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APPLYING NASA'S EXPLOSIVE SEAM WELDING

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ABSTRACT

This paper summarizes the status of a novel explosive seam welding process, invented at NASA's Langley Research Center in the 1960's, developed and evaluated for a wide range of metal joining opportunities and now being used commercially. The process employs very small quantities of explosive in a ribbon configuration to accelerate a long-length, narrow area of sheet stock into a high-velocity, angular impact against a second sheet. At impact, the oxide films of both surfaces are broken up and ejected by the closing angle to allow atoms to bond through the sharing of valence electrons. This cold-working process produces joints having parent metal properties, allowing a variety of joints to be fabricated that achieve full strength of the metals employed. Successful joining has been accomplished in all aluminum alloys, a wide variety of iron and steel alloys, copper, brass, titanium, tantalum, zirconium, niobium, telerium and columbium. Safety issues have been addressed and are as manageable as many currently accepted joining processes. The Atomic Energy of Canada is evaluating this process for zirconium attachments in nuclear reactors. DEMEX International has licensed a NASA tube-joining patent and is applying it to tube plugging.

INTRODUCTION/BACKGROUND

Although the demand is increasing for highly reliable, metal joining processes both for hazardous or inaccessible operations and for the applications of advanced metal alloys and combinations, there is a general reluctance to accept explosive welding processes because of a perception that explosive materials cannot be safely managed. This combination of safety concern and the resistance to accepting novel joining methods has virtually reduced the potential user community to those that have exhausted all other alternatives. The purpose of this paper is to compile the history of the NASA explosive seam welding technology and provide the logic to show the practicality of its application in modern joining requirements. This will be accomplished by introducing the principles of explosive joining and the attendant variables, and presenting the NASA explosive seam welding process in terms of types of joints created, capabilities, the safety issue, and the applications considered for its use.

EXPLOSIVE JOINING PRINCIPLES

Explosive welding is a cold-working process that produces metallurgical bonds, exhibiting parent metal properties, which 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. See references 1 through 4. The angular collision and parameters are shown in the top sketch of figure 1. The several thousand megapascal (several million psi) explosive pressure drives the flyer plate (in a near-fluid condition) to velocities of a thousand m/sec (3.28 thousand ft/sec). On impact, the kinetic energy is converted to skin-deep (less than 0.0025 cm (0.001 in)) melts, which are stripped from the surfaces and squeezed out by the closing angle. Two explosive joining processes now exist, cladding and seam welding.

The explosive cladding process (reference 1) utilizes bulk explosive, such as dynamite or nitroguanidine, to create an explosive pressure input that travels at a velocity of approximately 1,300 to 3,300 m/sec (4,000 to 10,000 ft/sec) to create the angular collision. For the lead-to-steel cladding process in reference 1, 79 kg (175 lbs) of loose-powder dynamite is literally shoveled onto the 1.2 x 4.9-m (4 x 8-ft), 0.3-cm (0.125-in) thick flyer plate, which is spaced in parallel to the base plate. The explosive is detonated along the 4.9-m (8-ft) edge. Explosive cladding is limited to lengths of approximately 4.9 m (10 ft), due to the inability to maintain the collision parameters. The resulting bonds exhibit parent metal properties, and are generally observed through polishing and etching as the wavy weld interface, indicated in the top sketch in figure 1. These waves are truly, "skin deep," usually less than 0.006 cm (0.002 in), peak-to-peak; a stainless steel flyer plate, 0.0025 cm (0.001 in) in thickness, has been successfully joined and exhibited the full strength of the parent foil. Each set of variables, described later, produces a "signature" interface, which is unique to that set of variables. This signature can be virtually free of waves to very deep

(0.013 cm or 0.005 in), complex patterns. Microscopic analyses of this interface has indicated some entrapment of oxides and a slight amount of work hardening, but the actual interface of the two plates is an indefinable line, only as pronounced as the grain boundaries in the metals themselves. Figure 2 shows an example of an explosively joined interface, that is impossible to achieve by any other joining process, aluminum alloys of 2024-T4 to 6061-T6.

