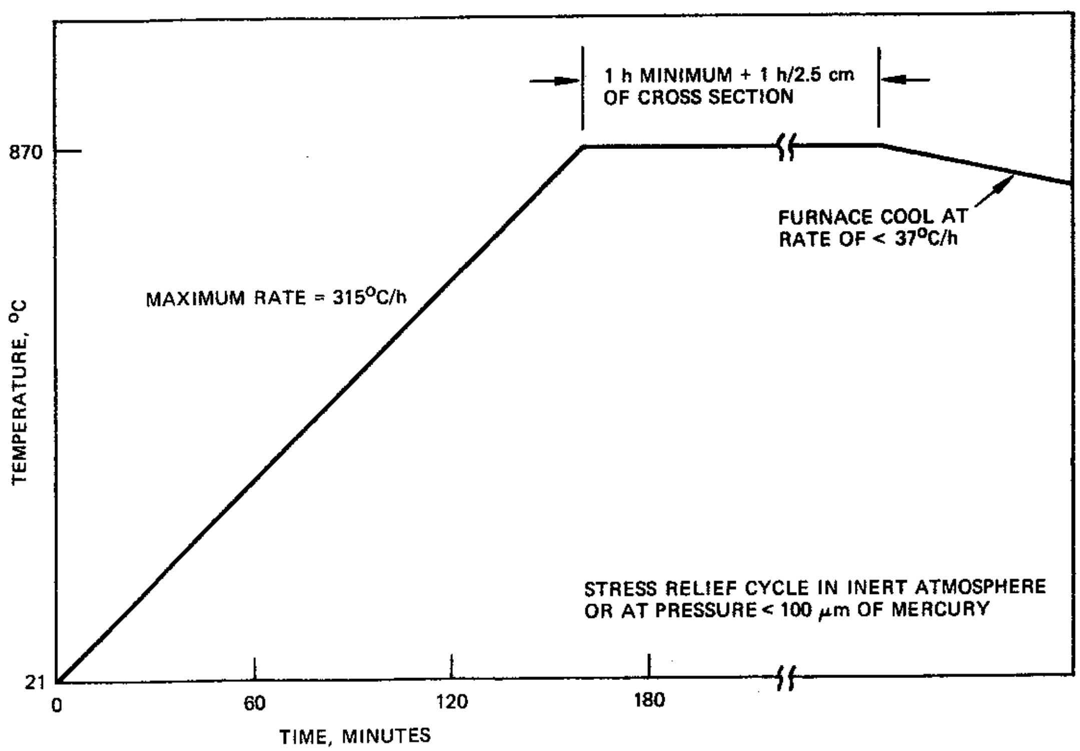

Fig. 5. Stress relief cycle for hot-pressed block.

3.5. Structural Inserts and Nut Plates

To prevent wear, corrosion, stripping, and galling of the beryllium threads, structural inserts are used in tapped holes. The best choice is a helical coil type insert covered by MIL-I-8846. This insert does not require staking into the part for retention and thus avoids the use of impact forces against beryllium after installation. Wherever nut plates are needed, it is advisable to bond the plates to beryllium rather than to attach them with rivets. Among its other advantages, the procedure requires fewer drilled holes than would otherwise be needed.

3.6. Rivets

If rivets are considered for use, squeeze types should be employed wherever possible to avoid the dynamic forces associated with blind and other more conventional types which depend upon impact principles to set the rivet.

