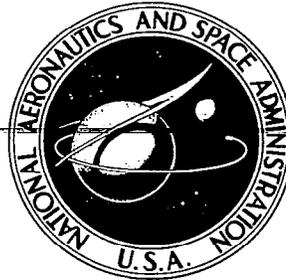


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**EVALUATION OF
NASA-LANGLEY RESEARCH CENTER
EXPLOSION SEAM WELDING**

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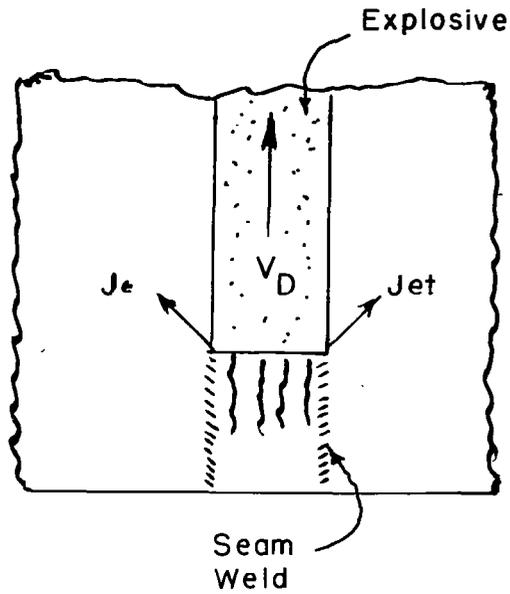
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16. Abstract To demonstrate the potential of the NASA-LRC explosion bonding technique to meet current fabrication requirements, a test program was conducted on explosion bonded joints, and compared to TGA fusion joints in 6061-T6 aluminum. The comparison was made in required fixtures, non-destructive testing, static strength and fatigue strength (tension-tension and flexural). The explosion bonding technique requires only simple tooling and no clamping to prevent distortion. However, in joining cylindrical sections, considerably more effort was required to maintain relative placements of plate materials to control necessary parameters. Following joining, ultrasonic inspection proved to be an accurate tool to identify bonding efficiency. In all cases of static and fatigue strengths, the explosion bonded flat plates outperformed the fusion joints (discussion on comparisons). In fabricating vessels, difficulty was encountered in using both explosion joining and fusion welding. The explosion bonded joint's strength was reduced by the heat-affected zone of the fusion joint, introducing a failure which propagated down the explosion joint. In a simple vessel, using only explosion joining, no such strength loss was indicated. Further, an absolute hermetic seal was achieved.					
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I. INTRODUCTION

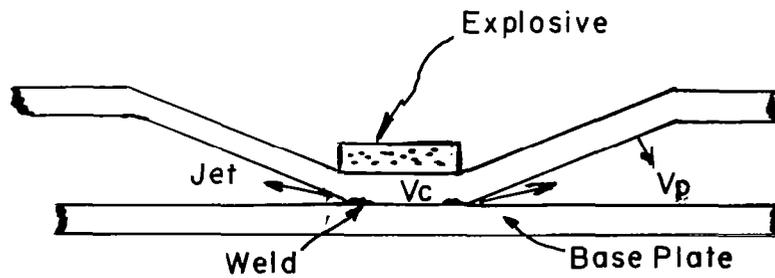
Explosion welding is a solid-phase welding process in which explosives are used to accelerate one or both of the components to be joined so a high velocity oblique collision is obtained. Over 260 combinations of similar and dissimilar metals and alloys have been welded using the process. The process is currently used in numerous applications ranging from fabrication of large metal clads to use in the electronics and communications industry. The most famous application of explosion bonding is a titanium-steel transition joint used in the Apollo spacecrafts, while the most common is the explosion bonding of a portion of the sandwich carriage used in the United States. Explosion bonding is characterized by the jetting action that occurs in high velocity oblique collisions. During an oblique collision the jet is responsible for scraping or cleaning the surface of the metals as they move to the collision point and at this point the clean metal surfaces are forced together by the high pressure generated by the explosions effecting a bond. Figure 1 is a schematic of an oblique collision showing the essential relationship that occurs.

NASA has developed an explosion seam welding process that offers many advantages over conventional seam welding (See Figure 2). This process has been developed to a high degree of efficiency and simplicity, producing joints that have mechanical properties of up to 100 percent of those of the parent metal.

To prove the advantages of the process mechanical property data has been developed on laboratory scale specimens and also on a realistically useful assembly in which the process was used for fabrication. The purpose of the tests was to provide sufficient verification and justification of this process, comparing it to the well-known tungsten arc seam welding process.



