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PRACTICAL SMALL-SCALE EXPLOSIVE SEAM WELDING

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ABSTRACT

A small-scale explosive seam welding process has been developed that can significantly contribute to remote metal joining operations under hazardous or inaccessible conditions, such as nuclear reactor repair and assembly of structure in space. This paper describes this explosive seam welding process in terms of joining principles, variables, types of joints created, capabilities, and applications. Very small quantities of explosive in a ribbon configuration are used to create narrow (less than 0.5 inch), long-length, uniform, hermetically sealed joints that exhibit parent metal properties in a wide variety of metals, alloys, and combinations. The practicality of this process has been demonstrated by its current acceptance, as well as its capabilities that are superior in many applications to the universally accepted joining processes, such as mechanical fasteners, fusion and resistance welding, and adhesives.

INTRODUCTION

The demand is increasing for highly reliable, remote, metal joining processes for hazardous or inaccessible operations, such as nuclear reactor repairs or assembly of structure in Earth orbit or space. The NASA Langley Research Center-developed explosive seam welding process in creating narrow, long-length, uniform joints can contribute significantly to joining operations, due to many capabilities that exceed the universally accepted joining processes, such as mechanical fasteners, swaging, fusion welding, soldering, and adhesives. The purpose of this paper is to present this process in terms of the joining principles and variables, types of joints, capabilities, and current and potential applications.

EXPLOSIVE JOINING PRINCIPLES

Explosive welding produces metallurgical bonds that are impossible to achieve by any other joining process. The explosive welding process is accomplished by a high-velocity, angular collision of metal plates, which effaces the oxide films on both surfaces to allow interatomic (electron sharing) linkups through Van der Waal forces. (See References 1, 2, and 3.) The angular collision and parameters are shown in Figure 1. The several

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million psi explosive pressure on top of the flyer plate produces velocities in the plate of several thousand feet per second. On impact, the kinetic energy is converted to skin-deep (less than 0.001 inch) melts, which are stripped from the surfaces and squeezed out by the closing angle. The closest analogous metallurgical bonding process is vacuum bonding in which surface oxides are mechanically removed under hard vacuum to allow interatomic linkups. Two explosive joining processes now exist, cladding and seam welding.

The explosive cladding process (Reference 1) utilizes bulk explosives, such as dynamite or nitroguanidine, to create an explosive pressure input that travels at a velocity of approximately 4000 to 10,000 ft/sec to create the angular collision. The loose-powder explosive is literally shoveled onto the flyer plate, which is spaced in parallel to the base plate. For example, in Reference 1, 175 pounds of dynamite was used in cladding a 0.125-inch thick, 4- by 8-foot lead sheet to a 0.25-inch thick steel plate. Explosive cladding is limited to approximately 10-foot lengths, due to the inability to maintain the collision parameters.

The explosive seam welding process (References 2 and 3) differs from cladding in the explosive used and the angular collision mechanisms. The explosive used is considerably more powerful, cyclotrimethylene-trinitramine (RDX), which is encased in a lead-sheathed "ribbon," as shown in Table I. The explosive load is measured in grains per foot (7000 grains per pound), and has a velocity of explosive propagation of 26,000 ft/sec. The plates are initially separated and the ribbon explosive is taped to the flyer plate. On initiation of the explosive, the center portion of the flyer plate is bent, as shown in Figure 2, to produce angular collisions on both sides. The resulting joint is highly uniform and less than 0.5 inch in width. As a comparison of efficiency, a 175-pound quantity of RDX could produce a continuous joint in 0.125-inch aluminum 49,000 feet long. With an approximate weld width of 0.25 inch, the total weld area would be over 1020 square feet, as compared to the 32 square feet in the cladding operation.

SEAM WELDING VARIABLES

The following explosive welding variables must be optimized for every joining configuration (References 2 and 3):

1. Plate materials
2. Plate thickness
3. Explosive quantity
4. Standoff (plate separation)
5. Surface finish and cleanliness
6. Mechanical shock

Metal alloys, conditions, and thickness present a wide range of density, mass, hardness, and malleability. These variables directly influence the quantity of explosive necessary to bend and accelerate the plates to achieve explosive joining. As the above variables increase, more explosive is necessary.

A plate standoff or separation is required to achieve the high-velocity, angular collision. The amount of standoff can be as little as 0.010 inch, the maximum (to minimize material deformation and energy losses in bending) is 0.025 inch. This standoff can be achieved by shimming, fixturing, or machining. Any convenient shim may be used, including masking tape. A notch can be machined in the surface of either or both plates. The plates can be configured to present a parallel interface, or, to maximize efficiency, an angular interface (inverted "V") can be machined into one or both plates; that is, 5^{o} angular faces, sloping from the center of the desired joining interface outward to a depth of 0.015 to 0.020 inch. An example of the latter approach follows in the applications section.

Surface cleanliness and smoothness must be carefully managed to achieve explosive joining success. The properties of substantial amounts of oxide films, such as rust or that on aluminum alloys, as well as water, grease, or oil, prevent the explosive joining process. Iron alloys must be polished and degreased to remove mill scale and corrosion-protective greases; 100 grit emory paper and an alcohol wipe, or other solvent that leaves no deposit on drying, is adequate. Stainless steel alloys need only degreasing. Pure aluminum has a minimal oxide film, requiring only degreasing. However, the aluminum alloys develop oxide films that prevent joining. These oxide films have considerably different properties than the parent metal. These oxide films are dependent on manufacturing processes and environmental exposure. Chemical etching to remove the oxide films allows reliable bonding under laboratory ambient over a several-week period. Since explosive joining is a "skin deep" process (0.001 inch penetration), surface scratches more than 0.003 inch deep prevent joining. A surface finish of 32 rms assures complete bonding. The surface finishes on virtually all sheet metal stock are smoother than 32 rms.

The mechanical shocks generated by the explosive pressure used to accelerate the plates and that generated on impact are the most damaging influence in the explosive joining process. The relative amplitude and influence is dependent on materials and structural configuration. These shock waves can not only damage sensitive structure in the area of the process, but can actually destroy a bonded joint immediately after its creation. Shock waves can be reduced by placing additional structure in the bond area. This additional structure can be a plate on the opposite side of a joining process (anvil), or clamping plate stock just outboard of the joining process. Once the joint has been made, the additional structure is removed. Adequate shock absorption can be achieved in the structure to be joined, particularly in thicker materials.

