Dr-96

RFP-2299
April 20, 1976

RFP-2299
April 20, 1976

MASTER

THE DEVELOPMENT OF
ALL-BERYLLIUM RIVETED STRUCTURES

Dennis R. Floyd

William W. Leslie

Delmar V. Miley

Ronald W. Nokes

GENERAL FABRICATION

Rockwell International

Atomics International Division
Rocky Flats Plant
P.O. Box 464
Golden, Colorado 80401

U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
CONTRACT E(29-2)-3533

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LEGAL NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from the
National Technical Information Service
U. S. Department of Commerce
Springfield, Virginia 22161
Price: Printed Copy \$4.00 Microfiche \$2.25

Printed
April 20, 1976

RFP-2299
UC-25 MATERIALS
TID-4500-R64

THE DEVELOPMENT OF ALL-BERYLLIUM RIVETED STRUCTURES

Dennis R. Floyd

William W. Leslie

Delmar V. Miley

Ronald W. Nokes

GENERAL FABRICATION

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

SUBJECT DESCRIPTORS

Beryllium
Fastening

ROCKWELL INTERNATIONAL
ATOMICS INTERNATIONAL DIVISION
ROCKY FLATS PLANT
P.O. BOX 464
GOLDEN, COLORADO 80401

Prepared under Contract E(29-2)-3533
for the
Albuquerque Operations Office
U. S. Energy Research and Development Administration

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED ^{EB}

CONTENTS

Abstract	1
Conclusions	1
Introduction	2
Fabrication Techniques	2
Sheet Metal	2
Rivets	3
Assembly	3
Mechanical Testing	5
Sheet	5
Rivets	6
Joints	7
Discussion	9
Strength Requirements	10
Dimensional Control	11
Cost Comparison	11
References	12
Illustrations	13
Figures 1 through 33	

ACKNOWLEDGMENTS

The authors express their appreciation to the following R&D machinists for their valuable contributions:

- W. O. Spencer, for developing the home-made riveting fixture and machining conical structures.
- J. E. Vollendorf, for developing the machine-countersunk joint that was used.
- B. L. Duesterbeck, for outstanding machining work on fixtures, rivets, test coupons, and structure.
- R. F. Biella, for directing and contributing to the machining effort.

Special appreciation is given to G. G. Gauger who performed all of the mechanical testing. Much of Gauger's efforts involved testing that had not been previously done at Rocky Flats. Excellent metallographic support was provided by J. F. Capeo, L. Stadtman, F. Luben, and R. Rhoads.

Early development of the resistance riveting procedures was ably done by R.T. Kettl, R&D Welding. Our appreciation is also extended to W. B. Sample and R. H. Karlsson who discovered the need for this work and who encouraged its development.

Many useful suggestions were also provided by the project sponsors, Donald Adolphson and Morris Mote at Sandia Livermore Laboratory and by B. G. Prentice at Sandia, Albuquerque. Their interest throughout the project and their many helpful contributions are sincerely appreciated.

THE DEVELOPMENT OF ALL-BERYLLIUM RIVETED STRUCTURES

Dennis R. Floyd, William W. Leslie, Delmar V. Miley, and Ronald W. Nokes

Abstract. Results are presented of a development program aimed at making a full-scale, all-beryllium frustrum by riveted assembly methods. Included are descriptions of the sheet-metal fabrication practices and assembly plans. Results of extensive mechanical testing of both ingot- and powder-source beryllium products that are presented include tensile, notch-tensile, bearing, and shear tests.

Although the full-size structure has not been built, examples are given of several conical and cylindrical structures that were made. The largest of these is a 20-in. diameter, 15-in. long cylinder that was roll-formed from one 0.050-in. thick ingot sheet and assembled with 60 countersunk rivets. Tensile testing of riveted flat coupons is also reported as is bulge testing of riveted cylindrical shells.

A cost comparison of riveted deep-drawn and powder-source cylinders is made. In sum, the results show that when strength and dimensional tolerance requirements are not severe, a riveted assembly approach is warranted.

CONCLUSIONS

1. When requirements for strength and dimensional control are relatively loose, riveting is a good means of building low-cost, all-beryllium structures.
2. Cylindrical structures as large as 20 in. in diameter and conical structures up to 10 in. long have been made by roll-forming or die-forming followed by riveted assembly.
3. Beryllium rivets can be headed in a reproducible procedure using a converted resistance-welding machine.
4. Introducing rivet holes into ingot-source beryllium reduces the fracture strength by 40% and lowers the ductility at fracture from 5 to 1%.
5. The strength of ingot-source beryllium sheet in bearing is about twice the sheet's tensile strength. For example, sheet having tensile fracture strength of 50,000 psi fails at 110,000 psi in bearing. This same material has a tensile yield of 26,000 psi and a bearing yield of 60,000 psi.
6. The fracture strength in shear of ingot-source, powder-source, and extruded, powder-source rivet materials is 27,000, 37,000, and 64,000 psi, respectively.
7. The fracture of riveted joints comprised of 0.125-in. diameter, countersunk, powder-source rivets and 0.050-in. thick ingot sheet is limited by the strength of the sheet.
8. The fracture load of riveted coupons is only 70% of the load that would be predicted from uniaxial test data. The presence of a bending moment due to the test coupon design is the reason for the lower strength.
9. A method of bulge-testing riveted cylinders was devised. The test allows uniform distribution of stress along a line of five rivets. Failure strength of riveted cylinders ranged from 40 to 80% of the values predicted from tests of riveted flat coupons.
10. The per-part cost for riveted construction can be as little as 23% of the cost for alternate fabrication methods. Actual cost depends upon the geometry.