The NASA explosive seam welding process (references 2 through 9) differs from cladding in the explosive used and the angular collision mechanisms. The explosive used is cyclotrimethylene-trinitramine (RDX), which is encased in a lead-sheathed "ribbon," as shown in table I. The explosive load is measured in gr/ft (0.0198 g/m) with 7,000 gr/lb, and has a velocity of explosive propagation of 7,900 m/sec (26,000 ft/sec). The plates are initially separated by approximately 0.04 cm (0.015 in), and the ribbon explosive is taped to the flyer plate. On initiation of the explosive, the center portion is driven downward, as shown in the lower sketches in figure 1, to produce the high-velocity angular impact, from the center outward to both sides at a 60-degree "jet" angle. The resulting joint is highly uniform and just under the width of the ribbon explosive selected to accomplish the joining. As a comparison of efficiency to the cladding process described above, a 79-kg (175-lb) quantity of RDX could produce a continuous joint in 0.32-cm (0.125-in) thick aluminum 15,000 m (49,000 ft) in length. With an approximate bond width of 0.64 cm (0.25 in), the total bond area would be over 94 m^2 (1020 ft^2), as compared to the 3 m^2 (32 ft^2) in the cladding process.

EXPLOSIVE SEAM WELDING VARIABLES

The following variables must be optimized for every joining configuration, as described in references 2 through 4.

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

Metal alloy, condition and thickness present a wide range of density, mass, hardness, strength, rigidity and malleability. These variables directly influence the quantity of explosive necessary to bend and accelerate the plates to achieve explosive joining. As metal density, mass, strength and rigidity increase, the explosive quantity must be increased in a non-linear progression.

Standoff, or separation between the plates, is also required for the joining mechanism; standoffs of 0.025 to 0.064 cm (0.010 to 0.025 in) are readily achievable by means such as shims, tape, or fixturing. Larger standoffs not only reduce the efficiency of the joining operation, but also introduce fracturing of internal grain boundaries. A notch can be machined in the surface of either or both plates to achieve the necessary separation. The plates can be configured to present a parallel or angular interface. Prebending one or both plates efficiently introduces the necessary collision angle, which results in a larger bond area. The same result is achieved by machining a V-shaped notch, as shown in a later example.

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 the thinner, harder and tougher oxide on aluminum, as well as water, grease or oil, prevent explosive joining. Low-carbon iron alloys must be degreased and polished to remove corrosion-protective greases and mill scale (etching is not recommended, since rusting becomes extremely rapid). Stainless steel alloys need only degreasing and a final alcohol wipe. Pure aluminum has a minimal oxide film, requiring only degreasing. However, the oxide films on aluminum alloys require chemical etching for removal to allow reliable joining under reasonable, noncorrosive ambient conditions over a several-week time frame. Since explosive joining is a "skin-deep" process, surface finishes more than 0.008 cm (0.003 inch) in depth prevent joining; a surface finish of 32 rms, which is rougher than virtually all sheet metal stock, is adequate.

The mechanical shock generated by the explosive pressure used to accelerate the plates along with the shock generated by the impact of the plates are the most damaging influences in the explosive joining process. The relative amplitude and influence are 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 area. This additional structure can be a plate on the opposite side of a joining process (anvil), or clamping anvils in the immediate area. Adequate shock absorption can be achieved in the structure to be joined, particularly with thicker base plate materials.

TYPES OF JOINTS

Four different types of lap joints have been demonstrated, as shown in figure 3. The dissimilar-thickness joining process was described in the bottom illustration of figure 1. Similar-thickness joints can be achieved with the explosive ribbon on one side, but a more reliable approach places explosive ribbons on both sides of the separated plates. The ribbons are simultaneously initiated from a single source, such as a blasting cap, thereby balancing the explosive pressure waves. The sandwiched butt joint combines the above two approaches. The scarf joint (reference 5) 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. These basic joints can be applied in a variety of configurations, such as curved surfaces and tubes.

CAPABILITIES

The NASA explosive seam welding process has many capabilities which are comparable or superior to currently accepted joining processes. The following are summaries from the detailed descriptions found in reference 4.

Simple, high performance - This process is simple, requiring little material preparation and tooling, while producing high-strength, hermetically sealed, fatigue-resistant joints. Once the explosive joining parameters have been established, the setup becomes purely mechanical with minimal requirements for personnel training and certification. Explosive joining requires comparable preparations to currently accepted joining processes. Complex tooling to assure heat sinking and the prevention of material distortion as required for fusion welding are unnecessary; the explosive ribbon need only to be taped in place. Joints that exhibit full strength of the stock metals and parent properties throughout the bond will be achieved with explosive seam welding by proper selection of joining parameters. Since the joining process bonds at the atomic level, the joints achieve hermetic seals (described later in this text). The fatigue resistance of a 6061-T6 explosively welded lap joint (reference 6) was superior to a high-efficiency fusion welded butt joint, in spite of the asymmetry of the lap joint; the explosively welded joint was in fact comparable to the parent stock.