(a) Top View



(b) Cross-Section

Figure 1. Schematic Sketch of Parallel Plate Configuration for NASA-LaRC Explosion Seam Welding.

II. MATERIALS AND METHODS OF FABRICATION

The materials and fabrication procedures used in this program are presented in the sections that follow:

A. METALS

Aluminum alloy 6061-T6 was used throughout this program. This alloy has a nominal chemical composition as follows: Mg 0.8-1.2%, Cr 0.15-0.35%, Cu 0.15-0.40%, An 0.25%, Ti 0.15%, Si 0.4-0.8%, Fe 0.7%, Al-Bal. The material was not Al-clad and was used in the bare condition; thicknesses were 1.58 mm (.063 in) and 1.0 mm (0.040 in).

B. EXPLOSIVE

A lead encased PETN explosive in ribbon form was used for the explosion bonding. Two weights of explosive are used for welding, 0.002 and 0.003 grams/mm (10 and 15 grains per foot). This explosive has a nominal detonation velocity of 7900 m/sec (26,000 ft sec).

C. FABRICATION PROCEDURES

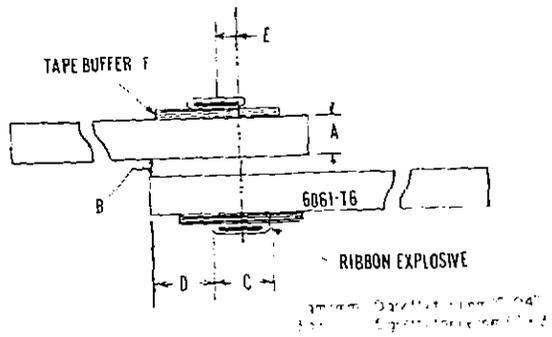
Both explosion bonded and gas tungsten arc seam welds were fabricated for comparison. The methods and configurations made are presented below.

1. Flat Plate Explosion Bonded Seam Welds

These welds were made by NASA-LRC using the NASA-developed method for explosion bonding seams. Two plates of aluminum were held apart at a suitable standoff distance as is shown in Figure 2. The ribbon explosive is attached to the sheets with a centerline offset as shown in Figure 2. The two ribbons are detonated simultaneously by one blasting cap, away from the weld area. The plates of 1.58 mm (0.0625 inches) 6061-T6 aluminum were overlapped about 38 mm (1.5 inches) in the present case and the explosive placed 13 mm (0.5 inch) in from the edge of the sheet. The weight of explosive used was 0.003 gram/mm (15 grains/foot). In addition to the 1.58 mm (0.0625 inches) thick material, some 1.0 mm (0.040 inches) thick specimens were also welded. The overlap amounted to about 20 mm (3/4 inch) with the thinner stock. Welds were about 355 mm (14 inches) in length. A simple two-height pedestal fixture was used with no clamps on the stock.

2. Flat Plate GTA Seam Welds

The flat plate seam welds were made by Beech Aircraft using an automatic gas-tungsten arc GTA method. Type 4043 aluminum filler wire was used to weld two sheets of NASA supplied 6061-T6 aluminum together. Welds were made in the 1.58 mm (0.0625 inches) thick material only.



A: 1mm (0.04")	A: 0.04mm (0.0015")
B: 0.25mm (0.01")	B: 0.35mm (0.0138")
C: 0.2mm (0.0079")	C: 0.38mm (0.015")
D: 0.35mm (0.0138")	D: 0.35mm (0.0138")
E: 0.2mm (0.0079")	E: 0.3mm (0.0118")
F: 89mm (3.5")	F: 89mm (3.5")

(a) Set-Up for NASA LaRC Seam Weld



(b) Results Showing Plate Bending to Achieve Plate Alignment

Figure 2. Schematic Sketch of NASA LaRC Explosion Bonding Parameters

3. Fabrication of Cylindrical Pressure Vessel

The vessels used in these tests were fabricated in two steps. First, a cylinder was made by NASA-LRC using the explosion bonding technique. Two semi-cylinders were welded together, one seam at a time. A tab was left on either end to compensate for run-in. (A small distance of weld length is required in explosion-bonding before welding parameters are established. These cylinders were approximately 305 mm (12 inches) in diameter and length.