INTRODUCTION

Fabrication of large beryllium components normally has been done by powder-metallurgy (PM) techniques. In many cases, PM is required because of thick sections in the desired parts. Sheet-metal fabrication works best for parts having a uniform wall thickness. In other cases (long hollow shapes for example), PM is used because the size is too large for one-piece construction by sheet-metal methods. And in those cases where multiple-piece construction is acceptable, the joining techniques may be unacceptable. For example, adhesive bonding limits the temperature and environment that the component can tolerate. Another example is brazing or braze-welding, which requires heating that is not always acceptable, introduces a dissimilar metal, and also limits the operating temperature range. Threaded connections cause stress concentrations and creates problems with removal of machining damage.

Fabrication by riveting, using beryllium rivets, is proposed as a more desirable alternative for multiple-piece construction. The process involves efficient use of material because this method allows the use of sheet that is rolled and etched to the desired gauge. No dissimilar metal is introduced if beryllium rivets are employed. Stress concentrations at the rivet hole are introduced, but machining damage can be accommodated by either chemical milling or heat-treating of piece parts. Another means of avoiding machining damage is the use of electro-chemical hole-drilling methods. Perhaps the most desirable attribute of riveted assembly is the possibility of repairing part of the structure if it becomes damaged. If a crack developed from drilling a hole, the damaged panel can be replaced. If a hole develops in a one-piece hollow body, a whole new piece is required. The biggest potential advantage of all-beryllium riveted structures is cost savings.

Interest at Rocky Flats in this subject stems from the need to build a conical substructure such as the frustrum shown in Figure 1. The anticipated loading was not excessive, and dimensional tolerances were not prohibitive. In fact, similar substructures made by riveting aluminum prompted the suggestion of making one by riveting beryllium.

This report describes the efforts aimed at making a beryllium substructure. The information concerns

methods of making beryllium rivets, of sheet-metal fabrication, and of rivet-assembly techniques. Also included is a mechanical testing section that covers the strength of the rivets, the sheet, and the assembly. And finally, the report concludes with an analysis of the cost of riveted structures and of the limitations to their use.

FABRICATION TECHNIQUES

Sheet Metal

The process used to make beryllium sheet at Rocky Flats has been described previously.^{1,2} It is an ingot-sheet process, which means cast ingots are converted into sheet by conventional hot-rolling methods. Typically a 9 by 9 by 20-in. ingot is sliced into rolling billets measuring 8.5 by 8.5 by 3.5 inch. Prior to rolling, the billets are clad with Type 304 stainless steel because the as-cast grains are large and therefore weak, and because beryllium oxidizes in the temperature range employed for hot working. Rolling commences at 1040 °C and finishes at 760 °C after 21 passes that reduce the beryllium from 3.5 to 0.210 in. thick. At this gauge, the beryllium has become fine-grained and can therefore be further reduced in thickness by rolling at 700 °C without the cladding.

For the present application, most of the sheet was rolled to a thickness of 0.065 in. and chemically milled to 0.060 in. to remove surface contaminants. After the final rolling pass, the sheet was annealed for nine hours at 760 °C to promote maximum ductility at room temperature. This heat treatment reduces the yield strength, but a high yield strength is not required in this case. Lower-temperature heat treatments can be used to retain a higher yield strength if desired.³ The reproducibility of yield strength in material made by this process is excellent. (see Table 1.)

The desired shape can be made by either roll-forming or die-forming. Both methods were used at Rocky Flats, and both cylindrical and conical shapes were made for test purposes. Roll-forming usually is done hot, using a three-roll machine such as the manual model shown in Figure 2 or the power-driven Berstch machine shown in Figure 3. Cylinders have been

TABLE 1. Reproducibility of ingot-sheet beryllium. Two bars were tested from each of 65 sheets to obtain this data.

	Mean Value	Standard Deviation
Transverse		
Ultimate Tensile Strength (ksi)	42.7	1.3
Yield Strength (ksi)	25.5	0.7
Elongation (%)	5.0	0.5
Longitudinal		
Ultimate Tensile Strength (ksi)	49.1	1.8
Yield Strength (ksi)	25.7	0.6
Elongation (%)	6.1	0.8

roll-formed to tolerances of ± 0.125 in. on the diameter. Sizing subsequent to roll-forming can be used to improve this value to ± 0.010 inch. Typical roll-formed parts are shown in Figure 4.

Better dimensional control is obtained by die-forming than by roll-forming. Tooling used to make one portion of the conical frustrum is shown in Figure 5. The tooling is preheated to about 250°C and the blanks to about 760°C prior to forming. The punch and die-cavity are canted at an angle to the horizontal, which is the same as the half angle of the cone; thus, when the punch contacts the blank, it does so along a line that is coincident with the centerline of the blank. This prevents tipping of the blank. Tipping would occur if both punch and die-cavity were horizontal so that initial contact would occur at a point on the centerline at the large end of the blank.

Tooling used to form a cylindrical test section is shown in Figure 6. This tool was made by slitting a thick-wall mild-steel pipe and machining the desired contour. Parts that were round within ± 0.002 inch were made with this tool.

Rivets

Countersunk rivets were used because the outer contour of the conical substructure must be smooth. A standard 0.125-in. countersunk rivet design was selected and used for most of the work.⁴ Both ingot-sheet and powder-source beryllium were used for

the rivets. The rivets were manufactured by one of the following processes:

1. machining of 0.325-in. thick ingot sheet
2. machining of cold isostatically pressed and hot isostatically pressed (CIP/HIP) Type P-1 powder-source beryllium*
3. hot forging of either ingot-sheet or CIP/HIP material using the tool shown in Figure 7.

With the split die arrangement (Figure 7), six rivets could be made every three minutes. These rivets were made using 0.125-in. diameter rod that had been cut to the desired length from either ingot-sheet or extruded CIP/HIP material. An automated process involving cutting and heading on a mechanical press using a similar split die could evolve rather easily from this process.