Thin to thick joints - This process can join very thin materials to very thick materials. Better results are achieved by joining thin to very thick materials, due to dissipation of mechanical shock.

Variety of alloys and combinations - A wide variety of metals, alloys and combinations have been demonstrated with this process. Table II lists the metals and range of thicknesses in which 100 percent strength joints have been achieved. Table III lists the combinations of metals that have been joined, again achieving full strength of the weaker of the two alloys.

Inspectable - These joints can be thoroughly inspected to assure complete integrity by using nondestructive ultrasonic methods. Since the surfaces and thicknesses of the resulting joints are highly uniform, the bond areas can be precisely located and evaluated.

No long-length limitations - Although an approximate 0.64-cm (0.25-inch) initial length is required to stabilize this welding process, there are no long-length limitations for explosive seam welding. The explosive ribbon can be manufactured in lengths of 100 m (328 ft), and can be spliced.

Remote joining capability - Explosive seam welding is ideally suited for remote operations and potentially hazardous conditions. This process has the potential for hands-on to deep-space operations. A totally confined process is described in reference 7. Placing the ribbon explosive inside a flattened steel tube, fully contains all explosive products to prevent harm to personnel or surrounding equipment. Once assembled and transferred to the use site, explosive initiation can be commanded by transmitters. This remote joining capability would be valuable for use in environments, such as nuclear radiation, toxic gases and extreme temperatures, that are hazardous to humans.

SAFETY

All safety aspects of the NASA explosive seam welding process can be controlled to levels comparable to currently accepted joining methods. Safety issues include the handling of the explosive materials, initiation and management of the explosive detonation products.

Explosive selection - Explosive materials are available that are insensitive to bullet impact and lightning, with demonstrated temperature stabilities to over 200 C (400 F) for 50 hours. These explosives used in the ribbon cannot be initiated by normal handling, such as cutting with scissors or a razor blade.

Initiation systems - Initiation systems must address both the prevention of inadvertent actuation, as well as reliable firing. Blasting caps, widely used industrial explosive initiators, are sensitive to a wide variety of extraneous inputs, such as impact, electrostatic voltages and stray electromagnetically induced or radio frequency energies. These potential hazards can be eliminated in a number of different ways; one approach is through the use of available exploding bridgewire (EBW) detonators rather than hot bridgewire blasting caps. Instead of a low-voltage/current input used for hot bridgewires, the EBW requires a unique high-voltage/current to "explode" a highly conductive bridgewire against insensitive explosive materials. Of course, interlocks and safing and arming systems for the actual firing system are still necessary. Mechanically initiated explosive transfer lines, used in the mining industry, are another approach.

Explosive containment - The greatest concern expressed by potential users are the products of the explosion; the energy in the pressure wave, the sound produced, the fragments and debris, and the smoke generated. The major advantage of the NASA explosive seam welding process is the use of very small amounts of explosive materials. For example, the joining of 0.32-cm (0.125-inch) aluminum requires 25 gr/ft (0.5 g/m) of ribbon explosive. A 6-m (20-ft) joint would require a total of 500 gr, or just over 28 g (1 oz) of explosive material. This small amount of explosive material actually generates few gas molecules; consequently, the actual pressure wave created decreases dramatically with distance from its original source (at a rate greater than the inverse distance, cubed). For example, within the first 30 cm (1 ft distance) away from the source, the pressure is less than 70,000 Pa (10 psi), and is much less than 7,000 Pa (1 psi) in the next 30 cm (1 ft). The debris created in the explosive joining process is primarily small-particle lead splatter and the tape used to position the explosive. The lead is easily captured by lightweight barriers, such as plywood. The residual airborne particles are primarily unreacted carbon, which can be collected in the same manner as arc welding fumes. Another approach for containment is to place the ribbon explosive inside a flattened steel tube, as described in reference 7; the tube fully contains all explosive products. In summary, properly selected explosive materials, initiators, firing systems and a 1-m (3.28 ft) width, height containment volume surrounding the length of explosive, or total confinement of the explosive at the source, will assure safe application of this joining process.

APPLICATIONAL EFFORTS

Several developmental efforts were made to apply this process in response to requests for support. One application is under evaluation, while another is now marketed commercially.

