Diffusion Welding of Beryllium: Part I—Basic Studies

BY T. J. BOSWORTH

The weldability of beryllium is influenced by BeO content and thickness, and for each combination of parts being welded there is a minimum amount of deformation required to cause welding

ABSTRACT. In this, the first of a two part series, the author discusses studies carried out under Air Force contract F33615-69-C-1622 to develop a diffusion welding process that would yield lap joints with usable properties at temperatures up to 800 F. This study was concerned with the development of basic welding parameters including the time-temperature-pressure-deformation relationships and the welding of sheet and plate of varying oxide contents.

This study demonstrated that the weldability of beryllium is influenced by the BeO content and thickness, and that for each of these combinations of parts being welded there was a minimum amount of deformation required to cause welding. Welding conditions of 3 hr at 1500 psi pressure at 1400 to 1500 F produced welds which had shear strengths exceeding 90% of the base metal shear strength at both room temperature and 800 F.

In the second part of this series, the author discusses the role of the microalloying elements on the welding process along with their influence on the strength and ductility of beryllium sheet.

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Introduction

The development of a beryllium joining process that would yield joints having mechanical properties approaching those of the base metal has been the goal of many researchers for a number of years. While fusion joining is possible by either gas tungsten-arc welding (GTAW) or electron beam welding (EBW), the properties of the joint are, at best, marginal. The major difficulty is that, once the beryllium has been melted, the fine grain structure of the base metal is destroyed and replaced by a brittle coarse grain cast structure.

Because the properties of fusion welds have been unsatisfactory, brazing, braze welding, mechanical fastening, and adhesive bonding are found to be the most common joining methods used; yet each method has its limitations in terms of either weight, versatility, mechanical properties, quality, or usable temperature range.

Diffusion welding is a most promising method for joining beryllium. It offers potential advantages over each of the above joining methods, including joint strengths nearly equal to that of the base metal even at elevated temperatures. Fusion joining of beryllium has been unsatisfactory because of low joint strength and lack of ductility; brazing and adhesive bonding produce temperature limited joints, and mechanical fastening is costly and increases weight. With diffusion welding, distortion is minimized, and close dimensional control is possible. Additional potential advantages of using diffusion welding of beryllium for structural applications are:

1. Smooth, aerodynamic surfaces can be obtained.
2. Weight reductions are possible by avoiding large overlaps or reinforcements in the joint area.
3. Local reinforcements or attachments can be diffusion welded rather than machined or chemically milled.

In 1969, the Air Force Materials Laboratory sponsored two programs simultaneously at The Boeing Company and Battelle Memorial Institute[1] to develop procedures for diffusion welding beryllium that would yield welds having strengths in excess of 90% of the base metal over the temperature range of 70 to 800 F. Factors to be included in the investigation were the BeO content and material thickness. These studies were concerned with determining the minimum time at temperature, amount of deformation and the permissible welding temperature range.

While the program discussed herein was concerned with the production of lap joints and the shear strength of welds, the program at Battelle provided the base metal data for both programs and developed procedures for producing butt joints by diffusion welding and the tensile properties of the resultant welds.

The data generated during these programs demonstrate the feasibility of diffusion welding beryllium using procedures that could be adapted to production practices.

Table 1—Identification, Certified Chemical Analyses, and Certified Mechanical Properties of Beryllium Sheet and Plate

Identification			Chemical analysis, wt-% (a)							Room temperature mechanical properties (b)					
										UTS, ksi		Y.S., ksi		Elong. % in 1 in.	
Sheet no.	Lot no.	Thickness in.	Be assay	BeO	Fe	Si	Al	Mg	C	L	T	L	T	L	T
1852B	6678	0.059	98.7	0.97	0.14	0.04	0.07	0.03	0.11	78.6	78.6	58.1	56.9	18.0	21.0
1612A2	5567	0.125	99.0	1.1	0.18	0.04	0.05	0.05	0.14	74.8	71.4	63.6	64.5	7.0	6.0
1907A	6958	0.250	99.0	0.88	0.13	0.03	0.07	0.03	0.11	79.2	78.4	53.5	56.2	20.0	25.5
1493B	4812	0.062	98.4	1.7	0.10	0.03	0.07	0.02	0.10	87.7	87.0	63.4	64.1	25.0	28.0

(a) Any other metallic elements are less than 0.04 weight percent.
(b) In respect to last rolling direction. L — Longitudinal; T — Transverse. Also: UTS — ultimate tensile strength; Y.S. — yield strength; Elong — elongation.

Test Materials

The sheet and plate used for this program was purchased from the Brush Beryllium Company per their specifications SR-200-D (for 1/16 and 1/8 in. thick sheet) and PR-200-D (for the 1/4 in. thick plate). Pertinent vendor data including chemical analysis and room temperature mechanical properties data are given in Table 1.

The reader is referred to the Battelle issued report (AFML-TR-70-143) for information on the evaluation of the base metal properties as influenced by the time at annealing temperature. A partial summary of this data is given in Fig. 1, which illustrates the limiting thermal exposure for maintaining a 10% maximum loss of the room temperature yield strength of the as-received material for three of the sheets used for this program. A similar curve prepared by Battelle for the yield strength at 800 F showed that a slightly longer exposure at 1500 F (3 hr compared to 2 hr) is the limit for a 10% loss in yield strength, otherwise the curves are similar.

In selecting a given time-temperature combination for diffusion welding beryllium, one should also consider the temperature exposure that the material will be subjected to during hot forming operations and add this to the diffusion welding time. The total time at temperature should not exceed the limit given in Fig. 1.

Preparation of Lap Joint Specimens

The 1 in. square test specimens were prepared for welding by etching in a 40% HNO_3-5% HF solution at room temperature to remove a minimum of 0.00075 to 0.001 in. from each surface, rinsed in hot water, air dried, then permitted to remain exposed to the shop atmosphere for about 45 min before being inserted into the vacuum chamber.

Before closing the furnace chamber and placing it under vacuum (10^{-4} to 10^{-5} torr), the parts were preloaded to the prescribed applied pressure. Except when the applied pressure equaled the welding pressure, the applied pressure/welding pressure combinations used were: 1710/500 psi, 3300/1000 psi, 5000/1500 psi, 6600/2000 psi, and 8250/2500 psi. The lapsed time between cleaning and the start of heating averaged about 75 min. During welding the temperature was controlled to within ± 10 F.

Evaluation of Lap Joints

The welded lap specimens were cut in half parallel to the final rolling direction, one half was examined metallographically and the other half broken using a wedge peel test. Primary considerations in the metallographic examination included grain size, joint quality, and evidence of cracking.

Figure 2 illustrates the test fixture and schematically illustrates the wedge peel test, including simulated illustrations of the typical fracture paths observed in the broken specimens. The specimens were fractured with a single bevel wedge which forced the free side of the specimen to be "peeled" from the supported side. The test was accomplished in a tensile machine using a crosshead speed of 0.005 ipm.

This test was used to determine the extent of welding and to provide a qualitative measure of the joint strength. When less than about 80% of the joint was welded, the load values obtained tended to reflect the area welded. On the other hand, if the welded area exceeded about 80% of the total joint area, the failure modes varied and were inconsistent. The extent of welding was determined by measuring the area welded and expressing this as a percent of the total interface area. Accuracy of the area measurements is considered to be ± 5%.