End caps were attached by GTA welding by Beech and the Denver Research Institute. The tabs on the end of the explosion welds were removed prior to welding the end caps on. The end caps were approximately 13 mm thick and were machined with a taper so the cylinder would fit the caps. Those vessels fabricated by Beech were dye penetrant checked on the GTA weld to assure no flaws were present.

A hole was drilled in the end of one of the caps and threaded so pressure fittings could be screwed on. The pressure fittings accommodated a 6.35 mm (0.5 inches) I.D. pipe and tubing.

4. Fabrication of Pressure Disc

A disc was fabricated by NASA-LRC, using a flat circular sheet of 0.81 mm (0.032-inch) thick aluminum, joined to a 6.35 mm (0.25 inch) thick circular plate. The diameter of the two pieces of aluminum was 305 mm (12 inches) in diameter.

The joining operation is shown by the sketch in Figure 3. The thicker plate has to be machined as shown which gives the standoff distance and preset angle for welding. The ribbon explosive was shaped to the necessary circle and attached to the disc with double-back tape; the disc was then positioned over the plate. A blasting cap was placed over the butted interface of the ribbon explosive and then detonated. A weld is effected around the periphery of the disc using this procedure.

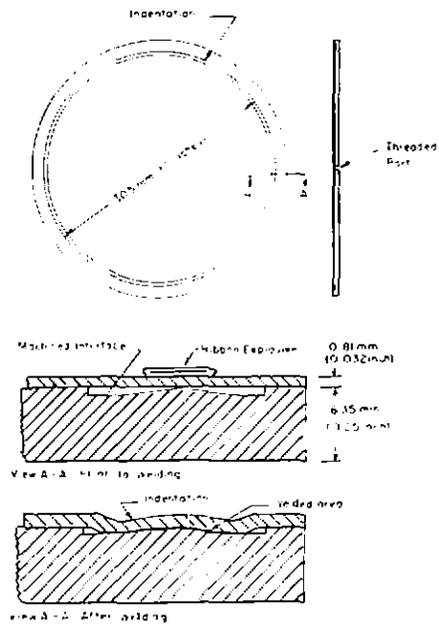


Figure 3. Sketch of Welding Parameters Used to Fabricate Disc

III. TESTING PROCEDURES

The testing procedures, both destructive and non-destructive are described below.

A. INSPECTION OF WELDED JOINTS

Three methods were used to evaluate the joints (1) X-ray, (2) ultrasonics, and (3) metallographic. The procedures used are presented below.

1. X-ray Inspection

The X-ray inspection of GTA welded joints was done by Beech Aircraft. All welds were inspected to ASTM specification E94, Radiographic Testing.

2. Ultrasonic Inspection

The cylinder prepared by NASA-LRC was ultrasonically inspected for non-bond. The technique used gave a "C" scan display which was recorded on an oscilloscope. A 10 MHz transducer with a 13 mm(0.5-inch) diameter and a 102 mm(4-inch) focal length was used as the head. The testing was conducted under water to give coupling of the transducer and the metal component.

3. Metallographic Inspection

Metallographic specimens were cut from the flat plate welds in both transverse and parallel to the weld seam. The purpose of the metallographic inspection was to determine if non bond was present, the amount of welded area and the wave amplitude at the explosion bond interface.

B. TENSILE TESTING

Flat plate tensile samples were cut from the explosion and TIG seam welded specimens with the tension axis orientated perpendicular to the seam. The specimen design is shown in Figure 4. A slight taper to the weld seam was used on the gage width to concentrate the stress at the seam. Specimens were also cut from plain non-welded sheet stock to provide base metal data. All tests were conducted at a strain rate of .02 mm/mm/min. Tensile specimens were also made from the welded cylinders used in the pressure vessel tests.

C. FATIGUE TESTING

Two types of fatigue tests were used on this program; tension-tension and flexural. The tension-tension specimens were made using the same design and procedures as the tensile specimens. The tension-tension tests were conducted on an Instron testing machine at a cyclic

rate of about two cycles per minute. These are described as low cycle fatigue. The specimens were preloaded at a tensile stress of $1.03 \times 10^7 \text{ N/m}^2$ (1500 psi). All specimens were then loaded to a predetermined stress at a rate of 0.2 inch/inch minute. The predetermined load ranged from about $2.24 \times 10^8 \text{ N/m}^2$ (32,500 psi) to $3.24 \times 10^8 \text{ N/m}^2$ (47,000 psi). These loads ranged from 70 to 99 percent of the ultimate strength. After each stress cycle the load was allowed to return to the lower stress level of about $2.24 \times 10^8 \text{ N/m}^2$ (1500 psi). The comparison criteria was the number of loading cycles to failure.