Sealing of Vessels

Three requests were received: the first for a method to close and seal a spacecraft vessel after collecting a sample from the surface of another planet, the second for a thin foil to seal an X-ray source and the third for a method to repair a puncture in the aluminum external tank for the Space Shuttle. All applications required joining a flat sheet to a plate.

Spacecraft vessel - For the spacecraft vessel, a 0.08-cm (0.032-in) thick, 6061-T6 aluminum disc was used, placing the explosive ribbon opposite the V-notched machined interface in the like-alloy base plate, shown in figure 4. Once joined, the vessel was helium leak-checked through a threaded port in the base plate with no leakage, pressurized to 0.7 MPa (100 psi) dry nitrogen, and again leak-checked with no leaks. A second 0.7 MPa (100 psi) pressurization caused the disc to burst, leaving the bond line completely intact.

X-ray source - The second request was to join a 0.0025-cm (0.001-in) thick, 300 series stainless steel foil to a 0.127-cm (0.050-in) thick, steel plate. A 5-cm (2-in) diameter bond line was accomplished in the foil, which could not be torn from the plate. This joint required the adhesive bonding of the foil to a 0.05-cm (0.020-in) thick sheet stock of aluminum, which increased the mass of the flyer plate and reduced the dynamics of the operation and prevented the crush-cutting of the foil. The adhesive shattered in the joining operation, debonding the foil from the aluminum and leaving the foil completely exposed.

Space Shuttle tank repair - The approach proposed for the third request, to repair a puncture in an aluminum vessel, is shown in figure 5. In this case, the two weld plates (patches) were prenotched to a 12.7-cm (5-in) diameter circle. Plates were to be placed on both sides of the skin to produce symmetrical loading during the joining operation. Two mild detonating fuses (MDF) transmitted the explosive initiation signal through simple flexible electrical conduit to the ribbon explosives. The explosive products would be contained by the firing box and acoustic chambers. The actual process was demonstrated with Space Shuttle 2219-T87 aluminum specimens. Again, full strength, hermetic seals were achieved.

Wire Splicing

The problem of achieving high-strength, fully conductive joining of wire to itself or to terminals is a universal problem. This explosive seam welding operation produces such joints, in the approach shown in figure 6. The solid wires are stripped of insulation and laquers, spread into a flat plane, alternating the wires from each side of the splice. A prebent copper (or other compatible metal) strip on which is mounted the ribbon explosive is slid over the wires and the explosive is initiated. There is no limit on the number of wires. Splicing of 0.063 and 0.23-cm (0.025 and 0.090-in) diameter copper wire has been demonstrated, using 0.076-cm (0.030-in) copper sheet stock. Once joined, the strip could be rolled and swaged into a smaller diameter. Since this is an atomic-level bond, conductivity would be expected to be very high.

Joining of Tubes and Strips to Tubes for Nuclear Reactors

Two collaborative efforts have been conducted with the Atomic Energy of Canada (AEC), a civil service organization responsible for technology development for the design and maintenance of the Candu nuclear reactor. The reactor generates high temperature/pressure water in 360, 10-cm (4-in) diameter, zirconium pressure tubes that are positioned horizontally through the reactor's containment (calandria) vessel and contain the fuel rods around which the water flows. These pressure tubes are contained within thin-walled, low-pressure (calandria) tubes that are sealed at the interior cylindrical faces of the calandria. Secondary 400 series stainless tubes are mounted on the outboard sides of the cylindrical calandria faces and adapted with fittings to interface to the pressure tube.

Large-diameter tube joint - The first request in 1981 was to develop a method to join a 20-cm (8-in) diameter, low-carbon steel sleeve on a bellows assembly to a similar steel adaptor flange, as shown in figure 7. The adaptor flange was machined to a 0.076-cm (0.030-in) thickness, V-notch interface. Full parent strength of the flange material was achieved, even when the adaptor flange was deliberately undersized by 0.15 cm (0.060 in) on the diameter. Direct joining of the low-carbon steel adaptor flange to the 403 stainless steel tube to replace a shrink-fit joint was also demonstrated. The implications of this effort are presented in reference 8. The use of this process could reduce the down time of the reactor and the radiation exposure to personnel 100 fold, compared to the currently accepted fusion welding process.