There were three different ways that the fracture occurred in the specimens. These are graphically illustrated in Fig. 2 and described below:

1. *Joint Interface* — This type of failure was most often observed in specimens with small welded areas, or those welded under low pressures or deformation levels. Intermittent

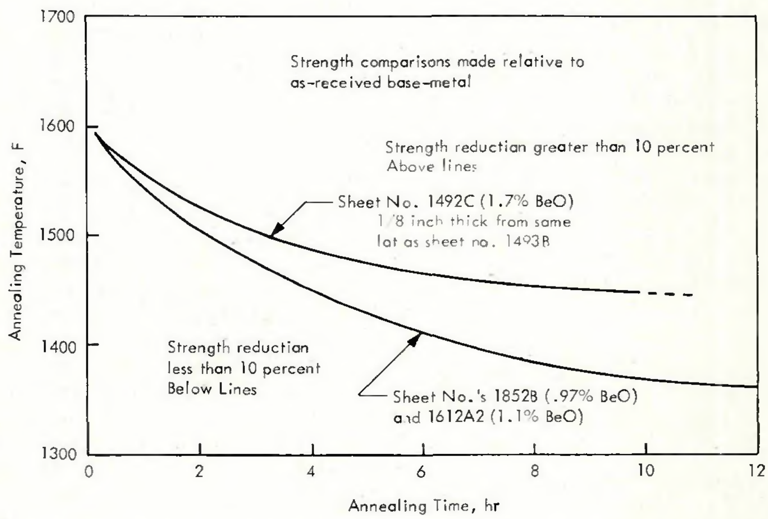


Fig. 1—Effect of annealing time and temperature on room-temperature yield strength of beryllium sheet used in the program

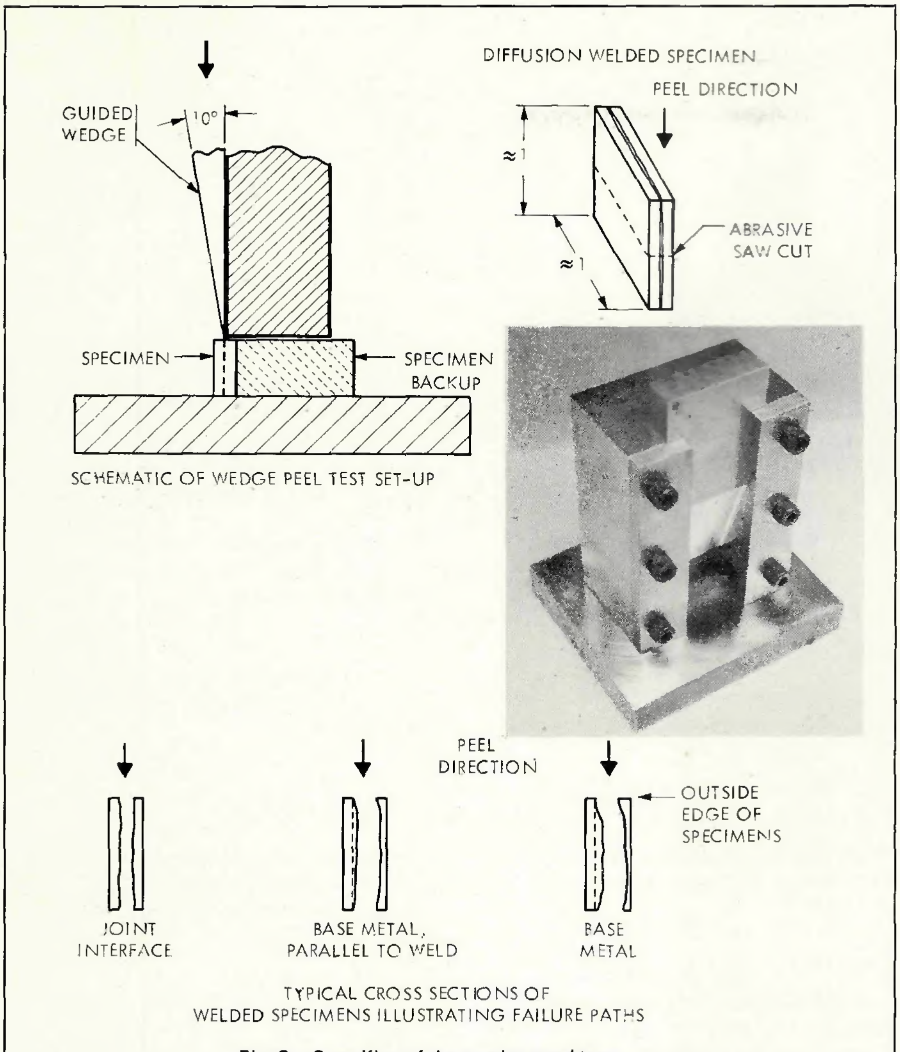


Fig. 2—Specifics of the wedge peel test

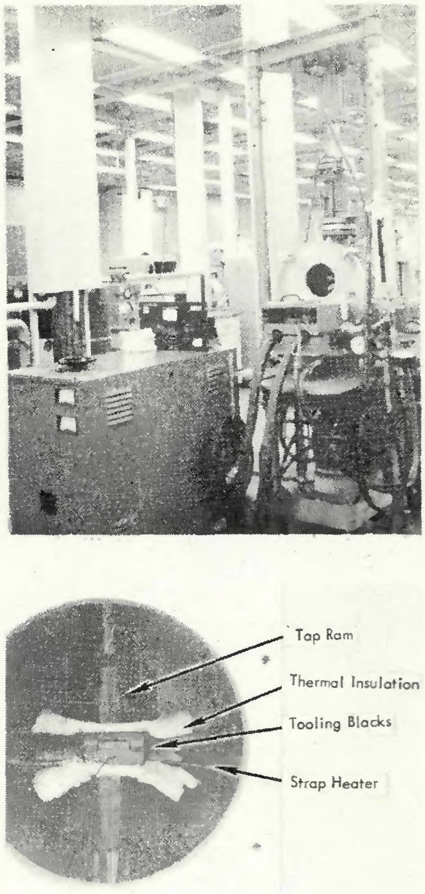


Fig. 3—Vacuum hot press used for diffusion welding. Top—overall view of vacuum hot press used for diffusion welding studies; Bottom—internal view of vacuum hot press

welding was often observed in these specimens. The failure path did not deviate significantly from the original joint interface.

2. *Base Metal Parallel to the Weld* — This type of failure appeared to be an intermediate manner of failure, having been observed in specimens whose welded area is from 40 to 95% of the total area. The failure path was similar to that occurring along the joint interface, except that the failure path was parallel to the original interface. Except at the edges, the original interface was not evident.

3. *Base Metal* — This type of failure was most often observed in those specimens having relatively large weld areas and requiring the highest breaking loads. The failure path progresses immediately away from the joint interface at the edge of the welded area, into the base metal, and occasionally to the outer surface. Most often the failed surface on the support side of the specimen is convex, rising 0.015 to 0.020 in. from the original joint interface.

The fracture surfaces of specimens that failed by the first two modes tended to be of a more brittle nature, whereas those that failed by the latter mode tend to be more fibrous in appearance.

Welding Equipment

Lap joints were welded in the vacuum hot press shown in Fig. 3 using resistance heated Inconel straps that wrap around the tooling blocks shown in Fig. 4. The straps are electrically and thermally insulated from the press assembly and electrically insulated from the tooling blocks.

Test specimen deformation was controlled by adding or removing "U" shaped shims to the tooling block assembly. In practice, the load was fully applied to the specimen only, causing deformation of the part until the top plate came to rest upon the shims, causing an increase in area and a reduction in the load per unit area. The combined area of the tooling and the specimen was such that with an applied load of 5000 lb, the uniform pressure distribution was 1500 psi.

The retaining ring and punch set shown in Fig. 4 was used to restrain specimen deformation while maintaining a constant and uniform pressure throughout the entire welding cycle. In this application, the applied pressure and the welding pressure were essentially the same and no pressure decay due to creep was experienced during welding. Retaining rings had inside dimensions of 1.010, 1.020 and 1.030 in. on a side, and the beginning specimens were 1.000 in. square.