TYPES OF JOINTS

Four different types of lap joints and tube joining have been demonstrated, using explosive seam welding.

The four joint types are shown in Figure 3. The dissimilar-thickness joint was described earlier. The similar-thickness joint is created by placing explosive ribbons on both sides of the separated plates. The ribbons are simultaneously initiated by one blasting cap. The explosive pressures are exactly balanced. The sandwiched-butt joint combines the above two approaches to accomplish a butt joint. The scarf joint (Reference 4) is created by shifting the longitudinal axes of the explosive ribbon to create unbalanced forces. The plates are bent into axial alignment and joined in a single operation.

One setup for explosive seam welding to accomplish tube plugging is shown in Figure 4. Cylindrical plugs are machined to provide an "inverted V," angular interface, and are inserted into the tube. The explosive ribbon is wrapped around the outside circumference, opposite the inverted V, and initiated.

Tube joining is accomplished in the setup shown in Figure 5. Following tube insertion, the explosive is initiated by the blasting cap indicated. The inner tube is driven into the outer tube to accomplish the joining mechanism. The anvil ring prevents distortion of the female tube. Conversely, the outer tube (without the anvil ring) could be wrapped with explosive and driven into the male to accomplish the joining mechanism. The V-notch can be machined into either tube, or partially in both.

CAPABILITIES

The following is a general description of the capabilities of the explosive seam welding process.

1. Performs under hazardous conditions - This process can be used in hostile environments or conditions to reduce risks to personnel and facilities. The explosive materials (a number of different types are available with different characteristics) and joining process have a low sensitivity to environments, such as nuclear radiation, toxic atmospheres, inert gases, vacuum, hot (+450°F) and cold (-320°F) temperatures, and high-intensity light and sound. The recommended approach would be to install the explosive materials on the structure to be joined, prior to insertion into the hazardous environment or condition.

2. Remote - This process has the capability of hands-on operation to separation distances of miles. A totally confined explosive seam welding process has been developed, as shown in Figure 6 (Reference 5). The explosive ribbon is placed inside a flattened steel tube with closed end fittings, which accommodate the initiator and initiating method. On initiation, the explosive pressure is coupled through the tube wall to accomplish the welding mechanism, and the explosive products are contained within the tube. This method not only allows hands-on operation, but prevents the contamination of surrounding areas by the explosive products. Long-distance operation can be achieved by transmission of command signals to self-contained receiving units

which initiate the explosive mounted on the structure to be joined. This transmission approach is routinely applied to orbital and deep-space functions.

3. Simplicity - Once the explosive joining parameters have been established, the setup becomes purely mechanical. Minimal training is required, typically less than eight hours.

4. Material preparation - Machining, polishing, and/or chemical degreasing and cleaning are comparable to other joining processes. The explosive ribbon and blasting cap are simply taped or bonded to the materials to be joined.

5. High-strength, fatigue-resistant joints - This is a cold-working process which does not affect the parent metal properties. The area of the metallurgical bond can be created, through preselection of joining variables, to exceed the strength of the material thicknesses by a considerable margin. The resulting joints greatly exceed the fatigue strength (tension-tension and flexural) of fusion-welded joints (Reference 6).

6. Ability to join a wide variety of metals and alloys - Table II lists the metals and range of thicknesses in which 100% strength joints can be obtained (References 2 and 3). The plates to be joined were placed in parallel (except as noted), separated by 0.015 inch.

7. Ability to join metal combinations - This process can metallurgically join a wide variety of metal combinations, as well as different tempers and conditions. Table III provides a summary.

8. Ability to join very thin materials to very thick materials - The highest efficiencies in this process are achieved, using very thin flyer plates to thick base plates. Thin materials are most responsive to acceleration, as well as bending to achieve the necessary high-velocity angular collision. Furthermore, the thick base plates quickly dissipate deleterious shock waves. The thickness of the flyer plate is limited by its ability to resist being crushed and pinched off (0.001 inch in steel, 0.010 inch in aluminum). There is no upper limit on base plate thickness.

9. Ability to join a wide range of lengths and tube diameters - The minimum length that can be joined by this process is approximately 0.040 inch; there is no long-length limitation. The explosive ribbon is routinely manufactured in several hundred-foot lengths. The ribbon can be spliced with no loss in efficiency. The minimum tube diameter that can be joined by this process is approximately 0.040 inch with no upper diameter limit.

10. Ability to join complex shapes - This process can join a wide variety of shapes from flat stock to irregular shapes to tubes (cylindrical and non-cylindrical). The explosive ribbon is highly flexible and can be shaped to conform to a wide variety of contours. Shaping limits are: a bend radius of

0.063 inch on the ribbon's flat surface, and approximately a 1-inch radius to shape the ribbon on its edge, maintaining a single plane.

11. Joint uniformity and reliability - The joints created by this process exhibit a high degree of physical uniformity, in terms of the plate surfaces, areas, and thicknesses worked by the explosive pressure, bond areas, and joint strengths. The ribbon is manufactured to exacting aerospace standards; the explosive load in the ribbon varies less than 5% down the length. The plate surfaces are protected from lead embedment by masking or double-backed tape. The plate thicknesses of softer metals are reduced by approximately 0.005 inch by the explosive pressure. Once the joining variables are established, the resulting joint variations are caused by material preparation and machining and stock uniformity.

12. Inspectability - The joints can be evaluated nondestructively, using ultrasonic techniques, such as those described in Reference 7. Since the surfaces and thicknesses of the joints are highly uniform, the bond areas can be precisely located.

13. Hermetically sealed joints - The metallurgical bond created by this process has demonstrated absolute sealing ability. No leaks were detected (less than 1×10^{-9} cc/sec of helium at one atmosphere differential pressure, or the instrument's sensitivity limit) on a 12-inch diameter aluminum joint, before and after pressurization to 100 psi dry nitrogen. A surface finish of 32 rms is required.