Flexural fatigue test specimens were made according to the sketch shown in Figure 5. The specimens are fixed in the machine at the large end of the specimen with the load being applied at the end with the holes. The bending stress, S , is then calculated from the formula

$$S = \frac{P6L}{bt^2}$$

where

P = applied load

L = distance between connecting pin and point of interest

b = width of specimen at length L from point of load application

t = thickness of specimen

A predetermined stress was calculated at the weld in these tests. The reported stress was then calculated at the point of actual failure. A Fatigue Dynamics machine was used at a cyclic rate of 60 cycles per minute. These tests were called high cycle fatigue in the reported results.

D. PRESSURE TESTS ON VESSELS

Pressure vessels were constructed using one foot diameter explosion bonded cylinders supplied by NASA. The material in the cylinders was 1.58 mm (0.0625 inches) thick 6061-T6 aluminum. These cylinders were GTA welded to aluminum end closures that had been machined to fit the cylinders.

A hydraulic system was used to pressurize the vessels with water as the pressure media. The actual stress on the welds is then a combination of the hoop stress plus the tensile stress exerted by the pressure on the ends of the vessel. The hoop stress, S_H , can be calculated from the formula

$$S_H = \frac{RD}{2t}$$

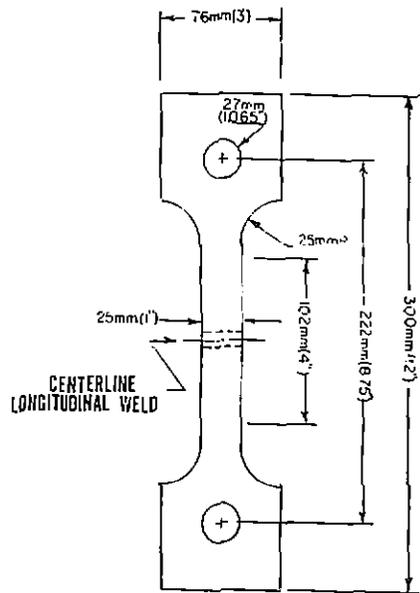


Figure 4. Sketch of Tensile Specimen Configuration

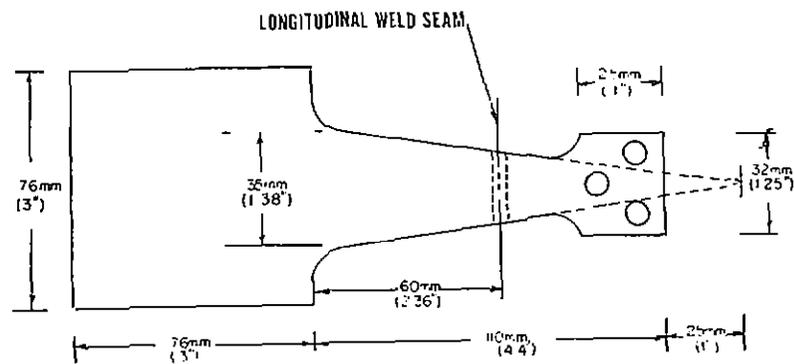


Figure 5. Sketch of Flexural Fatigue Specimens

where

R = pressure

D = diameter

t = Thickness

The longitudinal stress, S_1 , is calculated from the formula

$$S_1 = \frac{RD}{4t}$$

Plastic deformation was noted at failure so the effective stress can be calculated using plasticity theory. The effective stress, \bar{S} , for an element of volume is given by:

$$\bar{S} = \frac{1}{\sqrt{2}} \sqrt{(S_1 - S_2)^2 + (S_2 - S_3)^2 + (S_3 - S_1)^2}$$

where

S_1 = Loop stress

S_2 = Longitudinal stress

S_3 = Transverse compressional stress

The tests were conducted initially using the hoop stress as the governing criteria.

E. PRESSURE TEST ON DISC

The 305 mm (12-inch circular disc) was supplied by NASA that consisted of a plate of 6.35 mm (1/4-inch) thick 6061-T6 aluminum to which a sheet of 0.8 mm (.032-inch) thick 6061-T6 aluminum had been explosion bonded around the periphery. This disc was pressurized once with metric 100 psig ($6.89 \times 10^5 \text{N/m}^2$) dry nitrogen gas and helium leak checked; then it was fitted to the hydraulic system used for the pressure vessels tests. The system was cycled to a pressure of $6.2 \times 10^5 \text{N/m}^2$ (90 psig) ten times after which the cyclic pressure was raised to $6.89 \times 10^5 \text{N/m}^2$ (100 psig) and then cycled to failure.