The difference in pressure control, for the two types of tooling shown in Fig. 4, is schematically illustrated in Fig. 5. Because of the difference in the pressure profiles of the two methods, the initial rate of deformation differs by some unknown quantity that is related to the creep strength of the

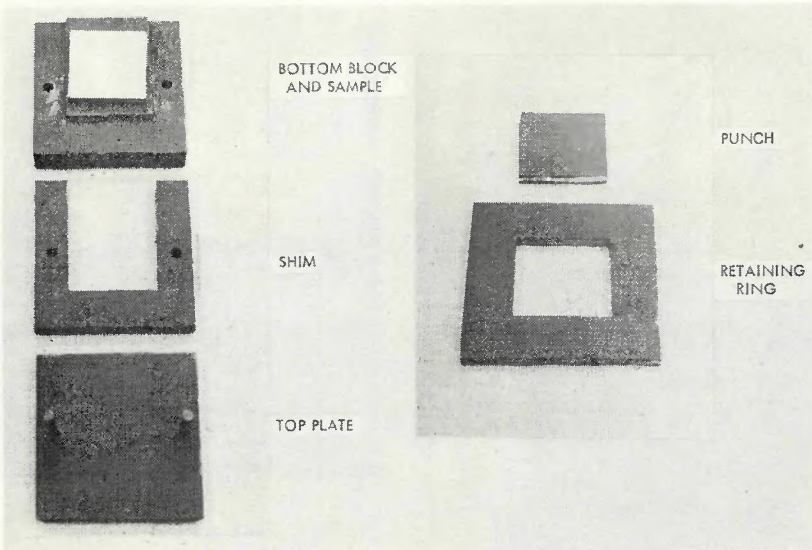


Fig. 4—Experimental tooling used for diffusion welding 1 in. square specimens

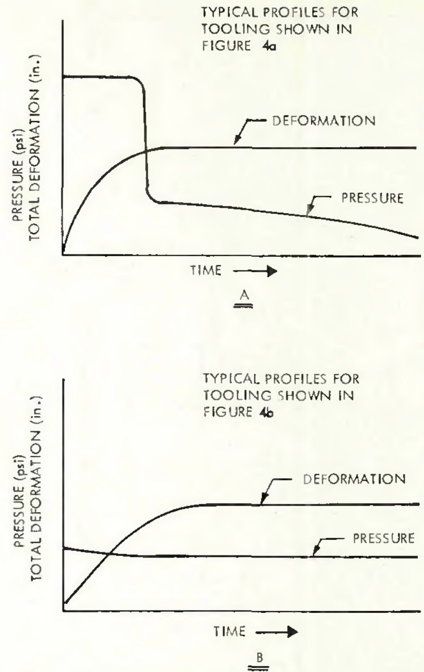


Fig. 5—Pressure and deformation profiles produced with diffusion welding tooling shown in Fig. 4

material, the applied force and the total amount of deformation.

Test Results

A nine step program was conducted to develop the parameters for diffusion welding lap joints. These steps included:

Step Objective

1 — Determine a suitable holding time between cleaning and welding.
2 — Preliminary screening of diffusion welding beginning at 1200 F to develop a 200 F temperature range for further study.
3 — Refine welding parameters and reduce temperature range to 100 F and determine the influence of time at temperature.
4 — Determine the influence of deformation on the welding parameters.
5 — Determine the influence of pressure on the welding parameters.
6 — Determine the shear strength of welds and compare with the base metal shear strength at room temperature and 800 F.
7 — Determine the influence of thickness on the welding parameters.
8 — Determine the influence of the beryllium oxide content on the welding parameters.
9 — Determine the influence of the mode of pressure applications on the welding parameters.

The basic development work was conducted on specimens from sheet number 1852B.

First Step

The first program step was conducted to determine a suitable hold time between cleaning and welding. For this series of tests, specimens were cleaned in a 40 HNO_3-5HF solution, dried, then held for times ranging from 15 min to 24 hr and then welded. Welding was accomplished for 3 hr at 1400 F. Deformation of specimens averaged about 7.5% under an applied pressure/welding pressure combination of 5000/1500 psi. The specimens were fractured using the wedge peel test and, from the loads recorded, it was determined that a holding period of one to two hr would be satisfactory.

Based on this data it was determined that hold times of 1 to 1½ hr would be used for the rest of the program work.

Second Step

Preliminary screening tests were conducted to determine a suitable 200 F temperature range over which parameter refinement could be conducted. The results indicate that a suitable temperature range would be 1300 to 1500 F. Below 1300 F a considerable increase in pressure would be required to obtain the desired joint deformation. This is shown by the fact that at 1200 F the specimen was subjected to a full 5000 psi throughout the entire weld cycle. No tests were conducted above 1500 F or beyond 3 hr at 1500 F.

Third Step

The third step of the program was conducted to determine the influence of time at temperature over the 1350 to 1500 F temperature range. Combining these results with those obtained from the second step, it was observed that at both 1300 and 1350 F the results obtained for welding times of less than 6 hr tended to be marginal. Above 1400 F, it appeared that 3 to 4½ hr would prove to be satisfactory, and at 1500 F good welds could be achieved in 1½ hr at temperature.

The interface of samples welded at 1300 and 1350 F for less than 6 hr and for 1½ hr at 1400 and 1450 F was readily detectable during metallographic examination at X100 magnification. There was also some indication that recrystallization was occurring at 1450 F and above. Moreover, in many of the samples the grain structure at the joint interface was finer than the rest of the base metal. It appeared that recrystallization may have begun, but grain growth or grain boundary migration across the joint interface could not be detected to any significant extent.

From these data it was decided to investigate the temperature range of 1350 to 1450 F during the fourth program step.

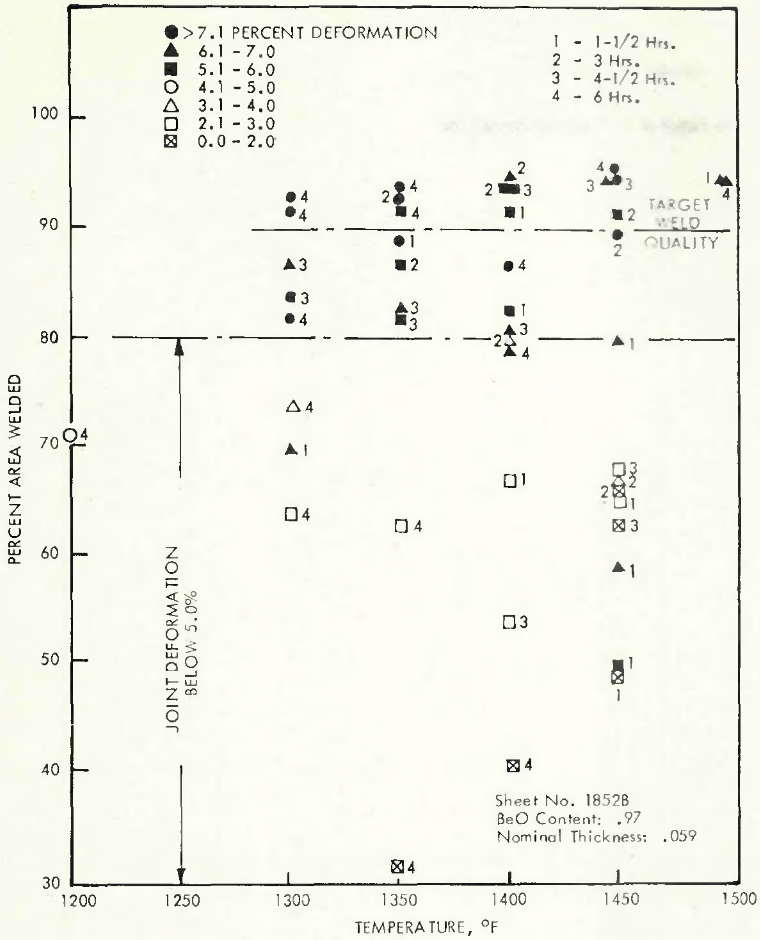


Fig. 6—Relationship of the percent area welded to the welding temperature

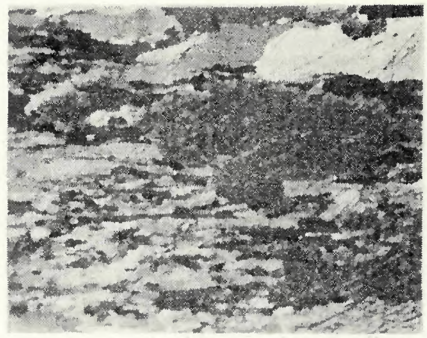


Fig. 7—Example of germinative grain growth occuring in specimen welded for 4½ hr at 1450 F with 1.8% deformation. Polarized light. 0.5% Hf etch. X250 (reduced 45% on reproduction)

Fourth Step

The fourth program step was conducted to determine the influence of deformation on the welding parameters over the temperature range 1350 to 1450 F under the same applied pressure/weld pressure combination previously used (5000/1500 psi). A summary of the data obtained in steps 2, 3 and 4 is given in Fig. 6 which illustrates the relationship of deformation and the area welded. When the amount of deformation was less than 5%, the area welded was less than 80% of the total joint area.