Figure 6 shows an antenna mast fabricated from cross-rolled beryllium

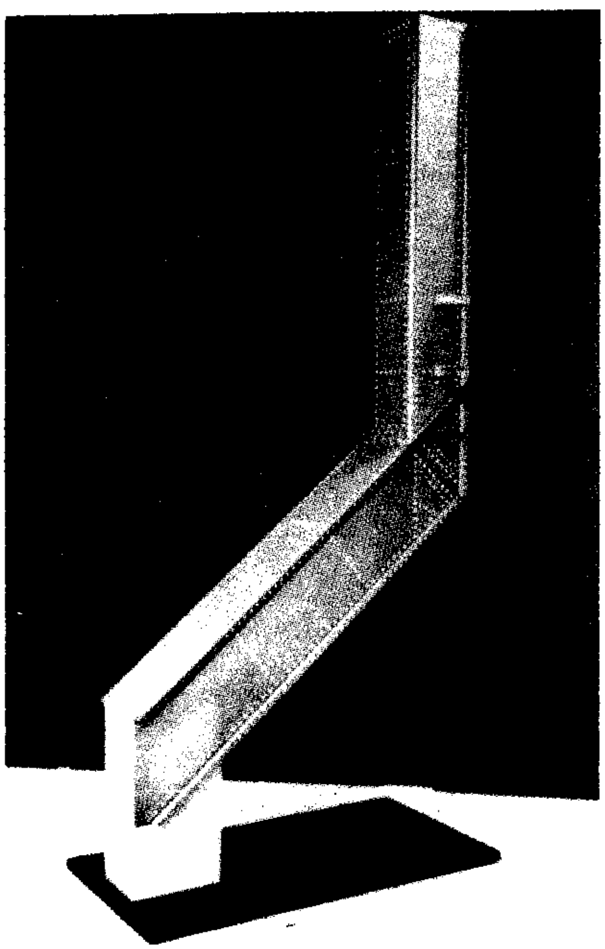

Fig. 6. Beryllium mast assembled with rivets.

sheet. The design utilizes simple manufacturing techniques to minimize the need for developing new processes. It was prepared as an alternate for the aluminum mast shown in Fig. 1 in the event additional stiffness or weight saving was needed. Before the rivets are installed, a shim is introduced between the faying surfaces to fill the gaps and thus avoid local bending stresses that would have occurred as the rivet squeezed the parts together. The shim is liquid epoxy adhesive, and it is cured for a minimum of 16 hr at room temperature before the rivets are installed.

4. JOINTS MADE WITH ADHESIVE

If environmental temperatures allow, adhesives offer many advantages in joining beryllium. Adhesive bonding permits utilization of the excellent combination of physical and mechanical properties of beryllium and minimizes the inherent problems of high notch sensitivity and low ductility.[4]

4.1. Adhesive Choices

Candidate adhesives are numerous, but the best choise is usually a room temperature curing epoxy. This adhesive is a mature, consistent product and should always be the first choice if structural temperature can be controlled between −50 and 120°C at the time maximum load occurs. For earth-orbiting missions, structural temperature extremes are well within these bounds for spin-stabilized satellites.

If temperatures are higher than 120°C, elevated-temperature curing epoxies are available which can extend the useful range to 200°C. However, this improvement in temperature performance does not come without disadvantages—complicated apparatus needed for elevated curing systems can become as sophisticated as the structure itself. Some polyimides now being developed promise to extend useful performance to 320°C, but such adhesive systems are not yet ready to be committed to structural applications and will also be encumbered with the need for curing apparatus.

4.2. Allowable Strength Values

It is not advisable to publish allowable strength values for adhesives used in beryllium structural joints because of the many variations possible in the total process. Some unpublished data exist showing single-lap shear coupons joined with room temperature curing epoxy have consistently demonstrated values averaging 245 kg/cm^2 with a 1σ value of 7 kg/cm^2; such performance demands stringent process controls.

However, allowable values must be developed to validate the design, and the only way to obtain such data is a test program wherein the user produces the data under the same environmental conditions as those under which the joint itself will be assembled.*

4.3. Surface Preparation

Of all the steps involved in producing a good bonded joint, surface preparation of the adherends is the most important. Beryllium is not unique in this respect; all reliable bonding operations demand a clean, dry surface that has been properly prepared.

By proper planning, the bonding surfaces of beryllium can be prepared as an adjunct to the final etch of the part following machining. This is accomplished by coating the entire surface of the part, within 8 hr after the part has been etched to remove local damage, with an epoxy-base paint primer. Such treatment offers two advantages: it gives protection from corrosion and provides a surface that can be stored indefinitely before bonding.

For a primed surface, the only preparation required before bonding is a thorough wipe using either MEK or acetone. No roughing of the surface is needed; the etch process leaves a matte finish on beryllium that seems to be optimum for good adhesive bonding.

Priming is not mandatory for good bonding, but good cleaning of the surface is. If the surface is not primed, it should be thoroughly scrubbed with a cleanser powder that is free from halogens until a water-break free surface is obtained. The part should then be etched to remove 0.003–0.005 mm from the surface, rinsed, dried in an oven, and bonded within 2 hr. The water used for scrubbing and rinsing operations should be deionized to avoid any possibility of corrosive attack from halogens or other chemicals normally found in tap water. Experience indicates that a slightly acidic water having a pH of 2.6–3.2 is optimum for preventing corrosion problems.