Assembly

Beryllium presents some unusual problems for assembly. Holes must be well located because one cannot depend upon localized plastic flow to redistribute stress. Furthermore, conventional drilling requires subsequent chemical milling to remove machining damage. During chemical milling, a countersunk hole increases in size in a nonuniform manner (Figure 8). Allowance for such changes must be provided for in the drill tools, and the necessity of chemical milling means that all holes must be drilled prior to assembly so that piece parts can be etched. For conical structures, the hole pattern in the main structure will not match the hole pattern in the backing plate after chemical milling, as shown in Figure 9.

The drawing in Figure 10 depicts the two basic types of rivet seams: longitudinal and hoop. The longitudinal seams are used to make the conical subassemblies. The hoop seam in the center is used to join the subassemblies, and the hoop seams at the ends are used to stiffen the structure. Close examination of Figure 10 reveals there are 11 individual pieces that

*This designation is from the supplier, Kawecki Beryllco Industries, and refers to an electrolyte flake source of relatively high-purity beryllium.

must be assembled into one structure by riveting. These pieces are: four conical shell sections (2, 5, 7, and 10),* four longitudinal backing strips (3, 4, 8, and 9), and three ring sections (1, 6, and 11).

To eliminate machining damage and mismatches, the following machining and assembly sequence was developed for the structures shown in Figure 10:

1. Drill countersunk holes in the four shell sections for both the hoop seams and longitudinal seams.
2. Chemically mill 0.010 in. from the thickness of the four shell sections.
3. Locate the positions of the through holes in the smallest ring (1)* by using the two smaller shell sections (2, 5) as templates.
4. Drill the through holes in the smallest ring.
5. Vacuum heat-treat the smallest ring to remove machining damage; take precautions to avoid warpage.
6. Rivet the shells (2, 5) to the smallest ring (1).
7. Locate the positions of the through holes in two of the back-up strips (3, 4) by using the two smaller shells (2, 5) as templates.
8. Drill the through holes in the two back-up strips.
9. Chemically mill the two back-up strips, removing 0.010 in. from the thickness.
10. Rivet the back-up strips (3, 4) to the shells (2, 5) beginning at the small diameter end and working to the large diameter end by moving back and forth from one longitudinal seam to the other.
11. Locate the positions of the through holes in the center ring (6) by using the riveted sub-assembly as a template on one side and the two larger shells (7, 10) as templates on the other side of the ring.
12. Heat-treat the center ring as in Step 5.
13. Rivet the center ring (6) to the riveted sub-assembly using clicoes* to maintain alignment while riveting. This step follows a pattern similar to tightening nuts on an automobile wheel when changing a flat tire.
14. Rivet the two larger shells (7, 10) to the center ring as in Step 6.
15. Repeat Steps 7, 8, 9, and 10 for the remaining two back-up strips (8, 9).
16. Repeat Steps 11, 12, and 13 for the largest ring (11).

This assembly sequence accommodates the machining damage problem associated with hole drilling while avoiding the positioning problem depicted in Figure 9. It has been determined that the reduction in ductility that accompanies machining damage can be eliminated by heat treating.⁵ Proper control during the heat-treatment will also prevent significant warpage.

Three devices have been employed for riveting. The manual riveting tool shown in Figure 11 has a shallow throat depth; consequently, it is used for rivet locations near the edge of the workpiece. For work further inside hollow parts, the homemade device shown in Figure 12 is employed. In both cases, the end of the rivet is heated with a small torch until the rivet tip turns red. At this point, the rivet head is upset. A cross section of a typical riveted joint is presented in Figure 13a. The polarized light views in Figures 13b and 13c reveal the considerable deformation that occurs in the upset head.

The resistance spot welder shown in Figure 14 has been adapted for heading beryllium rivets. An automatic cycle is used to pass direct current through the rivet to heat the tip by a predetermined amount and then to upset the heat with a hydraulically actuated punch. This process is preferred over the manual approach because of its reproducibility and speed. It also is flexible in that the edge and center rivets can be driven using the same setup. Figure 15 shows a cross section of a typical resistance-riveted joint (after testing).

*Numbers refer to the parts shown in Figure 10.

*Spring-loaded locating pins shown in Figure 14.

TABLE 2. Tensile properties of beryllium sheet used in the riveting program. Data result from specimens taken in the direction transverse to the last rolling pass. At least three specimens were tested for each data point given. The strength of notched specimens is the mean stress away from the hole at the time of yield or fracture.

Specimen Type	Surface Preparation	Material Source	Tensile Properties		
			Ultimate (ksi)	Yield (ksi)	Elongation (%)
Standard	Etched	Ingot	49.6	26.4	7.2
Standard	Etched	Powder	65.5	69.3/65.1 ^a	1.4
Notched-Through Hole	Etched	Ingot	30.4	25.5	0.75
Notched-Through Hole	Etched	Powder	56.7	49.3/49.1	0.80
Notched-Through Hole	Heat-treated ^b	Ingot	30.9	25.3	0.80
Notched-Through Hole	ECM ^c	Ingot	33.2	27.6	2.30
Notched-Through Hole	ECM	Powder	54.0	52.5	1.10
Notched-Through Hole	As-machined	Ingot	23.4	—	<0.2 ^d
Notched CS ^e Hole	Etched	Ingot	26.8	22.8	0.5
Notched CS Hole	Etched	Powder	43.2	41.3/41.2	<0.2
Notched CS Hole	Heat-treated ^b	Ingot	25.3	22.5	0.4
Notched CS Hole	ECM	Ingot	28.0	26.3	1.4
Notched CS Hole	ECM	Powder	42.9	—	<0.2 ^f
Notched CS Hole	As-machined	Ingot	17.7	—	<0.1 ^g

a. An upper/lower yield is reported because of a yield point occurrence.

b. Heat treatment: 760 °C for 1 hour in vacuum, furnace cool.

c. Electrochemically machined.

d. Failed before yield. Some fractures were away from the hole.

e. Countersunk hole.

f. One bar only. Others failed prematurely.

g. Failed before yield, all fractures were through the CS hole.