14. Tooling - No tooling is required, provided the variables are controlled. However, the plates can be positioned by fixturing, or removable "anvils" can be used to maximize joining efficiency by reducing deformations and absorbing shock waves, as described in the explosive seam welding variables section.

15. Rapid operation - The explosive ribbon can be installed quickly; the installation can be mechanized and automated. On initiation of the explosive, the joining process proceeds at a velocity of 26,000 feet/second.

16. Low input-energy requirements - The explosive ribbon produces all the energy necessary to create a joint. Typical electric blasting caps, used to initiate the explosive, require approximately 0.1 joule (watt-sec). A number of other aerospace approaches for initiation can be used, such as mechanically actuated percussion primers (using human, hydraulic, pneumatic, or electrical energy sources), explosive transfer lines, or lasers. Each initiation method has its unique advantages and disadvantages in terms of cost, availability, safety, and system effects.

17. Balanced forces - The explosive joining setups can be configured to produce opposing explosive inputs to minimize or eliminate offsetting forces. For example, placing explosive ribbons on both sides of a structure (with simultaneous initiation), and cylindrical joints would generate symmetrically opposed forces.

18. Safety - The RDX explosive ribbon cannot be initiated by routine handling and cutting by personnel or electrical inputs (Reference 3). Other explosive materials, such as dipicramide, are available, that are insensitive to rifle fire and lightning. Dipicramide is stable to 450°F for 50 hours, and will burn with low energy output, but will not detonate. Simple procedures on controlling personnel accessibility, handling, and storage will preclude potential hazards. Electric blasting caps must use electrical shielding, grounding, and fail safe firing systems. The explosive products (lead fragments, pressure wave, and carbon-particle smoke) can be easily contained by several cubic-foot volume shielding. Since only small quantities of explosive are used, the explosive pressure attenuates to less than one psi within the first foot of distance from the source.

APPLICATIONS

Small-scale explosive seam welding has been accepted for one major application. Although joining problems are virtually unlimited, a number of other potential joining applications that take advantage of the unique capabilities of this process are presented here.

Present application - The first major application in which small-scale explosive seam welding will be used (scheduled for 1985) is in the repair of four nuclear reactors in Canada (Reference 7). A total of 390 fuel channels must be removed and replaced in each reactor. This process was developed and demonstrated in six months to make the final joint on the reactor face for each fuel channel. A 30 grains/foot ribbon will be double-backed tape to the internal circumference of the end fitting attachment ring (Figure 7) with the ribbon centered on the machined "V." An electrical blasting cap will then be installed on the butted interface of the ribbon. The fuel channel with attachment ring will then be inserted into the reactor, positioning the attachment ring opposite the bellows flange sleeve, as shown. The resulting joint has twice the bond area necessary to support the fail strength of the 0.030-inch wall thickness tube. This large bond area compensates for the known range of variables, such as surface finish and diametrical mismatches to 0.060 inch. One joint was subjected to 100 thermal cycles of 560°F to ambient with no loss in strength. The use of this process, instead of a robotic fusion welder, is anticipated to reduce personnel radiation exposure from 11.43 man-rems to 0.7 man-rem, and reduce reactor downtime from 78 hours to 1.6 hours.

Potential applications - Potential applications may include pipelines, sealing of vessels, and assembly of large space structures.

This process could be used in joining and sealing thin-walled tubing. For thick-walled tubing, the primary loads could be carried through bolted flanges, and the joint sealed with an explosively joined internal sleeve. Tubes could be plugged by using closed-end cylinders, joined to the internal diameter of the tube.

Vessels could be remotely capped and sealed, as shown in Figure 8, for disposal of hazardous wastes or to prevent contamination of materials. As an example of the latter, a sample from the surface of another planet could be returned to Earth. An attempt to bring a sealed sample from the moon failed on the Apollo program, using mechanical seals.

Remote assembly of large space structures could be accomplished, using the concept shown in Figure 9. The explosive ribbon would be installed inside the closed, conically domed cylinder. The cone would assist in guiding and inserting the mating cylinder, which is part of a second structure. The closed volume would fully contain the explosive products.

A second space application could be the erecting and rigidizing of erectable structures, as shown in Figure 10. A 13-column structure can be erected by shortening the length of the central telescoping tubes. When erected to the desired shape, the telescoping tubes would be joined. Again, the structure would contain the explosive products.

Space assembly of continuous large-area structures may be desirable. Figure 11 shows an 18-inch diameter cylindrical model in which all the 0.040-inch aluminum (bulkheads, deck, and outer cylinder) was explosively joined to substructure.

CONCLUDING REMARKS

The demand is increasing for highly reliable, remote metal joining processes for hazardous or inaccessible operations. This paper describes a small-scale explosive seam welding process in terms of joining principles, variables, types of joints created, capabilities, and applications.

Explosive welding requires a high-velocity angular collision of explosively driven plates to break up and efface the plates' oxide films to allow interatomic linkups. Explosive seam welding utilizes lead-sheathed, small-quantity, explosive ribbons that have been loaded with several different quantities of explosive to create narrow (less than 0.5 inch), long-length, uniform joints. Explosive quantity is tailored to the metal alloy's properties, as well as thickness. Other variables include plate separation methods, surface finish and cleanliness, and the mechanical shock created by the explosive pressure input and plate impact.

Four different types of lap joints and tube joining have been demonstrated. The capabilities of this process include: remote operation under hazardous conditions, 100% of parent metal properties, join a wide variety of metals, alloys, and combinations (including steel from 0.001 to 0.050 inch and aluminum from 0.010 to 0.187 inch), simple operations, uniform, inspectable, hermetically sealed joints and fast, safe operations.

The current application of this process is to make 390 steel tube joints in each of four active nuclear reactors. This process has the potential for many hazardous and inaccessible operations, including assembly of structure in space.

The current development and acceptance of this small-scale explosive seam welding process has indicated that this process is indeed practical and has many capabilities that are superior in many applications to the universally accepted joining processes, such as mechanical fasteners, fusion and resistance welding, and adhesives.