4.4. Application and Curing Techniques

Epoxy adhesives are marketed as a two-part system: catalyst and resin. It can either be hand mixed immediately prior to application or can be obtained premixed, and stored at temperatures lower than −40°C until use. Quick-setting epoxies should be avoided, since useful pot life should be a minimum of 1 hr to allow sufficient time to perform all necessary operations during bonding. Also, care should be taken during hand mixing to minimize air entrapment, which will cause voids in the assembled joint. For this

*Suggestions for conducting such a program are given by Cagle,[4] Chapters 31 and 32.

reason, frozen premix is preferred, since it is mixed under vacuum conditions.

As noted above, the surfaces are cleaned immediately before adhesive application with either a solvent wipe (for primed surfaces) or by scrubbing and flash etching (for bare beryllium). Adhesive is applied to both surfaces to be joined using clean, lint-free tools. If a large surface is to be bonded, the adhesive should be put into a clean syringe and then applied with an air-driven dispenser. Frozen premix is packaged in such syringes, making it a convenient form for application.

To minimize adhesive squeeze-out during clamping and curing, spacing beads of 0.05–0.15 mm diameter are used in the adhesive to assure that the parts cannot touch. These beads are usually ceramic and are used in proportions of ½% by weight; this small amount does not reduce the joint strength. After adhesive application the wet surfaces can be worked with a comb-type tool to assure uniform thickness. Care must be taken not to create air bubbles; entrapped air creates voids in bonded structures and weakens the joint. Teflon-backed tape is used to mask the area and serves as a convenient means for removing excessive adhesive before the material cures. To minimize runout after assembly, it is best to let the adhesive gel slightly prior to assembling the wet surfaces. Times for open-face gel should be determined experimentally and then used to control the overall process from mix to joining. When joining the parts, sliding or swiping movements must be avoided to prevent introducing bubbles into the adhesive. If for any reason the parts must be taken apart after touching, the adhesive should be removed and the process restarted.

For room temperature curing systems, 16 hr is a minimum time for keeping the parts in a restrained position before handling. After that, the part can be safely removed from the tool and handled or put into the next assembly. Maximum loads should not be applied until 7 days after application. Epoxies can frequently be cured in an accelerated manner by holding the part at 90°C for 1 hr, following the 16-hr period described earlier. Such process variations should be verified, however, for the particular adhesive system being used.

4.5. Tooling and Assembly Considerations

Using a fixture to restrain the part as the adhesive cures is mandatory. As noted, 16 hr of immobility is a minimum cure time before the part can be handled, and 7 days is required before full strength is developed.

Figure 7 shows a structure made from cross-rolled sheet that supports an equipment platform in a large communication satellite. Many structural joints are involved in this assembly, and except for some local clips, the operation is self-jigging. Alignment pins are used on a master tool to

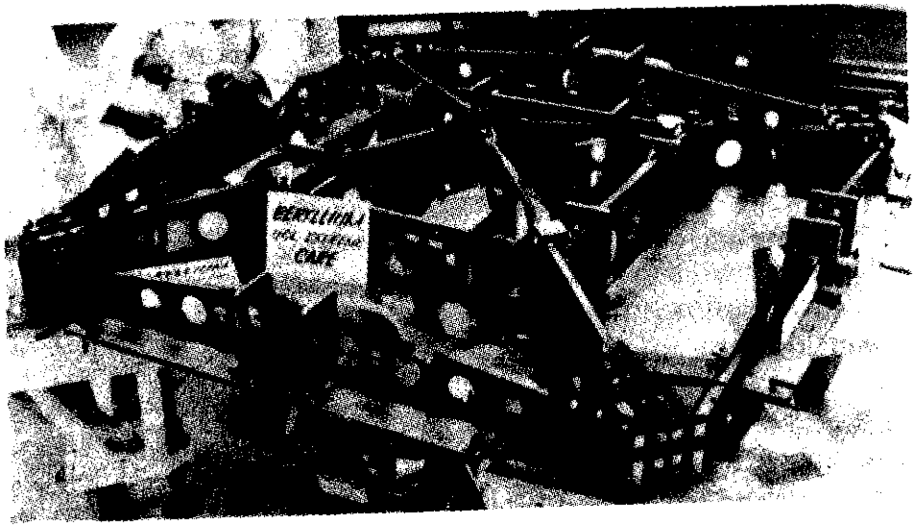

Fig. 7. Beryllium equipment platform support.