In this series of tests, metallographic examination of some samples revealed the presence of enlarged grains due to germinative grain growth — Fig. 7. This phenomenon was most apparent at deformation levels below 5% in samples welded at 1450 F, although it did appear in one sample welded with about 3% deformation at 1400 F. The presence of the enlarged grains did not appear to be influenced by the time at temperature.

Fifth Step

The last step taken in the preliminary development of welding parameters was to determine the influence that pressure had on the basic weld parameters. All previous tests had been conducted under an applied pressure/weld pressure combination of 5000/1500 psi. For these tests, combinations of 1710/500 psi, 3300/1000 psi, 6600/2000 psi and 8250/2500 psi were used.

The results indicated that lowering the applied pressure/welding pressure combination caused a reduction in the percent joint area welded, largely because of an increase in the degree of "alligatoring" or edge separation experienced. Increasing the pressure combinations above 5000/1500 psi failed to produce large welded areas at low deformation (below 5%) levels. Thus it appeared that no appreciable benefit could be gained from either an increase or decrease in pressure above the originally selected combination of 5000/1500 psi.

The data obtained in steps 2 through 5 for 1350, 1400 and 1450 F exposures was plotted in Fig. 8 through 13. From these figures, and from metallographic and visual examination of specimens, three candidate welding conditions were selected. These were:

1 —Minimum Deformation: 5%

2—Minimum Applied and Welding Pressure Combination: 5000/1500 psi.

3—Minimum Time at Temperature: 1350 F — 6 hr; 1400 F — 3 hr; 1450 F — 3 hr.

The following observations were made in determining the minimum welding parameters:

1 — A reduction in the area welded was experienced when the amount of deformation was reduced below 5%, even when the applied pressure/welding pressure combination was increased to 8250/2500 psi.

2 — A reduction in the area welded also was experienced when the applied pressure/welding pressure combination was reduced below 5000/1500 psi even when the amount of deformation approached 0.0095 (about 8%). The lower pressures tended to produce more edge separation than higher pressures, a problem that may be overcome through proper tool design.

3 — When the time at temperature was reduced below the minimums listed, a reduction in the weld area was generally experienced.

4 — It is doubtful that 100% joint closure can be achieved without containment of the material being welded. The reason is that as deformation occurs, the joint interface opens at the edges or "alligators," leaving an unwelded band about 0.010 in. or more wide about the periphery of the interface. One can anticipate a maximum weld area equivalent to about 95% of the total

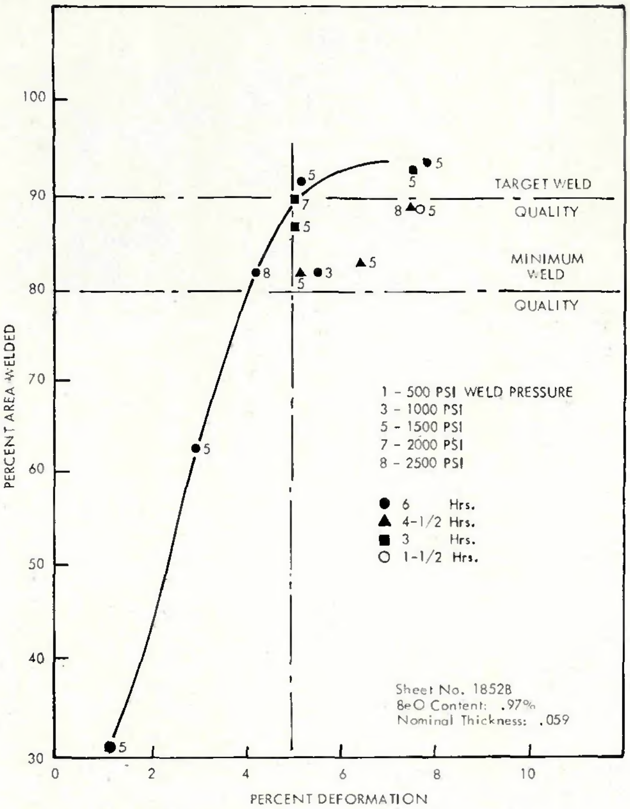


Fig. 8—Relationship of the degree of deformation and the joint area welded at 1350 F

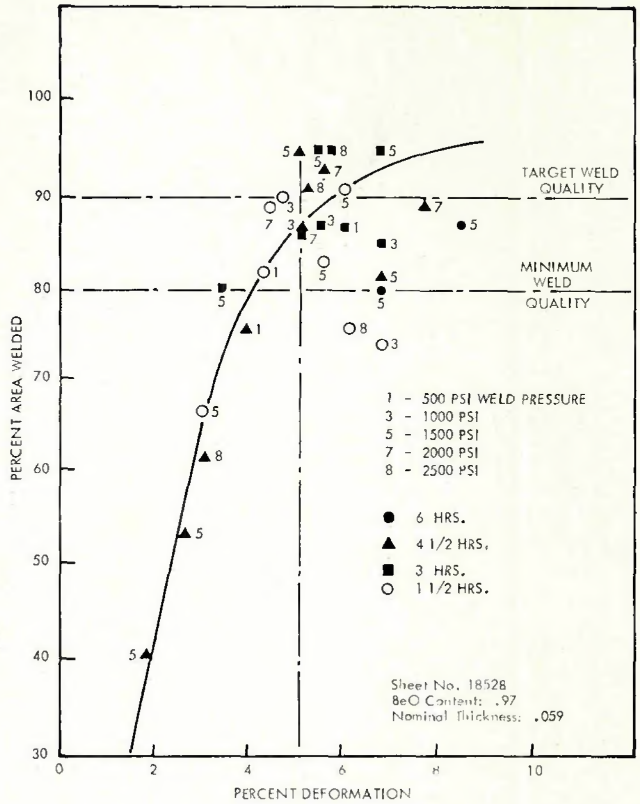


Fig. 9—Relationship of the degree of deformation and the joint area welded at 1400 F

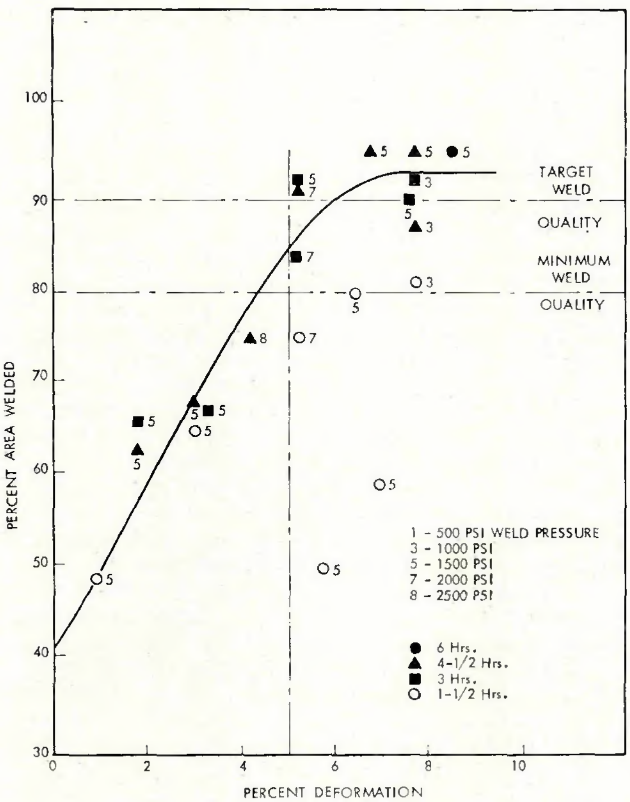


Fig. 10—Relationship of the degree of deformation and the joint area welded at 1450 F