MECHANICAL TESTING

The adage that a chain is only as strong as its weakest link certainly applies to a riveted structure. Failure can initiate in the sheet as the result of bearing, bending, or notched tension, or it can begin by the rivets being sheared. In this section, the strength of the sheet and of the rivets is examined independently. Examined next is the strength of joints comprising these two elements of a riveted structure—both in coupons and in parts.

Sheet

Tensile tests were conducted with both ingot-sheet and powder-source beryllium sheet using the test bar designs given in Figure 16. The powder sheet

was taken from a nominally 2-ft by 5-ft by 0.0625-in. sheet. This type sheet typically is made by can-rolling powder block followed by surface grinding and pickling.

The results of testing notched and unnotched sheet are presented in Table 2. In the unnotched condition, the ingot sheet has a much lower yield than powder sheet. This lower yield strength could be an attribute by permitting redistribution of localized stresses around a riveted joint before the stress gets too great. Note from Table 2 that the powder sheet exhibited a pronounced yield drop, and the ultimate strength was actually lower than the upper yield strength. As a result, fracture may precede significant plastic flow in the powder sheet.

It is evident from Table 2 that the presence of a hole reduces the ultimate strength significantly.

Some improvement is obtained if machining damage is removed by either heat-treating or etching, but the fracture strength is still almost halved by introducing the hole. Electrochemical machining (ECM) is seen to effectively eliminate machining damage. In fact, the best notched-tensile ductility was obtained with ECM bars for both ingot-source and powder sheets.

The presence of the hole is not as deleterious in powder sheet as it is in ingot sheet. In both cases, the larger countersunk hole lowers the strength and ductility more so than does the cylindrical hole. Presumably this results from the larger size of the countersunk hole.

The significance of machining damage is evident from two facts gleaned from Table 2. First some test bars failed away from the drilled hole. This means that the combined effect of machining damage and stress concentration near the hole is worse than the maximum stress concentration at the edge of a hole in plate.⁶ Secondly, avoiding or eliminating machining damage increased the ultimate tensile strength in every case.

The bearing strength of ingot and powder sheet also has been measured. The bearing test coupon, shown in Figure 17, was designed in accordance with ASTM requirements.⁷ The test is conducted in a manner that allows measurement of hole deformation during testing. This deformation can in turn be used to establish a bearing yield stress, as indicated in Table 3. The reproducibility of bearing yield data for ingot-source beryllium is good as is evident in Table 3. The bearing yield of the powder-source beryllium, however, varied considerably. This variation was possibly due to the yield point effect mentioned above.

The interest in bearing strength for riveted structures arises because failure of a structure could occur as a result of bearing stresses transmitted by the rivets. An extension of this concern is that the rivet hole might be so close to the edge of the sheet that failure would occur by a tearing-out through the end of the hole. For this reason, a series of tests was made wherein the hole gradually was positioned closer to the end of the sheet. The effect observed is shown in Figure 18. Both

TABLE 3. Results of bearing tests of beryllium sheet used in the riveting program. All bars were taken transverse to the last rolling direction. Stress values were obtained by dividing the product of the pin diameter and sheet thickness into the applied load.

Material	Ultimate (ksi)	Yield* (ksi)	Hole Deformation At Fracture (in.)
Ingot	104.5	58.4	0.022
Ingot	114.3	59.6	0.027
Ingot	107.4	59.9	0.023
Ingot	110.2	59.3	0.023
Powder	161.7	113.1	0.025
Powder	147.6	—	—
Powder	130.1	109.1	0.010

*Taken at 2% deformation of the pin hole.

the ingot and powder sheet exhibited a linear decrease in fracture strength as the hole location was placed nearer the end of the sheet in increments of 0.03125 (1/32) inch.

Rivets

There is concern about the strength and ductility of the rivet material as related to the heading operation. Strength is important if manual squeezing methods are used. Ductility is important to avoid cracking during heading. To measure these two parameters as a function of temperature, the fixture shown in Figure 19 was devised to simulate riveting conditions within an Instron testing machine. The furnace enabled the heating of rivets to within $\pm 10^\circ\text{F}$ of the desired temperature prior to heading. Heading was done at a strain rate of about 4 in./in./min using powder-source (KBI Type P-1, CIP/HIP product) and ingot-source rivet stock. The height reduction of the rivet head was varied to promote different degrees of cracking.

Results of the rivet heading tests are presented in Figure 20. In general, ingot- and powder-source beryllium performed equally in these tests, and the

TABLE 4. Double shear strength of beryllium rivet material. HP-1 refers to powder-source beryllium derived from electrolytic flake. Test conditions are those defined in Figure 22. Data are averages of at least three tests.

Material	Test Condition	Shear Stress At Failure (ksi)	Fracture Type
Ingot	Rivet Head	20.5	Heads sheared off
HP-1	Rivet Head	27.3	Heads sheared off
Extruded HP-1	Rivet Head	38.5	Heads sheared off
Ingot	Rivet Shank	34.3	Both sides sheared
HP-1	Rivet Shank	37.3	One side sheared
Extruded HP-1	Rivet Shank	64.0	Both sides sheared
Ingot	Headed Rivet	24.7	Head sheared off
HP-1	Headed Rivet	31.6	Head sheared off
Extruded HP-1	Headed Rivet	41.4	Head sheared off

boundary line drawn in Figure 20 applies to either material. Cracking during riveting can be avoided by using conditions below and to the right of this line.