establish location of the main beams, and the cross-tie members are held in place with clamping Teflon pins until the adhesive cures. Titanium bolts are put into the holes after 7 days to minimize peel action and are secured in place with titanium nuts, with generous-size washers under both wrenching surfaces.

Another fixture is shown in Fig. 8. A structural cone is being assembled from cross-rolled sheet 0.81 mm thick wherein eight individual panels

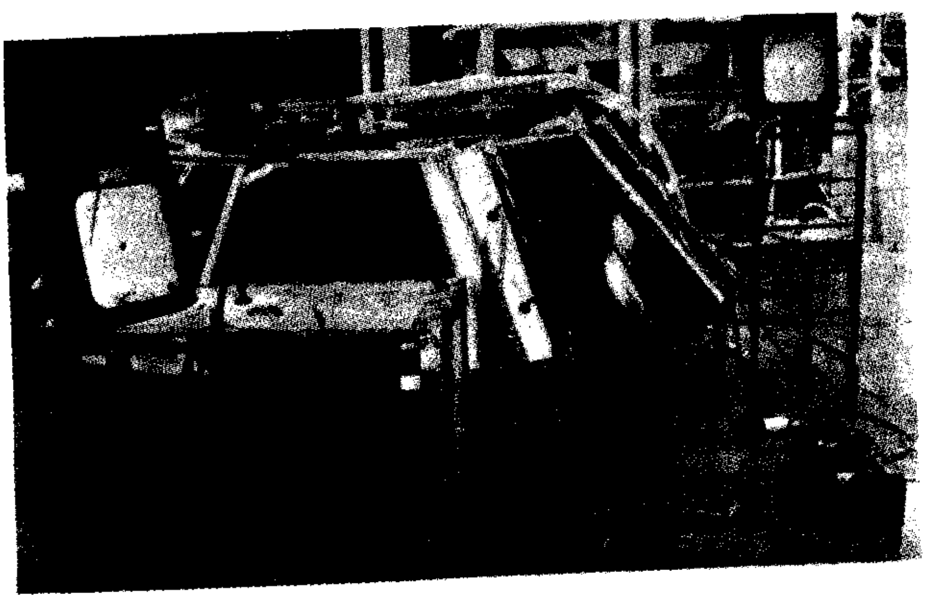

Fig. 8. Assembly of beryllium conical transition structure.

are joined in a contiguous fashion to complete the monocoque structure. This cone serves as the transition structure from a satellite base to a booster of smaller diameter; it carries all the spacecraft primary loads until the satellite is separated from the booster.

Each of the eight panels is joined to its neighboring panel in butt-shear fashion. Since joggled edges are impractical with beryllium, a 10-cm splice plate is bonded over the butt joint inside and outside the cone, and load is transferred in shear. Restraint during adhesive cure is furnished by vacuum bags; note the plastic hoses going from the part being cured to the vacuum pumps, which maintain a pressure differential of approximately 0.7 kg/cm^2 during the 16-hr curing operation.

Still another configuration using beryllium joints in spacecraft is a tubular truss structure (Fig. 9). Design considerations for this assembly center on the tube/socket joint. Materials compatibility is important, and the ratio of socket diameter-to-depth is another critical parameter. As the spacecraft changes attitude during its orbit, temperature extremes on the joint are an important consideration. If the metallic parts are incompatible,