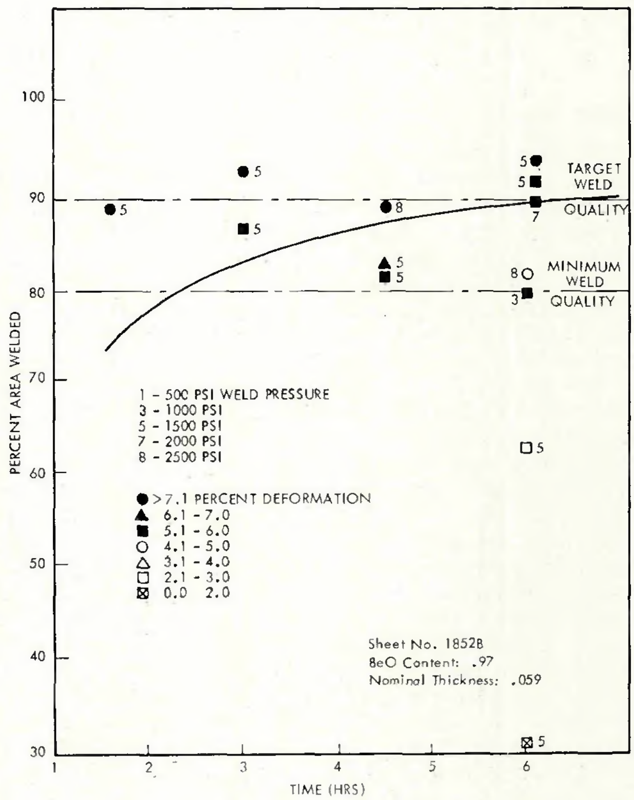


Fig. 11—Relationship of the time at 1350 F on the joint area welded

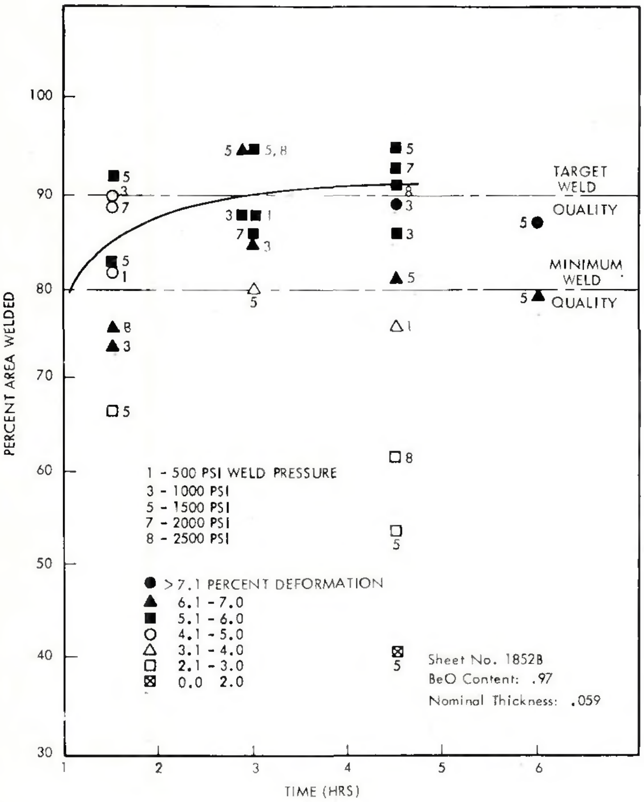


Fig. 12—Relationship of the time at 1400 F on the joint area welded

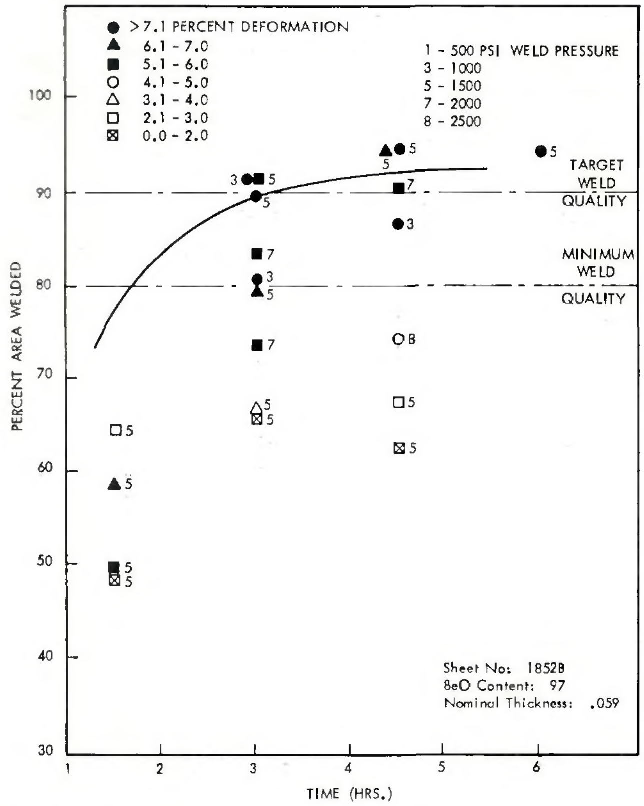


Fig. 13—Relationship of the time at 1450 F on the joint area welded

joint area, if the material is not contained.

5 — Of the three time-temperature combinations, the most desirable combination appeared to be 1400 F for 3 hr, while 1450 F for 3 hr is the least desirable. Recrystallization and germinative grain growth have been experienced at low deformation levels (1 to 3%) at 1450 F and in a production application this could be undesirable or detrimental — Figs. 7 and 14. The third cycle chosen appears to be intermediate as far as weld quality is concerned.

Sixth Step

The sixth step of the development program involved verification of the selected welding parameters by comparing base metal and weld joint shear strengths. For base metal shear data we used the specimen used by Fenn, et al[2] in their investigation of Lockalloy (Fig. 15) and for weld joint data, the specimen shown in Fig. 16.

This configuration eliminates the influence of laminations and the sharp notch on the shear strength, however the high ductility of this material (as evident in Fig. 15) could influence the actual shear strength level.

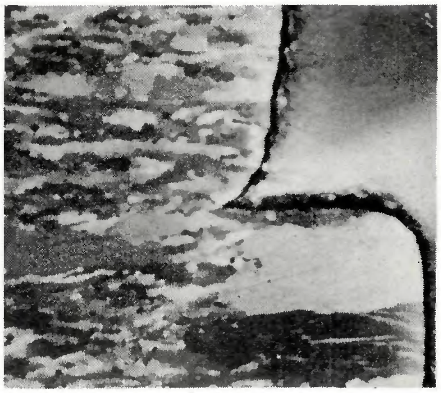
Both the base metal and welded joint shear strengths are given in Table 2. In addition to obtaining weld shear strengths on the 1/16 in. sheet, some shear data is also listed which was obtained on welded 1/4 in. plate using a specimen similar to that which was used for gathering base metal data. These specimens were welded with the joint perpendicular to the plate thickness, so that the strength values would not be influenced by base metal laminations.

The room temperature weld strengths are considered to be invalid because of the aforementioned difficulties with rotation of the test area. The one specimen tested at 800 F that was welded at 1350 F did fail in the weld joint, and based on appearance of the joint, the strength listed appears to be valid. The specimens welded at 1400 and 1450 F broke partly in tension and partly in shear, hence the shear strengths should actually be greater than those listed. The results obtained on the 1/4 in. thick plate bear out the results obtained in the seventh step in that welding at 1400 F was not practical for this gage, whereas welding at 1450 F was.