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TABLE 1

Cross-sectional Dimensions of Linear Ribbon RDX Explosive

Explosive Load, grains/foot	Thickness, inch	Width, inch
7	0.020	0.220
10	0.020	0.300
15	0.025	0.315
20	0.030	0.365
25	0.035	0.370
30	0.035	0.510

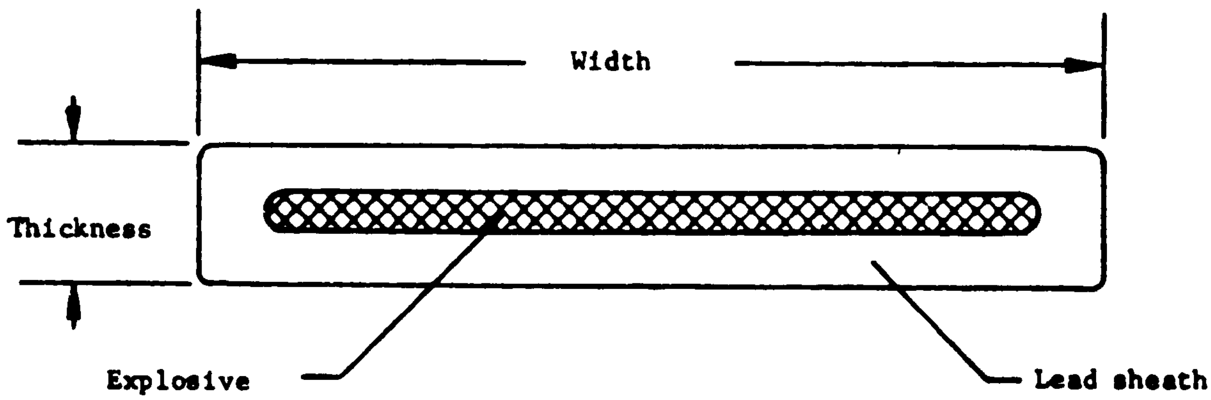

TABLE II

Like Metals Joinable by Explosive Seam Welding
(100% Strength Joints)

Metal	Range of Thickness (inch)
a. Iron/steel Low-carbon to 300 and 400 stainless	0.001 to 0.050
b. Aluminum - any fully annealed alloy and all age and work-hardened alloys except 2024 and 7075	0.010 to 0.188
c. Copper/brass	0.010 to 0.150
*d. Titanium (Ti-6Aℓ-4Va)	0.005 to 0.050

*Each plate prebent 5^{o}

TABLE III

Metal Combinations Joinable by Explosive Seam Welding

a. Low-carbon to series 300 and 400 stainless steel are joinable in any combination

b. All aluminum alloys and conditions are joinable to any other alloy and condition, except a combination of 2024-T3, T4, etc. and 7075-T3, T6, etc.

c. Any combination of copper, aluminum, and brass can be joined

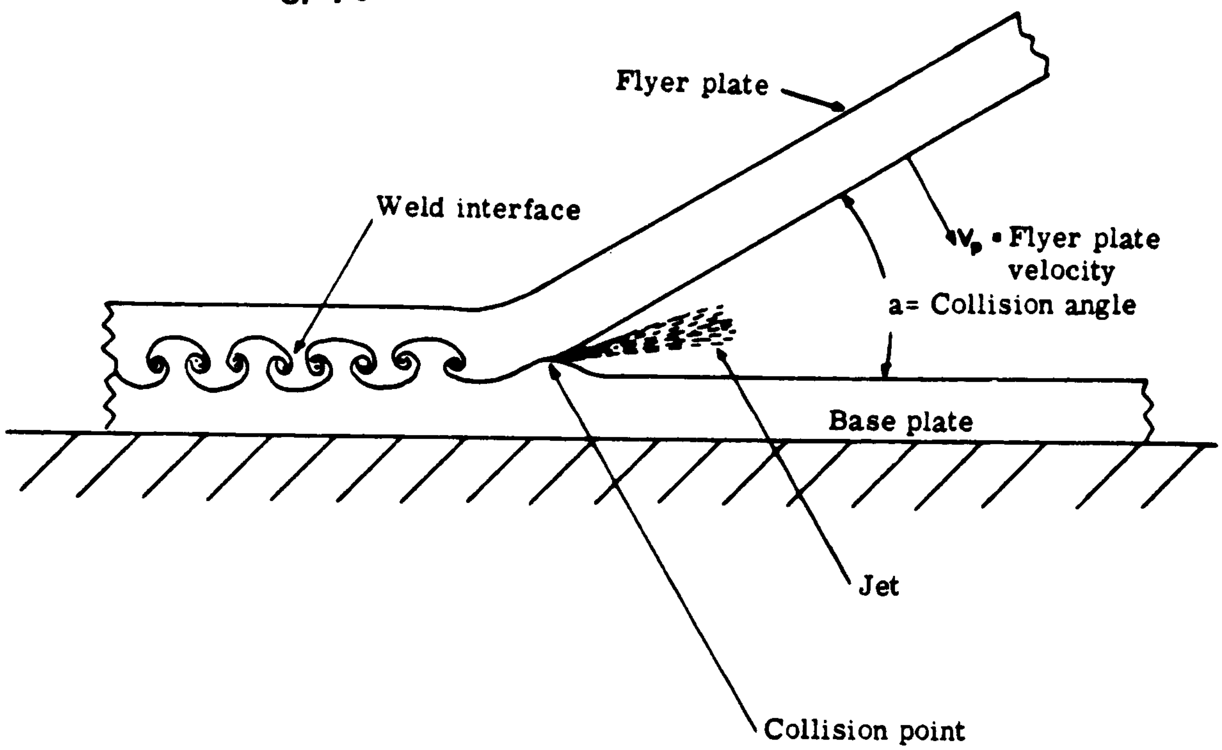

Figure 1.- High-velocity angular collision of metal plates in an explosive welding operation.