The shear strength of the rivet must be known to predict allowable service loading conditions. To identify this strength, a testing fixture was developed that used hardened steel to simulate a riveted joint. Testing was done using the conditions shown in Figure 21. Tested were the rivet head, rivet shank, and headed rivet. Results are presented in Table 4. The ultimate shear stress is calculated by dividing the load at fracture by twice the cross-sectional area of the rivet shank. Shear strength is best with the extruded Type P-1 beryllium. Placing the countersunk head in shear decreases the strength by 25% compared to the case where just the rivet shank is subjected to shear. Heading the rivet does not alter the shear strength, as failure occurs at the head and shank intersection.

Joints

Initial testing of riveted joints was intended to answer questions about various ways to make the joint. For example, to produce a flush outer

surface, the sheet can either be dimpled or drilled to accept countersunk rivets. Dimpling avoids machining damage but must be done hot and thus compounds assembly problems. It was therefore decided to dimple some flat coupons and machine-countersink others (Figure 22). In some cases, the doubler was machine-countersunk; in others it was dimpled. During these feasibility tests, failure usually occurred between 700 and 800 pounds of applied axial force. Sometimes the countersunk rivet head failed; sometimes the sheet failed, and other times it was the doubler. It was concluded that joints with machine-countersunk rivet holes were at least as strong as those with dimpled rivet holes; consequently, the sheet-dimpling approach was abandoned.

Another early question was the effect of rivet-hole spacing and edge distance on joint strength. This question is discussed in a similar paper by Van Hamersveld.⁸ Data scatter caused by failures in the rivets rather than in the sheet prevented a firm conclusion. It appeared, however, that little strength difference existed between spacings of either five or six rivet diameters. Edge distance of three to three and one-half rivet diameters also had little influence on failure load.

The effect of heading pressure on joint strength was another early concern. Since heading of the rivets was done using a Tinius-Olson testing machine, it was easy to record the force used to accomplish the rivet heading. It was noted that the joint strength increased as the heading force increased between 600 and 3000 pounds. Beyond 3000 pounds of heading force, no increase was noted. Figure 23 compares the rivet heads resulting from two extremes in heading force.

An examination of the type of beryllium, ingot-source or powder-source, to use for the rivets and for the sheet was also undertaken. Flat coupons, as shown in Figure 22, were used. The weakest combination occurred when both the rivets and the sheet were made from ingot-source beryllium (575-pound failure load). The strongest combination was obtained using powder-source rivets and sheet (920-pound failure load). Ingot-sheet riveted with powder rivets was a close second (905-pound failure load). Normally the rivet failed first, with the

failure always occurring at the blend point between the countersunk head and the shank. Occasionally the sheet would fail through the rivet holes before failure occurred in the rivets.

Figure 24 shows the effect of the bending moment that accompanies the loading of flat coupons. As the load is transmitted through the rivet line into the doubler plate, a moment is set up that tends to bend the sheet and tear the rivet head off. As shown in Figure 25, the tensile stress in the sheet is not due merely to the applied force but is also a result of the bending moment. Similarly, the rivet does not experience simple shear but a complex combination of shear tension (from the head trying to pull off) and residual tension (from the riveting operation).

A series of nine coupons of the type shown in Figure 22 was riveted by the resistance welding machine. This was done to study the effect of weld current and upset load on joint strength. The results are presented in Table 5. Failure loads were all in the 800- to 950-pound range. For every coupon except No. 5, failure occurred both in the sheet and in one or more of the rivets. Only the sheet failed in coupon No. 5. Figure 26 shows the fractures in Coupons 7-10. A closer view of Coupon 10 is given in Figure 27 to illustrate the crack pattern extending between the holes and to show how both the countersunk heads and the upset heads sheared off in many coupons.

According to data in Table 5, reduction in the height of the rivet head does not depend upon applied load in the 1250- to 1650-pound range, but the reduction is slightly lower at 800 pounds of load. Reduction does appear to depend upon the weld setting. Reduction increases with an increased weld setting. Regardless of the amount of reduction, all upset rivet heads were cracked as shown in Figure 28.

Data in Table 5 also indicate that lighter-applied loads and higher weld settings will promote higher joint strength. Best strength should result from a load in the 800- to 1250-pound range and a weld setting between 66 and 76%.

Most of the initial testing of riveted joints in flat coupons was done to select design parameters.

TABLE 5. Results of riveting with a converted resistance welder. Each coupon had four rivets, all of which were headed with the parameters indicated.

Coupon Number	Applied Load (lb)	Weld Setting (%)	Rivet Head Reduction ^a (%)	Joint Failure Load (lb)
1	1650	66	54	843
2	1550	66	54	842
3	1400	66	52	837
4	1250	66	54	937
5	800	66	48	905
6	800	46	(55)?	800
7/8	800	36/56	36/54	800
9	800	76	52	947
10	800	80	50	915

a. $\%R = (H-h)/H \times 100$, where $\%R$ = percent reduction, H = rivet shank height before heading, and h = the rivet height after heading.

Once these parameters were established, a series of six coupons were made and tested using conditions as nearly identical as possible. Countersunk holes in the sheet and through-holes in the doubler plates were drilled and then chemically milled to remove machining damage. Powder-source rivets (Type HP-1) were headed by resistance riveting using 1000-pound applied load and 70% weld setting. Ingot-source sheet and doubler plates were used. The failure loads for these six tests ranged from 900 to 975 pounds with a mean of 950 pounds and a standard deviation of 25 pounds. Failure of the sheet and rivets was observed in this range.