The trend of results obtained for welding temperatures above 1400 F compare favorably with tensile results. Based on our experience with trying to obtain valid shear data, it is apparent that considerable attention must be given to future specimen design, preparation, and testing procedures in order to obtain reliable shear data. The main problem in obtaining valid shear data is that the combination of notch sensitivity (fracture toughness) of beryllium and the small shear test area imposed by the specimen thickness makes for a high degree of inaccuracy in the test data obtained. In the thickness tested (1/16 in.) it is impossible to provide a notch free terminus of the test section.

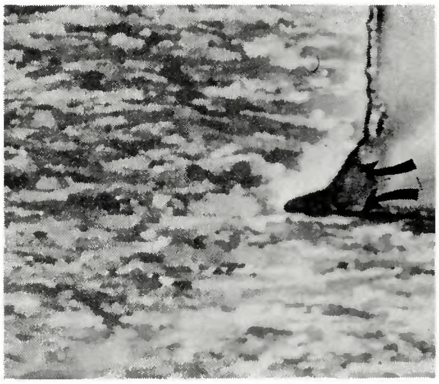
Seventh Step

Following the verification of welding parameters by the comparison of shear strengths we investigated the influence of base metal thickness on welding parameters. For this series, 1/8 and 1/4 in. thick sheet and plate containing a nominal 1% BeO were diffusion welded starting with the base weld schedule of 1400 F, 3 hr, 1500 psi and 5% deformation. It was found necessary to increase only the amount of deformation to about 10% for welding the 1/8 in. thick material. On the other hand, a satisfactory joint was not achieved in the 1/4 in. ma-



Typical edge of joints welded at 1450°F for 3 hours, 5.2% deformation and weld pressure of 1500 psi.

Note germinative grain growth at edge of joint.



Typical edge of joints diffusion welded at 1400°F for 3 hours, 5.1% deformation and weld pressure of 1500 psi.

Note "alligatoring" of edge

Mag. 250X
Etch: 0.5%HF
Polarized Light

Fig. 14—Typical diffusion welded joints in beryllium sheet containing 1% BeO. Polarized light. 0.5% Hf etch. X250 (reduced 33% on reproduction)

terial even when the temperature and deformation were raised to 1450 F and 15% respectively.

Examination of the fracture face revealed extensive point welding in the areas of the joint interface that appeared to be unwelded. It did not appear feasible to increase either the temperature or deformation above those already tested, since the high deformation and longer times or higher temperatures would be objectionable. Rather it appears that when welding thick sections, the support tooling should be designed to prevent "barreling" and restrict the deformation to the area of the interface. The primary reason for doing this is derived from the following discussion on static forging of billets. It will be evident from this discussion that, as the height of the parts being joined increases, the pressure distribution across the surface becomes more uniform and it is reasonable to assume that the rate at which welding progresses from center outward is reduced significantly. Thus, as the height of the stack increases, the problems of support and material containment becomes more acute.

The following analysis[3] relates to the forging pressure distribution on a cylindrical billet during static forging: *Forging Pressure.* A cylindrical billet upset between two parallel plates develops a non-uniform pressure distribution across its surfaces. The pressure distribution at any time during the upset will depend on the following:

1 — The original height and diameter of the billet.

2 — The instantaneous height at the time under consideration.

3 — The original flow stress of the material and its strain hardening characteristics.

4 — The fractional forces generated at the interfaces during deformation.

The pressure distribution is determined from the equation:

$$\rho = \sigma_0 \, e^{\frac{2\mu}{h}(R - r)}$$

where: ρ = axial pressure; r = radial distance from center of billet; σ_0 = tensile yield stress (uniaxial); h = billet height; μ = coefficient of sliding friction (Coulomb friction); R = billet radius.

The peak pressure occurs at the center of a given billet where r = 0

$$\rho_{(max)} = \sigma_0 \, e \, (2\mu R/h)$$

and the minimum die pressure occurs at the edge where (r = R) and $\rho_{(min)} = \sigma_0$.

For the conditions of test imposed during the test program, the yield stress (σ_0), the coefficient of friction (μ) and the radius R are the same, hence the pressure distribution is directly related to the billet or stack height (h).

In Fig. 17 are plotted the stress distributions for 0.125, 0.250 and 0.500 in. high stacks (billets) assuming σ_0 = 5000 psi, μ = 0.2 and R = 0.5 inch. It is apparent from this figure that higher unit pressures are achieved at the center of thinner sections than in thick sections.

Several approaches may be undertaken to increase the unit stress in thick sections. The first is to increase the amount of deformation, thereby reducing the height, h, and increasing the outside radius, R, without increasing the tensile yield stress, σ_0. The second approach is to restrain the material away from the joint so that the effective height, h, is reduced and σ_0 can be increased if desired. This would be accomplished through proper tooling design that would restrict material deformation and flow to the joint area. Either of these methods will cause an increase in the unit pressure at the center of the sample and increase the potential for welding to be initiated.

Eighth Step

The eighth program step involved an evaluation as to how the BeO content influenced the basic parameters established with sheet containing 1% BeO. It was found that the conditions for welding the higher BeO content sheet were considerably different from what had previously been established.

Increasing the pressure or amount of deformation at 1400 F did not produce satisfactory welds. Moreover, it was not until the deformation and temperature were respectively increased to about 15% and 1500 F that the area welded exceeded 90%. It appeared that satisfactory welds could be produced in as little as 1½ hr and that the recrystalization temperature had not been exceeded.

Ninth Step

The last step in the development effort was to investigate the influence of a constant pressure-controlled de-

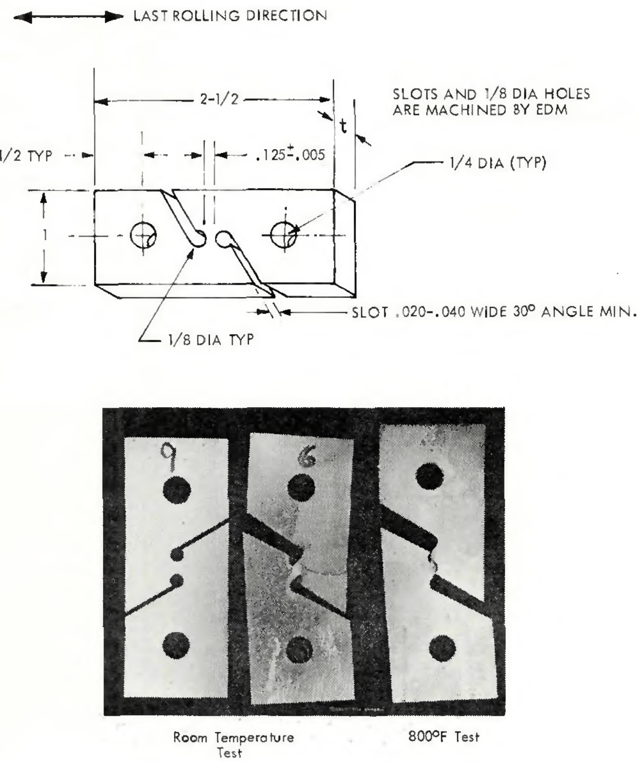


Fig. 15—Base metal shear test

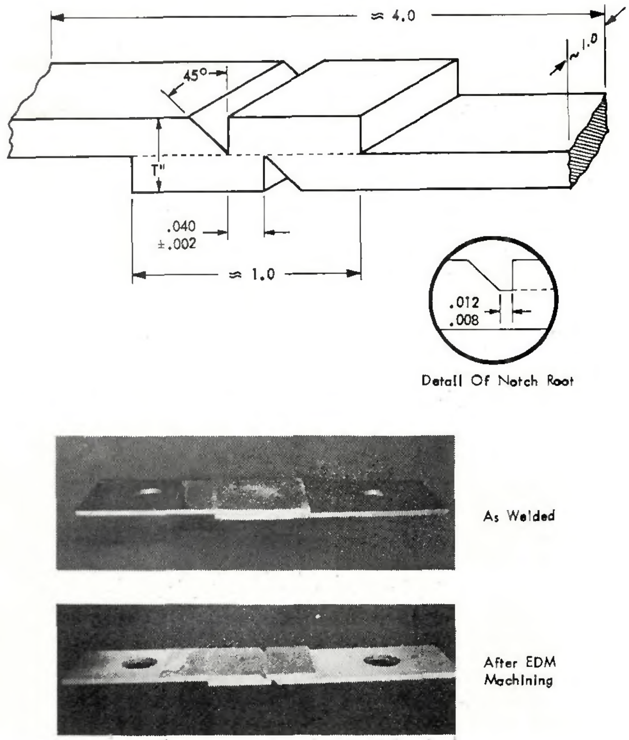


Fig. 16—Weld shear test

formation, welding method on the primary weld properties. For this phase of the program, the samples were placed inside the retaining rings shown in Fig. 4. By using retaining rings of varying dimensions, the amount of deformation could be controlled to different but reasonably predictable amounts. Deformation of the specimen was ended when the cavity of the retaining ring was filled. Since the greatest area change was 6%, the maximum difference between the applied and welding pressure was only 90 psi from the start to the end of the weld cycle. This compares with a difference of perhaps 4000 psi when welding was accomplished in the other tooling.