IV. RESULTS AND DISCUSSION

The results of the evaluation and testing conducted on the various specimens and configurations are presented in the sections that follow. The results are presented together where applicable to a particular test configuration.

A. METALLOGRAPHIC EVALUATION

Metallographic evaluations were conducted on specimens cut both perpendicular and parallel to the test seam. Examination of specimens cut perpendicular to the explosion bonded seam showed that the seam consisted of two parallel welded strips separated by an unwelded gap. Each welded strip was slightly wider than the sheet thickness. The unwelded gap between the two welded strips was about 2.3 mm (0.090 inches) wide.

The inspection of the specimens parallel to the seam of the explosion bonded material showed the wavy interface typical of explosion bonds. The bond waves contained large (relative to wave size) pockets of solidified melt with few defects. Wave amplitude was about 0.076 to 0.102 mm (0.003 to 0.004 inches). The characteristic features of the waves suggest that the collision velocity was between 3000 and 4000 meters per second which is slightly higher than ideal for this alloy but certainly within the regime of producing acceptable welds.

The non-bond in the center of the seam is due to too high a collision velocity to effect welding. Since in the plate collapse, the area under the edges of the explosive collide at a lower velocity than those at the center, welding is effected at the edges to give the dual strips of weld.

B. COMPARATIVE TENSILE TESTS

Tensile tests conducted on the parent material without welds indicated that the average tensile strength was on the order of $3.26 \times 10^8 \text{ N/m}^2$ (47,250 psi) and the average yield strength was $2.70 \times 10^8 \text{ N/m}^2$ (39,100 psi). These values are within those given for the aluminum alloy 6061-T6. Tensile tests were then conducted on the 1.58 mm (0.0625-inch) thick explosion bonded specimens. These were cut with the sheet rolling direction both parallel and perpendicular to the weld seam. In all cases, the tensile fracture occurred outside the weld joint area in the parent sheet material. The average tensile strength in these tests was 3.35 N/m^2 (48,600 psi) and the average yield strength was 2.86 N/m^2 (41,500 psi). There was no significant difference with respect to sheet orientation. The results of these tests are presented in Table I.

The tensile tests show no great difference in tensile strength between the parent material and the explosion bonded stock. A comparison of the yield strength of the parent material and the explosion bonded specimens is also about the same. One of the yield strengths

TABLE I. Results of Tensile Tests Conducted on Flat Sheet Specimens

Type Specimen	Weld Orientation to Sheet Rolling Direction	Tensile Strength,		Yield Strength,	
		$\text{N/m}^2 \times 10^8$	psi	$\text{N/m}^2 \times 10^8$	psi
As Received	Perpendicular	5.47	47,800	2.77	40,200
As Received	Perpendicular	3.27	47,500	2.81	40,700
As Received	Parallel	3.20	46,450	2.52	36,500
NASA	Parallel	3.35	48,600	2.88	41,700
NASA	Parallel	3.33	48,300	2.86	41,500
NASA	Parallel	3.32	48,100	2.86	41,500
NASA	Perpendicular	3.41	49,500	2.89	41,900
NASA	Perpendicular	3.35	48,600	2.79	40,400
NASA	Perpendicular	3.34	48,500	2.90	42,000
NASA ¹	Perpendicular	3.15	45,700	2.78	40,300
NASA ¹	Perpendicular	3.14	45,500	2.76	40,100
NASA ¹	Perpendicular	3.12	45,300	2.76	40,100
GTA	Perpendicular	2.48	35,900	2.07	30,050
GTA	Perpendicular	2.43	35,200	2.07	30,000
GTA	Parallel	2.42	35,100	2.06	29,900

¹ 1.02 mm (0.04 in) thick

in the parent stock was lower than in the other two tests but this is within the scatter usually found in tensile tests.

The tensile tests of the gas tungsten arc welded specimens showed the tensile and yield strengths were reduced by fusion welding. The average tensile strength was $2.44 \times 10^8 \text{ N/m}^2$ (35,400 psi) and the average yield strength was $2.06 \times 10^8 \text{ N/m}^2$ (30,000 psi). The failures occurred within the heat affected zone. Fusion welding would change the T6 temper to essentially an as cast condition (O) or depending on the rate of weld deposit to possibly an as quenched condition (T3). Failure occurred in the anticipated area in the GTA welded specimens. A comparison of the GTA welded specimens with the parent material and the explosion bonded specimens shows a significant drop in the strength.