Having tested flat coupons, it remained to test cylindrical structures. A test devised for this purpose consisted of bulging open-ended cylinders such as that shown in Figure 29. The internal pressure was promoted by applying an axial force to a plug of Room Temperature Vulcanizing (RTV) rubber that had been cast within the cylinder. The test setup is shown in Figure 30. Calibration of the test setup was accomplished by first testing a one-piece cylinder section that had been machined from a deep-drawn part and had been drilled with countersunk holes to simulate the stress-risers present in a riveted structure.

TABLE 6. Data resulting from internal bulging of a one-piece beryllium cylinder. The mean stress is calculated from the equilibrium of force condition and is measured using strain gauges. The peak stress is obtained from strain gauges attached near the countersunk holes drilled into the cylindrical shell. The stress concentration factor is computed as the ratio of the measured mean stress to the peak stress.

Applied Load (lb)	Mean Stress		Peak Stress (psi)	Stress Concentration Factor
	Calculated (psi)	Measured (psi)		
2000	4,800	4,900	17,500	2.85
3000	7,300	8,800	19,200	2.18
4000	9,700	12,600	21,600	1.71
5000	12,100	16,100	24,300	1.51
6000	14,500	19,100	26,800	1.40
7000	17,000	21,400	29,000	1.35
8000	19,400	23,500	31,100	1.32
9000	21,800	25,400	33,000	1.30
8650*	23,400	26,300	34,100	1.30

*Failure occurred at this load.

One of these one-piece test cylinders is shown, after testing, in Figure 31. Also evident in the figure are some of the 29 strain gauges that were attached to the one-piece test part. These gauges measured the uniformity of strain around the cylinder and also the stress concentration near the holes. A detailed report of this test has been written.⁹ The major conclusion was that the rubber-plug loading mechanism did distribute stress uniformly around the cylinder. Strain values at corresponding locations around the test piece usually agreed within 2% and never departed by more than 14% as the stress was increased. Failure eventually occurred through a line of holes as a result of the stress concentration effect. The measured plastic strain near the hole was 1.25% at failure. As shown in Table 6, the stress concentration near the hole was close to the theoretical value of 3.0 at low stress levels where the material was behaving elastically. As the stress level increased, the stress concentration factor decreased because of plastic flow.

One hand-riveted cylinder was tested by this technique. Failure occurred when the rivets

sheared at an applied axial load of 2980 pounds. Assuming the stress was uniformly distributed through the cylinder wall, this corresponds to a stress of 7260 psi. The peak stress in the wall, based on a stress concentration factor of 2.2 taken from Table 6, would be 16,000 psi at failure. Strain gauges were distributed around the cylinder as in the first test. These gauges indicated a significant variation in strain along the rivet line. The strain near the bottom rivet, just prior to failure, was 69 microinches. The strain near the top rivet was 535 microinches. After failure, these strains were -1279 and +646 microinches respectively. These data suggest that a bending action was occurring near the rivet line during testing, which put the bottom of the cylinder in compression and the top in tension.

If the applied load were distributed uniformly between the rivets, then each rivet withstood 175 pounds just before failure. But if most of this load was concentrated near one of the rivets, that rivet would have experienced a load of about 800 pounds, which from earlier data is close to the expected failure load. Once one rivet failed, the load would be dumped on the next and would cause that rivet to fail—and the process would continue through the other rivets.

Two additional cylinders of the same design were built and tested using the resistance riveted method. The first unit experienced a rivet failure at an applied axial load at 5110 pounds. The second unit failed in the doubler plate at an applied axial load of 6160 pounds.

Another cylinder section was built with a double row of rivets (Figure 32). This section was tested as a simulated substructure by impacting the superstructure with a flyer plate at a level of 3000 taps. The riveted substructure survived this test without any evidence of fracture.

DISCUSSION

Before committing a design to the use of a riveted assembly, a designer must be satisfied that minimum strength requirements can be exceeded, that adequate dimensional control can be assured,

and that a cost savings will be realized from such a design. Each of these three design aspects will be discussed in this section.

Strength Requirements

From the data presented earlier, it should be possible to predict the allowable line load per rivet in a riveted assembly. The simplest riveted joint is the four-rivet assembly shown in Figure 22, which is used to test joint strength. Data in Table 6 show the force per rivet that would develop the stresses necessary to cause failure by each of the modes shown. The limiting factor appears to be either notch tensile or bearing. Both of these failure modes will occur when a line-load of 625 pounds per rivet is developed.

It will be recalled from earlier data that the failure strength of the test coupon is 800 to 950 pounds or 400 to 475 pounds per rivet. This means that the 625-pounds-per-rivet prediction based on failure in the sheet is not realized in the coupons. The most likely reason for the lower strength is the addition of a bending moment to the uniaxial tensile component in the sheet. For example, for a failure load of 900 pounds, the stress present in the sheet away from the rivet hole is

$$S = \frac{P}{A} = \frac{900 \text{ lb}}{(1 \text{ in.})(0.050 \text{ in.})} = 18,000 \frac{\text{lb}}{\text{in.}^2}$$

Where

S = stress

P = force

A = area

Near the rivet hole, the stress can be as high as three times the uniaxial stress because of elastic stress concentration. This would correspond to 54,000 psi ($3 \times 18,000$ psi), which exceeds the ultimate tensile strength. But plastic flow reduces that stress concentration factor to a value of about 1.44 from the data presented in Table 6. Using this factor, the notch tensile stress near the hole, when 900 pounds is applied, is 25,900 psi ($1.44 \times 18,000$). This stress is still below an

expected fracture strength of 49,000 psi (Table 2). The difference must be caused by the bending moment. The fact that sufficient stress can be developed in bending to make up this difference is readily apparent from an elastic stress analysis. The peak stress in bending a plate can be found from the relationship

$$S = MC/I$$

Where

S = stress

M = bend moment = force $\times$ (thickness $\div 2$)
 $= 900 \text{ lb} \times 0.025 \text{ in.} = 22.5 \text{ in./lb}$