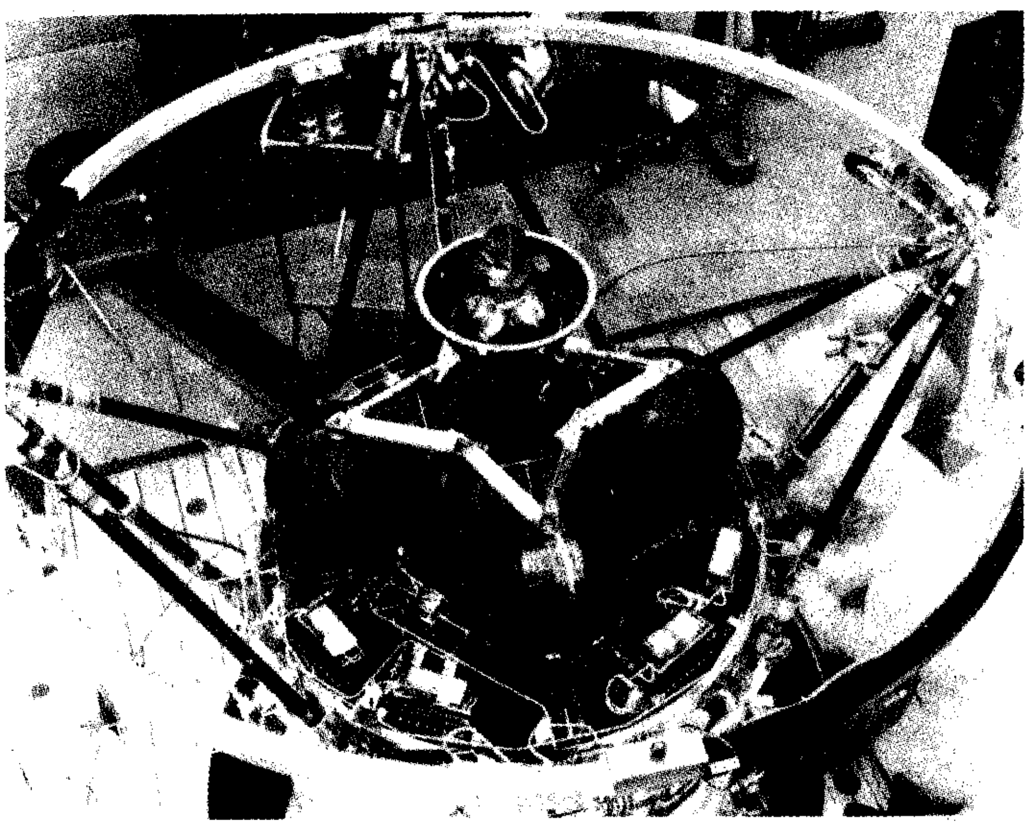

Fig. 9. Spin truss assembly using beryllium tubes.

excessive stresses due to thermal expansion could cause the adhesive to fail. Titanium was eventually selected as the socket material. The ratio of diameter-to-depth was established empirically, and varied from 0.6 for 15-cm-diameter tubes to 1.5 for 2.5-cm tubes. For the truss in Fig. 9, extruded beryllium tubing 5 cm in diameter is used for the struts, and unlike examples described earlier, this structure is completely assembled prior to applying any adhesive. Before the tubes are inserted into the sockets the ends are capped with aluminum disks to prevent adhesive from flowing into the tubes. As the tubes are installed, they are centered in the socket by three Teflon strips having the same thickness as the desired bond line, and the joint is tack-bonded at four points to maintain positioning. The Teflon strips are then removed and the joint is injected with room temperature curing epoxy until it exists from the top of the socket. Adhesive continues to flow until all evidence of bubbles in the runout disappears; in this manner a void-free joint is assured.

5. QUALITY CONTROL

Regardless of whether the joint utilizes mechanical fasteners or adhesives, quality control surveillance is an important part of the overall plan. Because of the neutral role this function serves, quality control personnel are best able to determine that all the engineering and manufacturing requirements are satisfied in preparing beryllium for joining. They must witness the verification after hole preparation to assure that the machining and tapping has not damaged the material. The best assurance that there will be no problem at the final stage is for quality personnel to also maintain discipline in the preparatory steps: drill control, machine settings, and proper etching after drilling.

For adhesive bonding, quality control presence during preparation and application of the adhesive is mandatory. Clear, concise requirements must be prepared by the engineering function to instruct quality personnel which steps of the operation are to be monitored. The most important steps include mixing (or thawing) of the adhesive, application thickness and surface wetting, and open-face time prior to joining the parts. In addition, witness samples as shown in Fig. 10 should be bonded at the same time as the production part. These coupons are beryllium tiles $2.5 \times 10 \times 0.15$ cm with a 2.5-cm overlap, and are subsequently tested to failure to demonstrate quantitatively that the process is properly followed. All materials should be subject to the same exposure as the production parts (e.g., priming, cleaning, storage, etc.). Minimum values are established as a requirement that the witness samples must exceed; if they fail to meet this minimum, the part should be disassembled and the process repeated.