The data indicate that, by confining the material so that a constant pressure is maintained during the overall weld cycle, a slight increase in the area welded can be experienced at either low pressure or low deformations over what is obtained when material flow is unrestricted. The difference is slight, however, and not significant enough to warrant lowering the welding pressure below 1500 psi. At welding pressures of 1500 psi or greater, the amount of deformation can be reduced to about 3%. However, the relative difference in the amount of deformation (0.004 in. compared to 0.066 in.) necessary to achieve adequate welding is hardly significant, particularly when one considers standard manufacturing tolerances and gage thickness variations. Thus it appears desirable to stay with the higher amount of deformation which should also improve reliability.

Discussion

It was determined that the successful diffusion welding of lap joints in wrought beryllium sheet was controlled by four major variables: time, temperature, pressure and deformation. This work demonstrated that successful welding could be accomplished in the temperature range of 1400 — 1550 F, whereas much of the past work associated with the successful diffusion welding of beryllium was accomplished at fairly high temperatures (1625 F for 15 mins at 2000 psi)[4] or (1550 to 2300 F for 1 hr)[5]. At these temperatures, however, grain coarsening is often observed and the strength losses incurred can be objectionable for many applications. In selecting an applicable maximum welding time, we assumed that hot forming of either the detail parts or the finished assemblies at 1400 — 1450 F would be required. Since that time would be additive to the welding time, it was deemed advisable to keep the welding time to below the maximum exposure times.

Passmore[5] conducted diffusion welding tests on both hot pressed and extruded beryllium bar over a wide range of temperatures using differential thermal expansion tooling. His data indicated that maximum tensile properties were achieved at a welding temperature of about 1640 F and that specimen deformation, based on diameter increases, ranged from 0.1 to 0.6% for the hot pressed product to 0.4 to 5.6% for the extruded product.

As a matter of course, the research efforts were directed at the development of minimum conditions for diffusion welding beryllium sheet that would be applicable to production welding of reasonably large beryllium structures; developing a balance between time, temperature, and pressure. The approach was to develop welding parameters that would permit a production assembly to be welded in a single shift without resorting to excessively high pressures. It was evident that below 1400 F either high pressures or long exposure times would be required to achieve satisfactory welds.

The data obtained indicates that the minimum welding pressure for lap joints in wrought beryllium sheet is 1500 psi (regardless of the BeO content) if welding is accomplished in the temperature range of 1400 to 1550 F. Higher welding pressures could be used but appeared to offer no significant improvement in weld quality, nor did they reduce the welding

Table 2—Shear Strength of Base Metal and Welded Joints

Specimen no.	Temp., F	Time, hr	Deformation, in.	Deformation, %	Shear strength (ksi) Room temp.	Shear strength (ksi) 800 F	Remarks
Sheet no. 1852B base metal							
F-1					55.1		
F-2							Broke in handling.
F-6					53.1		
F-7					57.1		
F-8					54.2		
					54.9 Avg.		
F-3						30.1	
F-4						32.2	
F-5						32.5	
						31.6 Avg.	
Sheet no. 1852B welded joint							
F13506055-1	1350	6	.007	6.0	16.4		
F13506055-2	1350	6	.007	6.1	34.7		
F13506055-3	1350	6	.006	5.3		19.5	
F13506055-4	1350	6	.0085	7.3	48.1		
F14003055-1	1400	3	.0065	5.6	35.7		
F14003055-2	1400	3	.0070	6.0	19.8		
F14003055-3	1400	3	.0070	6.1			Broke in fixturing.
F14003055-4	1400	3	.0070	6.0		33.1	
F14503055-1	1450	3	.0070	6.0	24.4		
F14503055-2	1450	3	.0070	6.0	47.4		
F14503055-3	1450	3	.0070	6.0		30.6	
F14503055-4	1450	3	.0075	6.5		32.6	
Plate no. 6958 welded joint							
K140030515-1	1400	3	.081	16.7		21.4	
K140030515-2	1400	3	.081	16.7		25.0	Did not fail.
K145030515-1	1450	3	.071	14.6			Broke in fixturing.
K145030515-2	1450	3	.071	14.6		36.3	
K145030515-3	1450	3	.064	13.4			Broke in machining.
K145030515-4	1450	3	.064	13.4		28.9	

time significantly. It was determined that 1/16 in. sheet containing 1% BeO could be welded with a minimum deformation of 5%, but that greater deformation was required as the thickness was increased or with higher BeO contents. Why higher deformation was required for joining the 2% BeO sheet is unclear.

Passmore[6] noted that there was no observable grain growth across the joint interface and concluded that welding occurred as a consequence of atomic contact across the interface. Even when germinative grain growth occurred (Figs. 7 and 14), the grains did not cross the joint interface. Instead, it was often observed that very fine grains were present on either side of the joint interface, probably nucleated by localized plastic deformation of the surfaces during welding. The fact that fine grains were not as readily evident in the sheet containing two percent BeO and the greater deformation at higher temperatures required for joining sheet containing the higher percentage of BeO would seem to indicate that the welding mechanism is more than a simple surface reaction between oxide layers. It would seem that if atomic contact were the only factor involved that there would be little difference in the weldability of wrought beryllium sheet containing different percentages of BeO.

A possible explanation for this difference might be developed from the observations of Hausner[7] and Scott and Lindsay[8] concerning the precipitation of minor elements, (mainly Fe and some Al and Si) both at the grain boundaries and within the matrix in the 1400 to 1500 F temperature range. Scott and Lindsay determined that an exposure of four hours at 1475 F caused a significant increase in the amount of Fe at the grain boundaries. They speculated that the presence of this precipitate might influence the degree of intergranular fracture and the ductility of the material.

A further suggestion was made concerning strain induced precipitation and that iron rich centers may be preferentially nucleated provided suitable sites were available even if a more general nucleation were not possible. If this were in fact true, then the nucleation of fine grains on either side of the joint interface may be related to the precipitation of iron at the interface. Certainly the localized deformation at the interface could cause strain induced precipitation. A further consideration is that if strain induced precipitation occurs at the interface during the early stages of welding then diffusion of iron or other minor elements across the joint interface might be the primary determinate of the welding process.

Further, one should consider the rate of diffusion through both metallic beryllium and through beryllium oxide, since the thickness of the BeO layer about each grain is to some extent related to the amount of BeO present in the sheet. Thus it might be possible that the relative difference in weldability between wrought sheet containing different BeO contents might be partially related to the difference in diffusion distances.