Another series of tensile tests was conducted on specimens of explosion bonded material that was 1.02 mm (0.040 inches) thick. The average tensile strength of these specimens was 3.45 N/m^2 (45,500 psi) and the average yield strength was 2.77 N/m^3 (40,200 psi). Again, the strength is within that given for 6061-T6. All of the failures occurred outside the explosion bonded seam area. The strengths of the 1.02 mm (0.040 inch) specimens is slightly lower than that of the thicker 1.59 mm (0.0625-inch) material. However, the parent material would have to be considered before a direct comparison could be made with respect to the effect of thickness on explosion bonding.

B. COMPARATIVE FATIGUE TESTS

Two types of fatigue tests were conducted, tension-tension and flexural. The results of both the tension-tension tests are presented in Table II.

Since the tensile strength of the explosion bonded specimens was on the order of $3.35 \times 10^8 \text{ N/m}^2$ (48,600 psi), the predetermined load for tension-tension testing was kept slightly lower on the order of 3.1 N/m^2 (45,000 psi) maximum. Cyclic rates were low so the tensile stress exerted was kept at 90 percent of the average tensile results or greater to reduce the testing time. Within the range of stress used the number of cycles to failure for the 1.59 mm (0.0625 inch) thick specimens varied from 63 to 2100 cycles.

A straight line was fitted to plot of maximum stress versus cycles to failures (log scale). There was little scatter in the fatigue tests results for the explosion bonded specimens. The linear least squares fit has a standard deviation of $1.4 \times 10^7 \text{ N/m}^2$ (2030 psi) and for example the fatigue strength (maximum stress amplitude) is $3.137 \times 10^8 \text{ N/m}^2$ (45,550 psi) $\pm 1.4 \times 10^7 \text{ N/m}^2$ (2030 psi) at 1000 cycles. The results are presented in Figure 6. The failures occurred in the weld in these specimens. This is not surprising since the weld in effect has a built in stress riser with the overlap of the two sheets.

Tension-tension fatigue tests were conducted on the GTA seam welded specimens for comparison purposes. Since the tensile strength

TABLE II. Results of Tension-Tension Low Cycle Fatigue Tests

Type Specimen	Maximum Load		Cycles to failure
	$N/m^2 \times 10^8$	psi	
ExB	3.10	45,000	63
ExB	3.13	45,400	92
ExB	3.26	47,280	210
ExB	3.21	46,545	409
ExB	3.15	45,750	409
ExB	3.07	44,500	1090
ExB	3.05	44,200	2100
GTA	2.41	35,000	1644
GTA	2.38	34,550	3500
No weld			

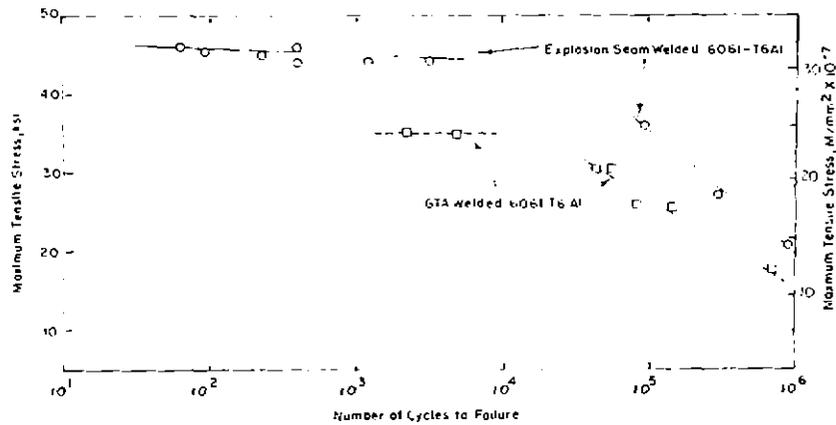


Figure 6. Results of Fatigue Tests Conducted on Explosion Seam Welded and Gas Tungsten Arc Seam Welded Specimens.

was considerably lower, the stress level was lower too. The fatigue tests showed the GTA seam welds to be very tough with the fatigue strength being (maximum stress amplitude) $2.4 \times 10^8 \text{ N/m}^2$ (35,000 psi) \pm $3.45 \times 10^7 \text{ N/m}^2$ (500 psi) at 1000 cycles. The fatigue strength approaches the tensile strength of the welded material in this case. The failures did occur in the heat affected zone in these specimens.