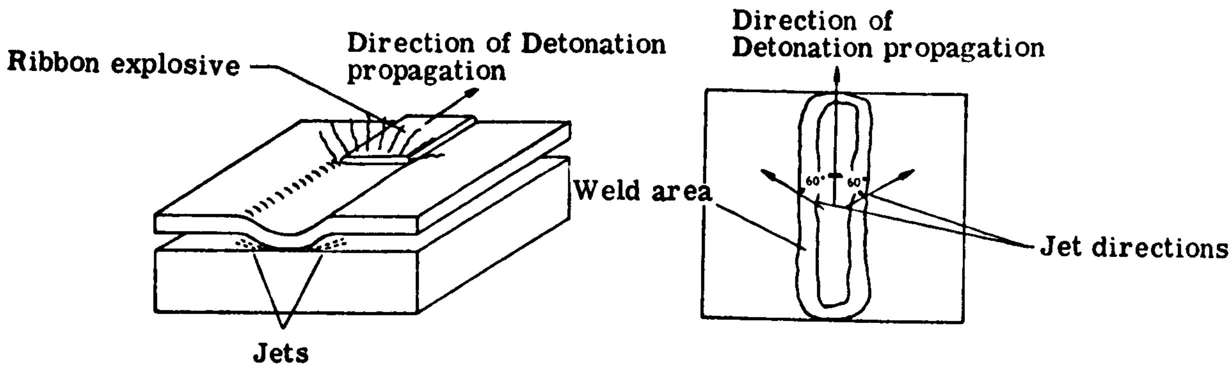

Figure 2.- Mechanisms involved in small-scale explosive seam welding process.

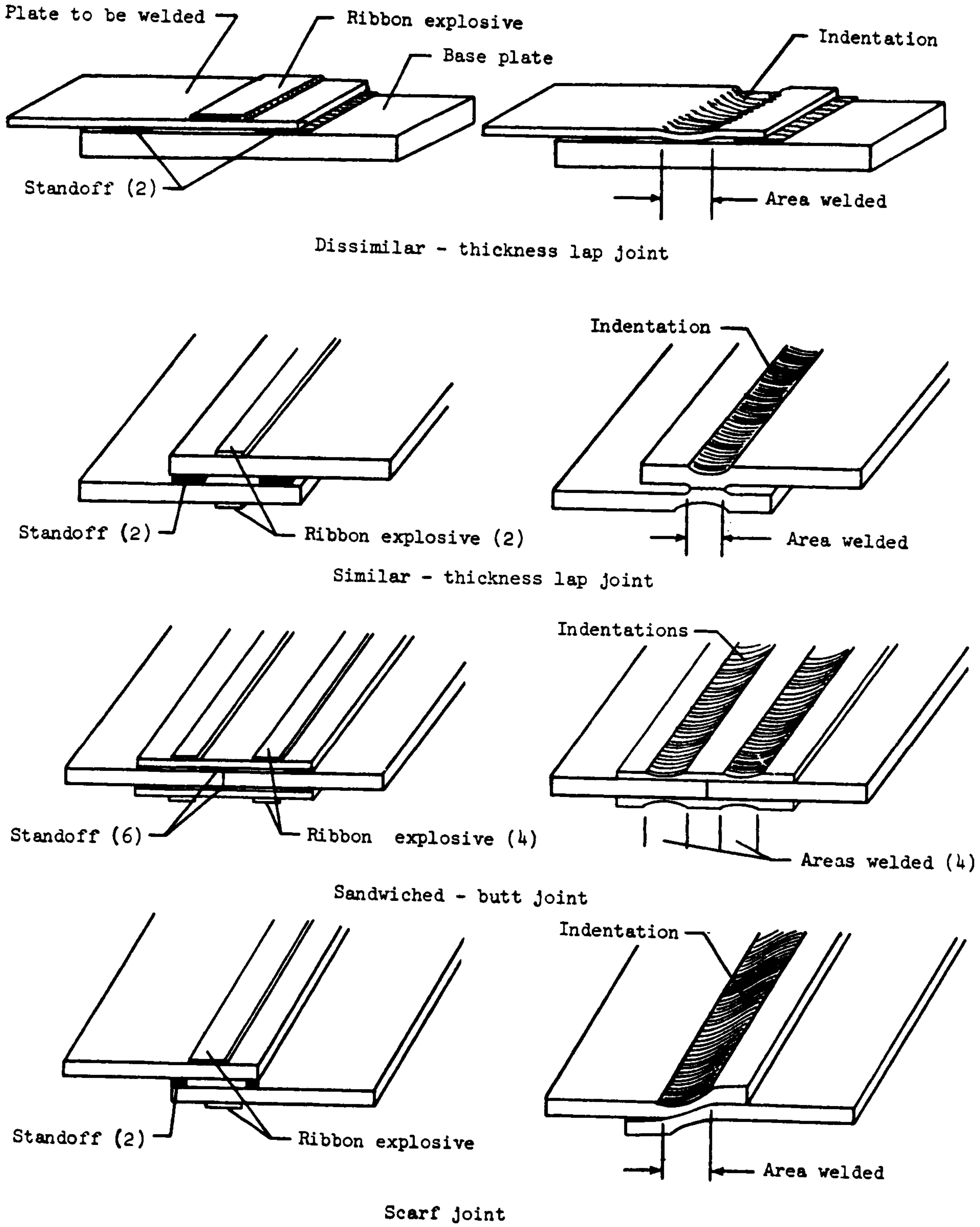

Figure 3.- Small-scale explosive seam welded joints.

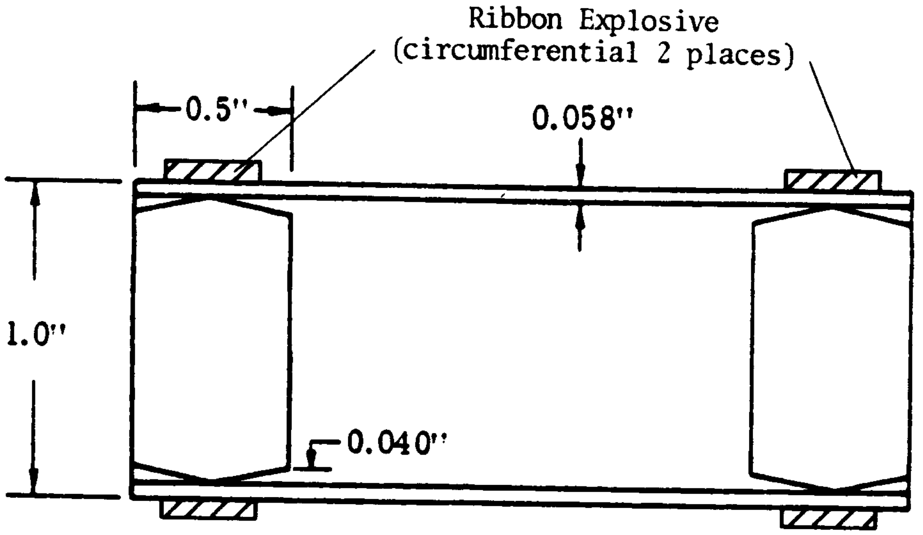

Figure 4.- Setup for explosive welding of 6061-T6 aluminum plug in 6061-T6 tube.