C = thickness $\div 2 = 0.025 \text{ in.}$

I = moment of inertia = $\frac{1}{12}$ width $\times$ thickness³
 $= \frac{1}{12} 1 \times 0.050^3 = 1.042 \times 10^{-5} \text{ in.}^2$

Thus

$$S = \frac{22.5 \text{ in./lb} (0.025 \text{ in.})}{1.042 \times 10^{-5} \text{ in.}^2} = 54,000 \frac{\text{lb}}{\text{in.}^2}$$

Before such a large stress can be developed, plastic flow occurs that reduces the bending moment. Sufficient stress should be available, however, to combine with the direct tensile component and cause fracture of the riveted coupon at about 900 pounds. Each of the final nine resistance-riveted coupons did fail in the sheet, and most also exhibited rivet shear.

The one riveted beryllium hoop that was tested failed at the disappointingly low strength of 150 pounds per rivet. Several factors combined to make this result. The load was concentrated near one rivet causing it to break. This dumped the load onto the next rivet and so forth until all five had fractured. Ingot-sheet rivets were used, and those are only half as strong in shear as powder-source rivets. In addition, manual riveting methods were employed, which limited the applied riveting force to less than 1000 pounds. Early results show that such low riveting loads will decrease joint strength.

TABLE 7. Manhours required to perform various operations in fabricating 16 cylinders (15-in. diameter by 12-in. long by 0.060 wall thickness)

Operation	Deep-Drawing Method		Roll-Forming Method	
	Units Processed	Manhours	Units Processed	Manhours
Cast Ingot(s)	2	14.86	1	7.43
Machine Billets	4	9.84	2	4.92
Clad Billets	4	8.04	2	4.02
Hot-Roll Sheet	4	23.60	2	11.80
Bare-Roll Strips	8	25.84	4	12.92
Prepare Blank	16	6.56	16	6.56
Form Part	16	6.40	16	6.40
Machine or Assemble	16	8.00	16	25.60
Chemical Milling	16	8.16	16	8.16
Inspection	16	9.76	16	9.76
Total Time		121.06		97.57
Time Per Part		7.57		6.10

Dimensional Control

Results of this work show that excellent dimensional control can be achieved in riveted structures. The nominally 7-in. diameter, 2.0-in. long, 0.050-in. wall thickness cylinders shown earlier were round within 0.002-in. total indicator runout (TIR). The other was round within 0.005-in. TIR, and each of these had been hand-riveted, using torch heating, with 20 rivets. Even better results could have expected if resistance riveting had been employed.

The problems associated with riveting a larger conical substructure will most likely cause an increase in the TIR value to something like 0.010. It must be recognized that tolerances for structures assembled by riveting cannot be as tight as tolerances for structures built from machined components. If tight tolerances are mandatory, riveting will not be suitable. If relaxed tolerances are acceptable, riveting may be the best approach.

Cost Comparison

There are certain structures that lend themselves to rivet assembly methods much more readily than

TABLE 8. Cost estimates for making 16 beryllium cylinders, 15-in. diameter by 12-in. long by 0.060-in. thick, by three different manufacturing routes. The deep-drawing and roll-forming routes utilize ingot-source beryllium.

	Deep-Drawing Method	Roll-Forming Method	Powder-Source
Material			
Beryllium	\$ 725 ^a	\$ 550 ^a	\$40,000 ^b
Steel	\$ 800	\$ 400	
Tooling	\$ 4,000	—	\$ 2,500 ^c
Labor	\$12,106 ^d	\$ 9,757 ^d	\$ 3,840 ^e
Total Cost	\$16,831	\$10,707	\$46,340
Cost Per Part	\$ 1,052	\$ 669	\$ 2,740

a. Based upon \$15 per pound, which is the replacement cost in the beryllium scrap recycle process at the Rocky Flats Plant.

b. Prorated from the price of three similar blanks purchased in October 1974.

c. Tooling needed to machine the blanks to the desired wall thickness.

d. Based on \$100 per hour using times in Table 7.

e. Based on \$30 per hour using eight hours per part to machine and inspect.

others. For example, a thin-wall, large-diameter cylinder could be made by either deep-drawing a circular blank and then removing the bottom, or it could be made by roll-forming a rectangular sheet and riveting the sides as shown in Figure 33. Because of the sheet-trimming waste associated with circular blanks, the sheet is more fully utilized when roll-forming is employed. Because of this material waste, the manhours required to make a part by deep-drawing is 25.9 greater than by roll-forming and riveting, as is evident from the data presented in Table 7.

A comparison of estimated costs for the two ingot-sheet routes and a powder-source route for making 16 beryllium cylinders is given in Table 8. The least costly route in Table 8 is the roll-forming and riveting method. Both ingot-processing routes are significantly less costly than the powder-source material, but this is because the geometry is ideal for sheet-fabrication methods. If the cylinder contained an internal stiffening bond, costs would be much more comparable because additional

assembly and material costs would be added to the ingot processing.

A detailed cost analysis of the riveted beryllium substructure has not been done. A full-scale substructure has not been built because of funding limitations and the natural reluctance to rely on a new process when an existing process can be used, albeit at a higher cost. Until more experience is gained in riveting large pieces, cost estimates of a full-size substructure would be inaccurate and of limited value.