The flexural fatigue tests were conducted at a lower stress level. Since a high cycle condition existed in these tests the starting stress approximated 50 percent of the tensile strength of the explosion bonded specimen as well as for the GTA welded specimens. The stress was raised as testing progressed. The results of the high cycle fatigue tests are tabulated in Table III and graphically presented in Figure 6. As can be seen by an inspection of Figure 6, the explosion seam bonding is superior to GTA seam welding. At 100,000 cycles, the fatigue strength of the explosion bonded material is on the order of $2.4 \times 10^8 \text{ N/m}^2$ (35,000 psi), while that of the GTA welded material is about 1.86 N/m^2 (27,000 psi). At 1,000,000 cycles the fatigue strength of the explosion bonded material is on the order of 1.38 N/m^2 (20,000 psi) and that of the GTA welded material is $1.03 \times 10^8 \text{ N/m}^2$ (15,000 psi). Most of the explosion bonded specimens broke in the parent material away from the weld. The GTA welded specimens broke in the heat affected zone.

C. PRESSURE TESTS ON VESSELS

The comparison of the tensile and fatigue data between the explosion bonded and the GTA welded material indicated that superior seams were obtained with the explosion bonded material. Based on these tests NASA supplied explosion bonded cylinders were fabricated into pressure vessels as is shown in Figure 7.

The first vessel was hydraulically pressurized using water as the pressure medium. This vessel failed in the explosion bonded seam at a pressure of 0.148 kg/mm^2 (210 psi). This vessel is shown in Fig.8. A second vessel was fabricated in which a record was available of the non-destructive testing results.

Figures 9 and 10 show the results of the ultrasonic inspection conducted by NASA on the weld seams. The dark areas are the welded portions in these Figures. As an inspection of Figures 9 and 10 indicate, there are two welded portions in each seam with a non-welded area in the center.

Tensile specimens were cut from another NASA supplied cylinder prior to fabrication of the second pressure vessel. The purpose was to conduct tests to insure that the proper strengths were being realized since the cylinder welding geometry required forming the cylinder halves before welding. Welding of the two halves required additional fixturing during welding than was encountered in making flat plate welds. The results of these tests are presented in Table IV. These tests indicated no loss in strength due to the different fixturing requirements. Therefore, it was decided to go ahead and fabricate the second pressure vessel. The seam marked C-D in Figure 9 broke during

TABLE III. Results of Flexural High Cycle Fatigue Tests

<u>Type Specimen</u>	<u>Load</u>		<u>Cycles to Failure</u>
	<u>N/m²x10⁸</u>	<u>psi</u>	
ExB	2.48	36,000	80,500
ExB	1.90	27,500	192,000
ExB	1.45	21,000	890,000
GTA	2.10	30,500	40,300
GTA	2.10	30,500	50,200
GTA	1.79	26,000	86,700
GTA	1.79	26,000	150,000
GTA	1.59	23,000	690,000
No weld	1.79	26,000	235,100

TABLE IV. Results of Tensile Tests on Explosion Bonded Cylinders

	<u>Tensile Strength</u>		<u>Yield Strength</u>	
	<u>N/m²x10⁸</u>	<u>psi</u>	<u>N/m²x10⁸</u>	<u>psi</u>
	3.44	49,900	2.70	39,200
	3.44	50,000	2.56	37,000
	3.45	50,100	2.57	37,300
	—	—	—	—
Average	3.44	50,000	2.61	37,800



Figure 7. Pressure Vessel Prior to Testing.



Figure 8. Pressure Vessel After Testing Showing Failed Seam.



Figure 9. Ultrasonic Tests Results on Seam C-D of Second Pressure Vessel - Dark Areas Are Welded.