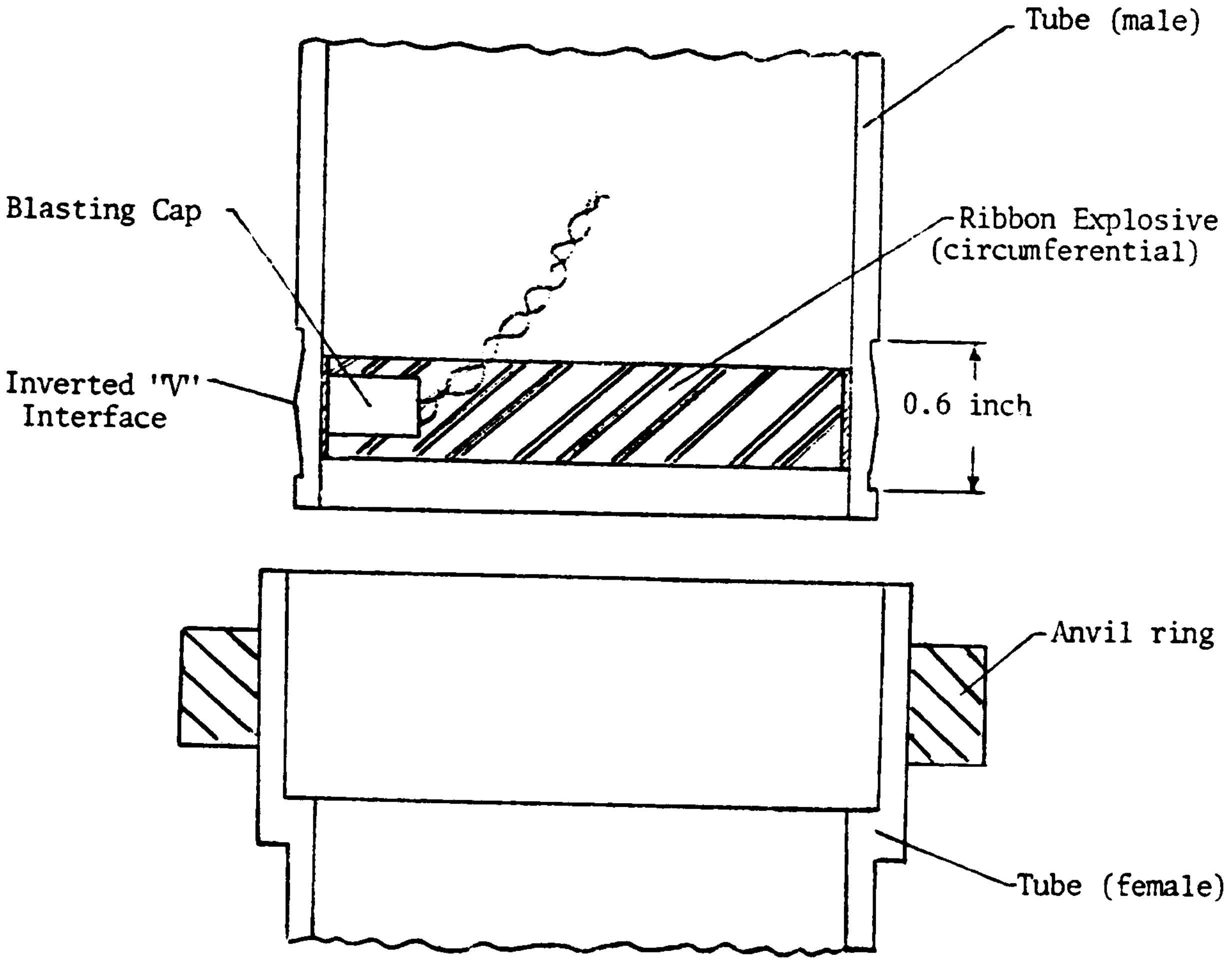

Figure 5.- Small-scale explosive seam welding setup for tubes.

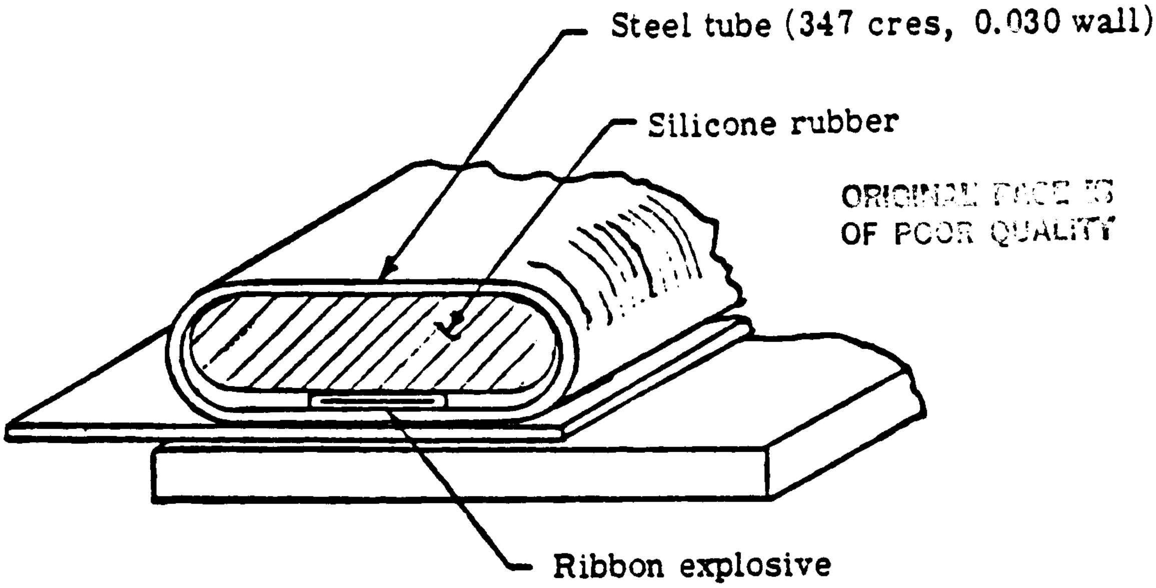

Figure 6.- Method for achieving a totally confined small-scale explosive seam weld.