REFERENCES

1. Julius L. Frankeny and Dennis R. Floyd. *Ingot-Sheet Beryllium Fabrication*. RFP-910. The Dow Chemical Company, Rocky Flats Division. February 9, 1968.
2. Dennis R. Floyd, William W. Leslie, and Leon F. Dolechek. *Can-Rolling of Beryllium Ingots*. RFP-2041. Dow Chemical U.S.A., Rocky Flats Division. October 15, 1973.
3. Dennis R. Floyd. *Development and Pilot Production of Three Ingot Source Beryllium Sheet Metal Parts*. RFP-1827. Dow Chemical U.S.A., Rocky Flats Division. May 7, 1975.
4. Erik Oberg and Franklin D. Jones. *Machinery's Handbook*. 18 Edition.
5. S. Beitscher. *Tensile Properties of Rocky Flats Division Ingot Sheet Beryllium, from Room Temperature to 250 °C*. RFP-1205. The Dow Chemical Company, Rocky Flats Division. December 11, 1968.
6. Fred B. Seely and James O. Smith. *Advanced Mechanics of Materials*. John Wiley and Sons, Inc., New York. p. 386.
7. ASTM F-238-68, *1973 Annual Book of ASTM Standards*, Metal-Physical, Mechanical, Nondestructive, Corrosion Test, Metallography, Fatigue, Temperature Effect.
8. J. A. Van Hamersveld. "Beryllium Spacecraft Structures—Rivet Fasteners and Assembly Methods." Paper 680653 presented at the Aeronautic and Space Engineering and Manufacturing Meeting, Los Angeles, California. October 7-11, 1968.
9. Dennis R. Floyd, internal communication. 1974.

ILLUSTRATIONS

Figures 1 through 33

FIGURE 1. All-beryllium riveted frustrum (also see Figure 10)

19304-11

FIGURE 2. A three-roll forming machine used to roll-form small beryllium cylinders

FIGURE 3. A Bertsch, three-roll, forming machine used to roll-form large beryllium cylinders

19304-7

FIGURE 4. Typical roll-formed parts

19304-9

FIGURE 5. Tooling used to form the frustrum halves

17334-12

19304-1

FIGURE 6. Tooling used to form cylinder halves prior to riveting

FIGURE 7. Tooling used to forge countersunk rivet heads on beryllium rod. A beryllium rod is shown in the second hole on the left, and a headed rivet can be seen in the adjacent hole. The six-station die is split to facilitate removal of the rivets.

FIGURE 8. Countersink after machining and chemical milling. The small diameter increases 0.022 in., the large diameter increases 0.003 in., and 0.008 in. is removed from the thickness.

FIGURE 9. Mismatch of holes on a conical structure after chemical milling

FIGURE 10. Longitudinal and hoop rivet seams required for conical assembly. Numbers identify individual pieces for assembly by riveting.

19304-6

FIGURE 11. Manual riveting tool used to assemble early riveted beryllium coupons

FIGURE 12. Homemade device for manual riveting within deep structures.

17360-3

FIGURES 13(a), (b), and (c). Metallographic cross section of an all-beryllium riveted joint. Shown are (a) the powder-source rivet, ingot-source sheet, and doubler, (b) close-up of the upset head, and (c) grain deformation that accompanies riveting.

(a)

(b) 15X

(c) 300X

19225-3

FIGURE 14. A resistance welder that was converted for riveting. Clicoos (spring-loaded pins) are shown positioning holes together.

FIGURE 15. Cross section of a resistance-riveted beryllium joint

FIGURE 16. Tensile bar designs used to test ingot-source and powder-source beryllium sheet. The through hole and countersunk hole represent the holes that will be present in riveted sheet.

FIGURE 17. Bearing test coupon used in the beryllium riveting program

FIGURE 18. Plot showing the decrease in fracture strength that occurs as the bearing test hole is positioned closer to the edge of the test sample

FIGURES 19(a) and (b). Fixture (a) used to head beryllium rivets. Sketched in (b) is the plate used to simulate the sheet and doubler plate. The sketch in (b) represents a close-up view of the area pointed out by the arrow in (a).

(a)

(b)

FIGURE 20. Cracking tendency of upset heads when riveting with beryllium rivets.

FIGURE 21. Three methods employed for testing shear strength

FIGURES 22(a), (b), and (c). A rivet test coupon design is shown in (a). Represented in (b) and (c) are two approaches to the smooth outer surface requirement of the substructure.

(b) Dimpled Sheet

(c) Machine Countersunk Sheet

(a) 600-lb rivet force. 9X

(b) 4000-lb rivet force. 15X

FIGURE 23. Resulting rivet heads when different force levels are used to upset the shank

FIGURE 24. Effectiveness of the rivet head in preventing bending of the doubler plate. The bottom sample was pulled using unheaded rivets. The bending moment caused the doubler to curve at 600-lb. applied force. The top sample was tested to 900-lb. applied force with the doubler plate having significantly less curvature.

FIGURE 25. The bending moment present during testing of a riveted test coupon

7/8

9

10

FIGURE 27. A magnified view of Coupon from Figure 26. Note the broken countersunk head (right) and two upset heads (left) that were sheared off.

FIGURE 26. Fractures in Coupons 7/8, 9, and 10, which were used to test the strength of resistance riveted joints. The objects above the coupons are rivet heads that sheared off during testing.

FIGURE 28. Upset head of a rivet in Coupon 10 that remained attached to the doubler plate after testing. Note the cracks around the perimeter of the head. These cracks were caused by the upsetting operation.

FIGURE 29. Fixture for bulge-testing cylindrical structures

19310-1

FIGURE 30. A bulge-testing fixture and a tested, all-beryllium riveted cylinder

FIGURE 31. A one-piece ring after internal bulge-testing. Failure occurred through the row of countersunk holes at a mean stress of 24,000 psi.

17918-6

FIGURE 32. Two riveted cylinders used for testing impact resistance. Note the double row of rivets used in this design.

FIGURE 33. Comparison of material utilization during deep-drawing and during roll-forming