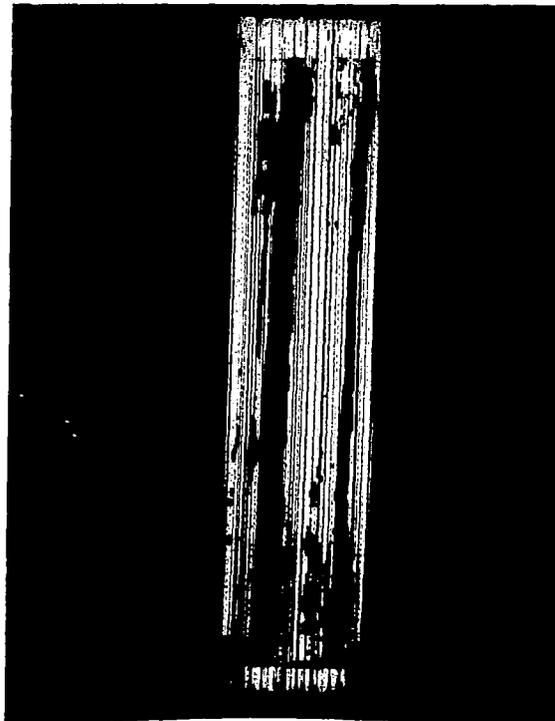


Figure 10. Ultrasonic Tests Results on Seam A-B of Second Pressure Vessel - Dark Areas Are Welded.

fabrication of the second vessel. This seam was repaired by putting a fiberglass overlay over the seam to hold the pressure. The second vessel was pressured and failed in the weld seam at a pressure of $1.97 \times 10^{-1} \text{kg/mm}^2$ (280 psig).

An inspection of the vessels after testing showed that the vessels had bulged around the circumference in the heat affected zone (Arrows in Figure 8). Since the fusion weld was heavy, the heat affected zone extended about one centimeter (0.4 inches) into the cylinder. Further inspection of the first vessel showed a crack had developed on the fusion weld at the base of the explosion bonded seam.

The results of this inspection would indicate that the heat affected zones were points of weakness and even though the explosion bonded seams failed, the start of failure was probably in the heat affected zone. The explosion bonded seams would have been tempered by the fusion welding process reducing their strength in the heat affected zones. Once a failure started in this zone it would act as a stress riser and the crack would propagate at a lower stress than the tensile strength of the material.

The actual strength of the material heat affected zone would probably be on the order of 6.89×10^7 to $1.379 \times 10^8 \text{N/m}^2$. (10,000 to 20,000 psi), since the material pressure test on the vessel was not an actual test of the strength of the explosion bond as would be done in the field but rather one of a tempered bond which would be notably weaker.

D. PRESSURE TEST ON DISC

An explosion bonded disc was supplied by NASA for pressure testings to circumvent the problem with a mixed welding system. Fabrication procedures for the disc were described previously.

The disc was pressurized to a load of $6.33 \times 10^{-2} \text{kg/mm}^2$ (90 psig). After each pressure cycle, the load was removed. This was done for 10 cycles and then the load was increased to $7.03 \times 10^{-2} \text{kg/mm}^2$ (100 psig). The disc failed on the fifth pressure cycle at $7.03 \times 10^{-2} \text{kg/mm}^2$ (100 psig). Both loads were above the elastic limit of the disc as the thin metal had started to bulge as is shown in Figure 11.

The disc failed immediately adjacent to the explosion bonded seam but not through the seam showing that the weld was stronger than the parent material.

V. CONCLUSIONS

To demonstrate the potential of the NASA-LRC explosion bonding technique to meet current fabrication requirements, a test program was conducted on explosion bonded joints, and compared to TGA fusion joints in 6061-T6 aluminum. The comparison was made in required fixtures, non-destructive testing, static strength and fatigue strength (tension-tension and flexural).

The explosion bonding technique requires only simple tooling and no clamping to prevent distortion. However, in joining cylindrical sections, considerably more effort was required to maintain relative placements of plate materials to control necessary parameters. Following joining, ultrasonic inspection proved to be an accurate tool to identify bonding efficiency.

In all cases of static and fatigue strengths, the explosion bonded flat plates outperformed the fusion joints (discussion on comparisons).

In fabricating vessels, difficulty was encountered in using both explosion joining and fusion welding. The explosion bonded joint's strength was reduced by the heat-affected zone of the fusion joint, introducing a failure which propagated down the explosion joint. In a simple vessel, using only explosion joining, no such strength loss was indicated. Further on absolute hermetic seal was achieved.

Based on these results of high static and fatigue strengths, inspectability and sealing capability, the NASA-LRC explosion bonding process shows a great deal of promise. However, more experimental work is necessary to control the joining variables, particularly in more complicated structures of this type of joint configuration.

Reference: Bement, L. J. "Small Scale Explosive Seam Welding", presented at Symposium on Welding, Bonding and Fastening, Williamsburg, VA, 1972.



Figure 11. Explosion Bonded Disc After Loading to $7.03 \times 10^{-2} \text{ kg/mm}^2$ (100 psig) Showing Bulging of Thinner Material.