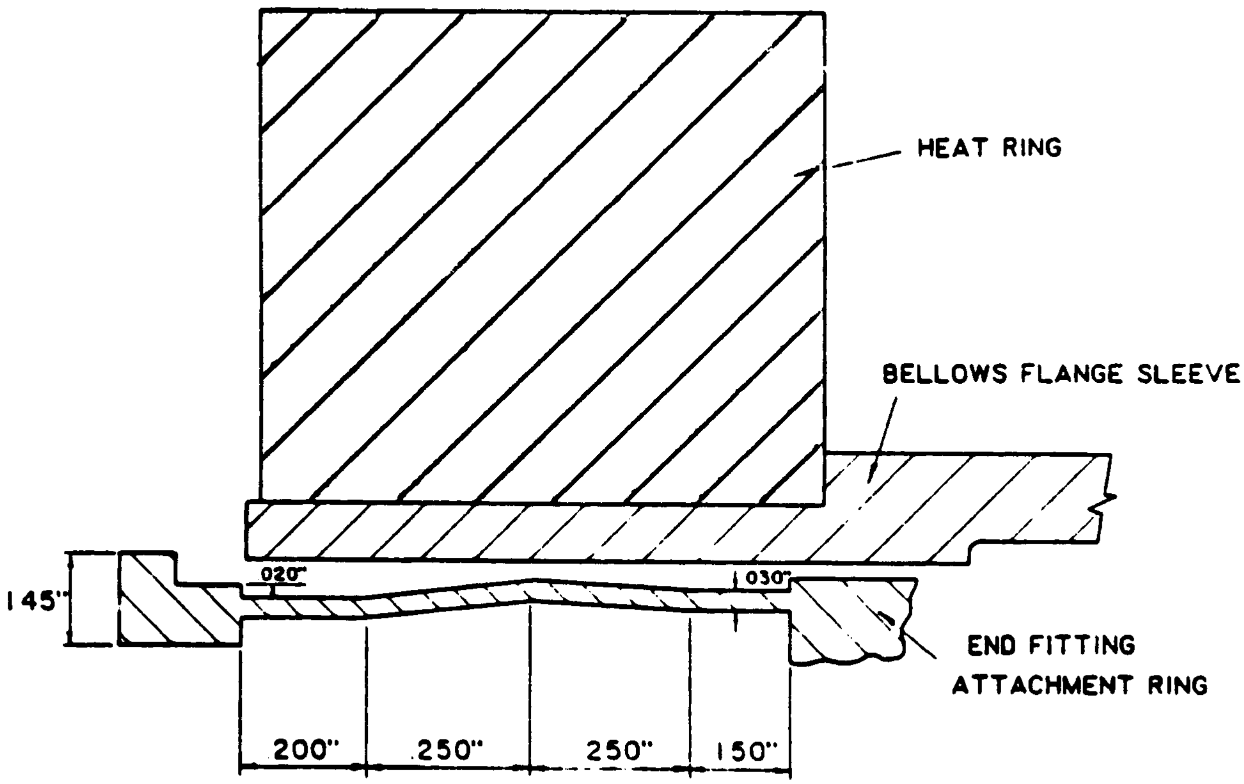

Figure 7.- Setup for explosive seam welding of nuclear reactor tubular joint.

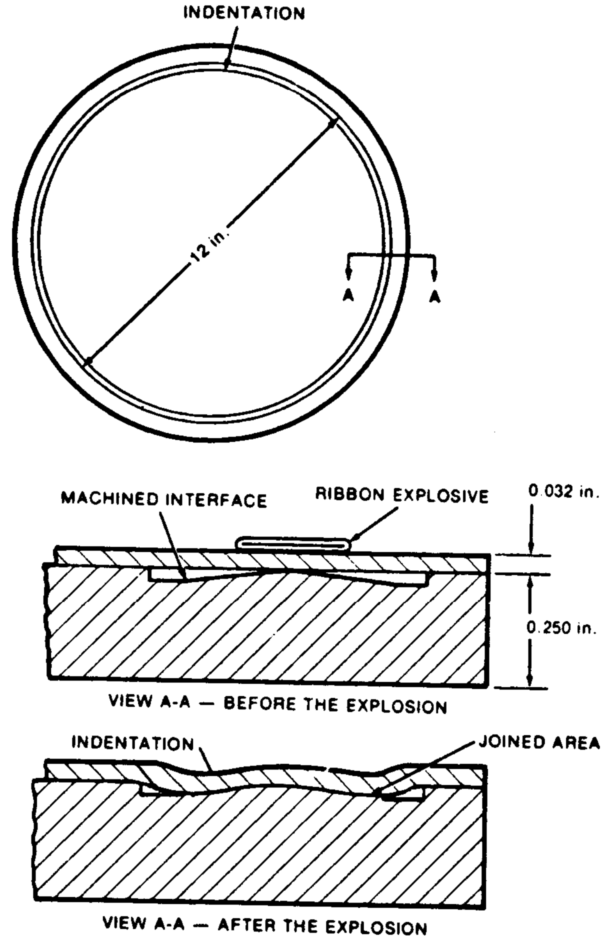

Figure 8.- Approach for closing and hermetically sealing a vessel.