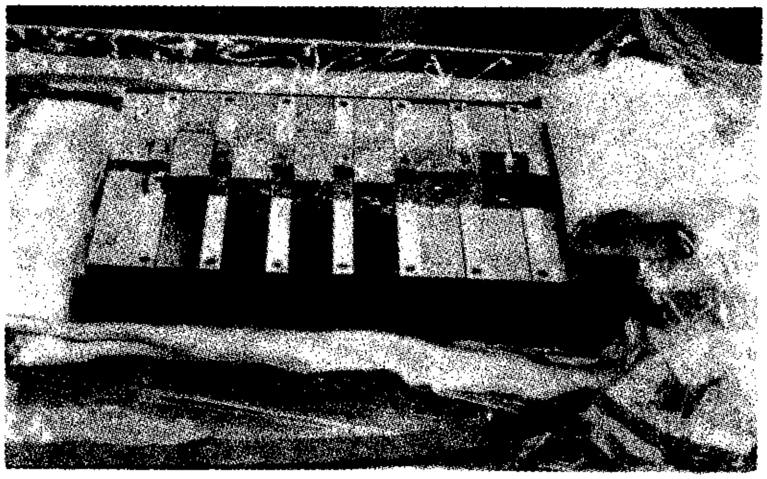

Fig. 10. Witness samples prepared during bonding operations.

After final cure, joints should be examined for evidence of voids caused by adhesive runout. If any are found that exceed the allowance specified on the drawing, the repair action described below must be initiated.

6. REPAIR TECHNIQUES AND PROOF TESTING

6.1. Hole Repair

If the beryllium is found to be cracked after drilling, the area can possibly be repaired by drilling a hole approximately 1.5 mm in diameter at the end of the crack and bonding a structural doubler over the damaged area to redistribute the load. For holes that are delaminated, the damage should be removed with an abrasive tool such as a fine-grit carborundum stone, or rubber tools impregnated with abrasive particles. This work is tedious, and should be done with deionized water to minimize any chance for beryllium particles to be liberated into the atmosphere. Following the repair, dye penetrant methods should be used to demonstrate a satisfactory hole.

6.2. Bonded Joint Repair

For bonded joints, the most common fault that might require repair is excessive voids in the bondline after curing. Two methods are available to repair the problem: either fill the void with additional adhesive, or disassemble the joint and do it again. Filling large voids does not, in many instances, produce a convincing fix, and the joint must be disassembled by subjecting the part to 350°C for 1 hr to crystallize the adhesive. The structure can then be taken apart, cleaned, and rebonded. This elevated-temperature exposure has no deleterious effect on beryllium. If, however, the void can be well defined by visual or X-ray techniques, then more adhesive can be applied to fill the voids.

6.3. Proof Testing

In addition to testing witness samples, proof tests should always be conducted on assemblies with bonded joints to the extent of applying limit load. The specification for adhesive bonding for aerospace systems, MIL-A-83377 (USAF) also makes this point strongly. Structures that are assembled with adhesives are totally dependent on process controls for satisfactory results, and without proper controls adhesives can be very unforgiving. In spacecraft work the last opportunity to demonstrate the joint is with proof tests; skipping this step can have disastrous consequences.

7. SUMMARY

Beryllium structures are very expensive, and efficient design practices must be used to develop the full potential of the material. Either mechanical or adhesive ties can be used to make structural joints, but for those designs that do not require disassembly, adhesive systems offer the most efficient means for joining. Further, room temperature curing adhesives are far less costly to implement than elevated curing systems.

Whichever method is used, process control is the most important factor in achieving acceptable results. Although design details must be tailored to the product, rigid adherence to established manufacturing processes is the key. Quality control personnel serve a vital function in enforcing discipline in this area.

Beryllium is not a forgiving material; however, it has no equal in efficient structural design, where minimum weight and maximum stiffness are important parameters. Experience has shown that where the time and money required to understand the product are invested, highly efficient structures which exceed the weight efficiency of any other design can be consistently produced.

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