As a result of the data obtained during this program effort, we developed sufficient confidence in the ability to diffusion weld beryllium on at least a

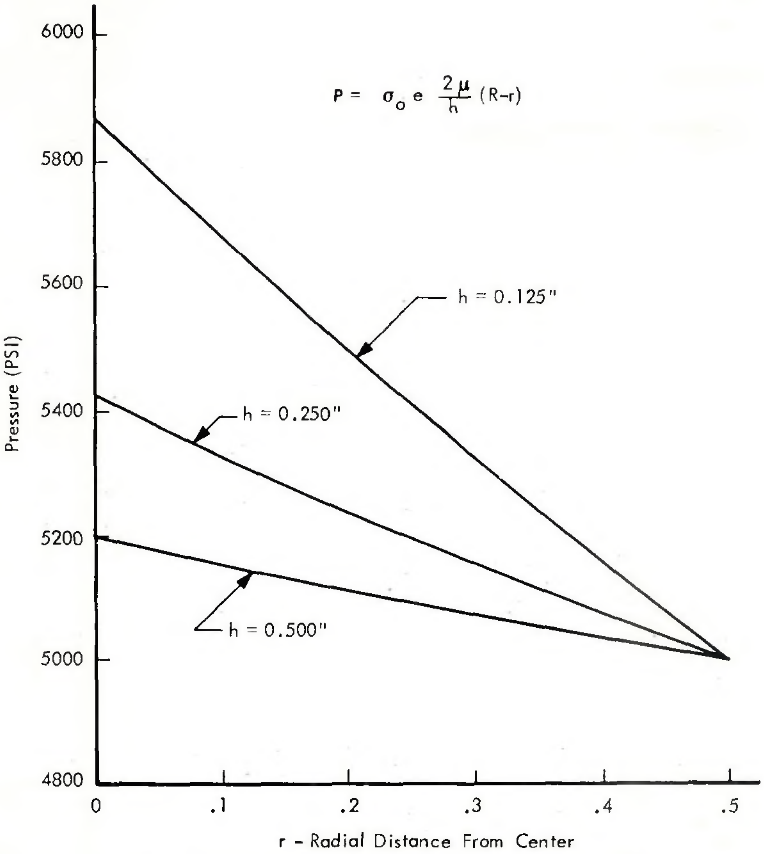


Fig. 17—Typical pressure distribution on cylindrical billets of varying height. σ_0 = 5000 psi; μ = 0.2

laboratory basis, developing joints having a substantial level of strength. However, there is a lack of understanding of the actual welding mechanism. As a result we are not sufficiently able to control the welding process. We have been able to establish, with a reasonable degree of certainty, the minimum levels of time, temperature, pressure and deformation required for welding lap joints in wrought beryllium sheet. These conditions (i.e. 1400 F, 1500 psi, 3 hr with a minimum of 5% deformation of 1/16 in. thick sheet containing one percent BeO) will produce welding over more than 90% of the joint surface. Increases in temperature and/or deformation were required to produce similar results in thicker sheet and plate, or sheet containing two percent BeO.

Future Potential

It has been demonstrated that wrought beryllium sheet can be diffusion welded without a significant loss of strength, either in the base metal or the weld. The conditions of time, temperature, pressure and deformation that were established during this program are amenable to production operations. However, it will be necessary to verify that structural elements of reasonable proportion can be repeatedly and reliably diffusion welded. Whether the cost of diffusion welding can be justified for many structures remains to be seen, for the investment in equipment including vacuum pumps and presses could be sizable.

From a manufacturing standpoint the welding conditions are such that hot forming of the structure and diffusion welding might be accomplished simultaneously, thereby helping to keep the fabrication costs down. Research to date indicates that no special processing will be required. (For example, chemical etching of the as-received surface or of a ground edge was satisfactory. Lapping and polishing of the surfaces was not necessary.) As developed, the process is fairly straightforward and within the realm of current manufacturing technology. Because of the temperature range in which it has been determined that welding is feasible, the cost of tooling materials should not be excessive since low cost, readily machinable materials could be used.

It has been shown that the loss of base metal strength can be kept to less than 10% and that the joint strength and base metal strength will be essentially the same. Thus the weight penalty for diffusion welded joints will be significantly less than for mechanically fastened or adhesive bonded joints. Diffusion welded joints are superior to brazed joints from the standpoint of strength at room and elevated temperatures, corrosion resistance and weight. Fusion joining of beryllium has not been successful because of the low joint strength and ductility. While diffusion welded butt joints currently have low ductility, the joint strength is approximately equal to that of the base metal.

With continued development of the diffusion welding process and an understanding of the welding mechanism, the use of beryllium in aerospace structures should become more common. Some of the applications where diffusion welded beryllium structures might be found include control surfaces, interstage and intertank structures, tube and cap assemblies such as spars, struts, actuator rods, and lightweight stiffened panels. Further, during the past few years, the beryllium producers have developed new processing methods that have significantly increased the fracture toughness of wrought products. Today, it is possible to procure wrought sheet having a K_{Ic} of 14 + ksi $\sqrt{in.}$ whereas several years ago a K_{Ic} of 10-12 ksi $\sqrt{in.}$ was about the best one could expect. This increase in fracture toughness will not go unnoticed by aerospace design engineers, and it can be anticipated that more beryllium will be found on future aerospace structures. Regardless of the increase in fracture toughness, however, the industry will still be faced with the problem of producing reliable joints economically and with minimum increase in weight.

While mechanical fastening and adhesive bonding will probably be used for the lion's share of joining applications, it will not be until diffusion welding reaches production status that designers will be able to take full advantage of beryllium's unique properties in design applications.

Conclusions

The following conclusions are based on the data collected during this program:

1 — Lap joints having strength properties equaling 90% of the room temperature properties can be produced in beryllium sheet, and plate containing approximately one percent beryllium oxide can be produced by diffusion welding in 3 hr at 1400 to 1450 F under a minimum pressure of 1500 psi.

2 — Under the conditions listed in conclusion 1 above a minimum

deformation in thickness is required for welding to occur. For 1/16 in. thick sheet, 5% deformation is required; for 1/8 in. sheet, 10% deformation is required; and for 1/4 in. thick plate, a minimum deformation of 15% is required.

3 — Welds produced under the conditions listed in conclusions 1 and 2 and tested at 800 F failed at loads exceeding 90% of the base metal shear strength. At 800 F the shear strength of the base metal is 31.6 ksi, whereas the shear strength of welds has ranged from 28.9 ksi to 36.3 ksi.

4 — Beryllium sheet (1/16 in. thick) containing approximately 2% BeO could not be welded with the parameters given in conclusions 1 and 2 above. Instead, a minimum time of 1½ hr at 1500 F was required along with a minimum force of 1500 psi and a minimum deformation of 15%.

5 — Grain growth across the joint was evident in localized areas only.

6 — Germinative grain growth was evident in the one percent BeO sheet when welded at 1450 F under low levels of deformation (1 to 3%).

7 — When the material being welded is confined by tooling so that sideways flow is controlled, "alligatoring" can be prevented. The minimum amount of deformation required to weld two 1/16 in. sheets of 1% BeO material together can be reduced from 5 to 3% without reducing the joint area welded below 90%. However, germinative grain growth has been experienced at low levels of deformation and welding at less than 5% deformation is not recommended.

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WRC Bulletin No. 175 August 1972

PVRC Recommendations on Toughness Requirements for Ferritic Materials

by the PVRC Ad Hoc Task Group on Toughness Requirements

One objective of the Pressure Vessel Research Committee (PVRC) of the Welding Research Council is to review and present the results of pressure-vessel research in a useful form for designers and code-making bodies. Many such reviews with recommendations have been presented. In January 1971, PVRC formed a Task Group, under the Evaluation and Planning Committee, to review current knowledge and prepare recommendations on toughness requirements for ferritic materials in nuclear power plant components. The recommendations were requested from PVRC by the ASME Boiler and Pressure Vessel Committee for their use in considering any revisions to the requirements for Class 1 Components, Subsection NB of Section III — Nuclear Power Plant Components.

Specifically, the Task Group undertook to recommend, on the basis of current knowledge, criteria for ferritic-material-toughness requirements for pressure-retaining components of the reactor coolant pressure boundary operating below 700 F. These criteria, when used in addition to the stress limits allowed by the ASME Code, should permit the establishment of safe procedures for operating nuclear reactor components under normal, upset, and testing conditions; emergency and faulted conditions should be considered on a case basis. The present report contains the recommendations of PVRC provided to the ASME, and also to the Atomic Energy Commission, in August 1971; with some revisions and additions developed since that date.

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