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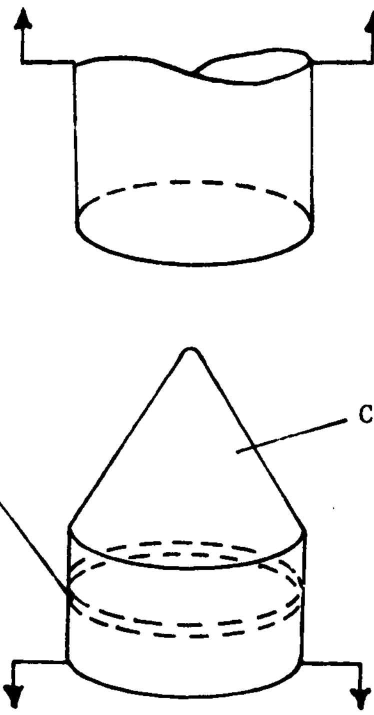

Figure 9.- Concept for totally confined, remote joining of structure in space.

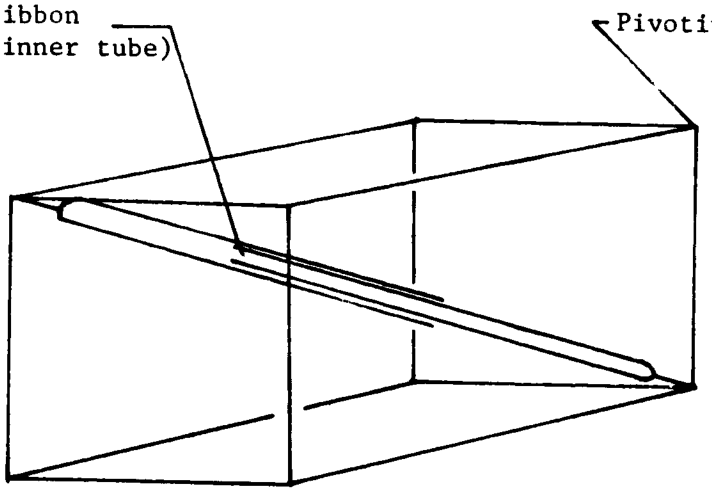

Figure 10.- Concept for totally confined, remote rigidizing of an erectable structure.

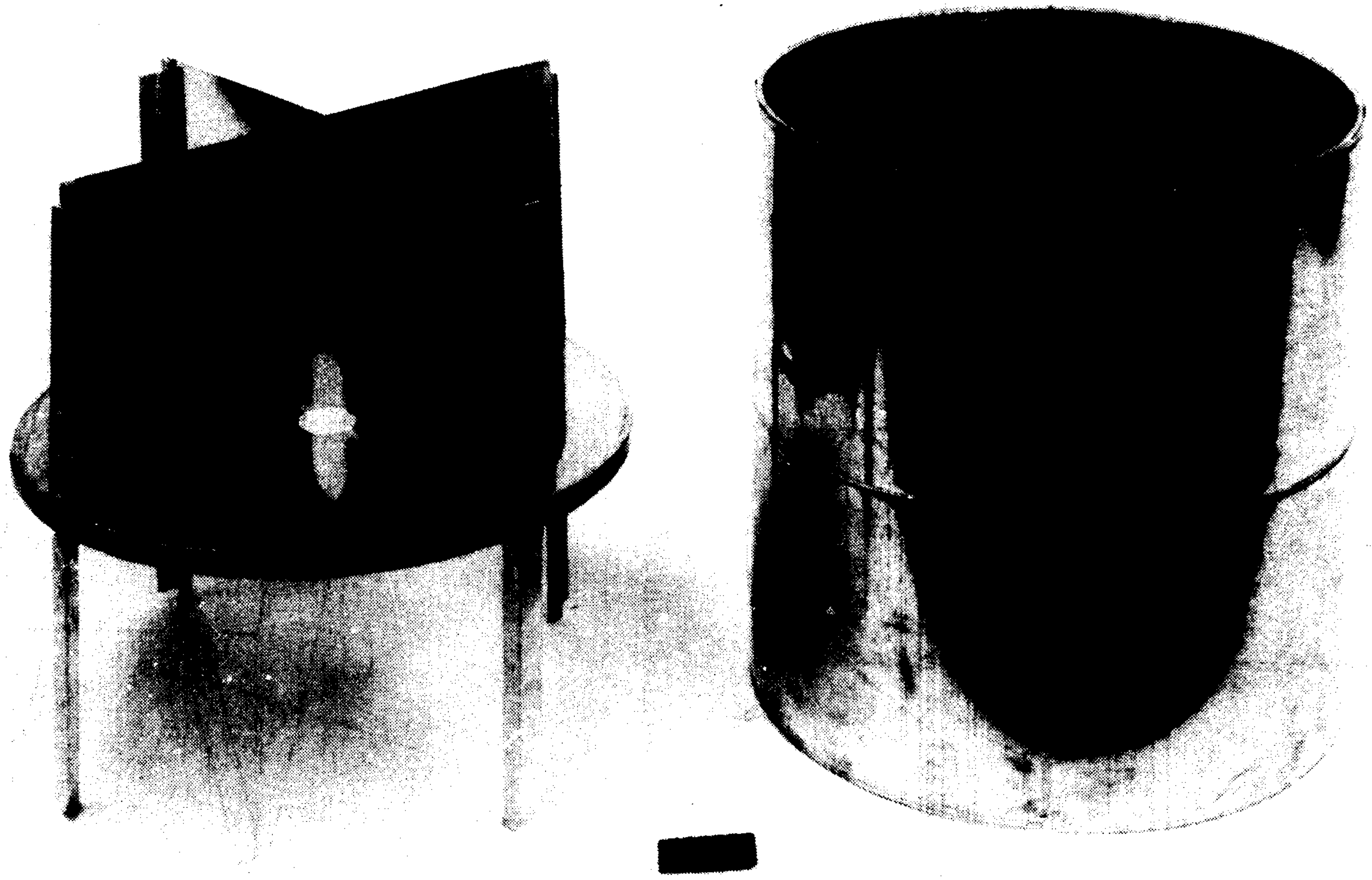

Figure 11.- Photograph of an 18-inch diameter model of a space station type structure fabricated by explosive seam welding; the internal structure of the model is shown on the left.