Strips to tube, exterior - The second effort, initiated in 1989, focused on joining 0.046-cm (0.018-in) thick zirconium strips to the outside of the 0.42-cm (0.165-in) wall thickness pressure tube to act as "ion getters" for the prevention of hydrogen embrittlement. The tubes were slipped over a close fitting mandrel to absorb the mechanical shock introduced into the tube, as well as to eliminate deformation of the tube. Considerable effort was made to protect both the tube and strips from damage from the explosive products. The results of these efforts are shown in figure 8. The AEC evaluation has shown excellent bonds, better than any other process they have examined. However, their metallurgists are concerned about stress lines that penetrate approximately 0.013 cm (0.005 in) into the tube. Long-term evaluations are now being conducted in which the joints are subjected to hydrogen-bearing compounds to accelerate the potential for hydrogen embrittlement.

Strip to tube, interior - The third effort applied the 0.046-cm (0.018-in) zirconium strips to the interior of the 0.127-cm (0.050-in) zirconium calandria tube to allow retention of ceramic spacers between the calandria and pressure tubes. An external mandrel was employed with dunnage and tape on the interior of the tube to capture the explosive debris. The requirements for this joining process are not as severe, since these tubes are not stressed as much as the pressure tubes. Samples are currently being evaluated by the AEC.

Small-Diameter Tube Joining

Two applications were evaluated, one to join tubes into fittings and the other to plug tubes.

Shuttle engine fitting - The liquid oxygen heat exchanger, located above the combustion chamber of the Space Shuttle's main engine, converts oxygen from a liquid to a gaseous state to pressurize the Shuttle's external tank. The assembly challenge was the joining of 316L steel tubing to Inconel 625, Incoloy 903 or Haynes 188 candidate materials for the end fittings. Requirements were temperatures from -162 to +427 C (-260 to +800 F) with the failure of the tubing being catastrophic. The effort was approached by using 30 gr/ft (0.6 g/m) of ribbon explosive to bond a 0.089-cm (0.035-in) thick 316L sheet stock to sample plates of the candidate materials, as shown in figure 9. No material indicated an advantage, since parent strength of the 316L was achieved in all three specimens. Figure 10 shows the assembly of the teflon tool (reference 9) used to join tubes to fittings. The small-diameter tube was loaded with an initiation charge, which was in turn initiated by the lead-sheathed explosive cord, projecting out of the centerline of the tool. The ribbon explosive was wrapped around the tool with its end butted into the initiator. Teflon tape was wrapped around the tool to assure a close fit with the tube. Figure 11 shows the joint achieved against a V-notched internal interface in a Haynes 188 fitting with a 0.66-cm (0.260-in) OD, 0.066-cm (0.026-in) wall tube. The upper figure shows the unsuccessful attempts to chisel/peel the tube out of the fitting.

Tube plugging - The above technology was adapted to tube plugging under a patent license to DEMEX International, as described in reference 10. Figure 12 shows the tools with external V-notches for several diameter tubes. The peak-to-peak ripple of the metallurgical bond, shown at lower right, is less than 0.005 cm (0.002 in). As stated in reference 10, in 1989 DEMEX and Southwestern Engineering Service Company "have made some 35,000 plug installations without an operational failure." The explosive welding technology , according to Southwestern Engineering, allows faster plugging, hence reduced down time, cuts plugging costs and increases reliability."

SUMMARY AND RECOMMENDATIONS

The NASA explosive seam welding process has demonstrated unique joining capabilities in sheet and tubular metal configurations, and has accumulated a history of consideration and acceptance that should provide potential users another fabrication option.

The small amounts of explosive used in this process produces narrow, controlled, full-strength lap joints in a variety of metal alloys and combinations. These joints exhibit hermetic seals, as well as resistance to fatigue.

This process not only can be managed safely in close proximity to personnel, but provides a capability for remote operation to eliminate the exposure of personnel to hazardous environments, such as from radioactive materials.

Successful demonstrations of this process in a variety of applications throughout the 20 years since its invention have shown its credibility. Considered were the sealing of vessels, wire splicing, joining of tubes and strips to tubes, joining of tubes to fittings and tube plugging. Its potential is being evaluated by the Atomic Energy of Canada for nuclear reactors. DEMEX, Incorporated has obtained a patent license from NASA for tube plugging.

With so many challenging joining problems in modern industry, as many joining methods as possible should be available; the NASA explosive seam welding process has achieved sufficient maturity to warrant its further consideration.

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TABLE I.-CROSS-SECTIONAL DIMENSIONS OF LINEAR RIBBON EXPLOSIVES

Explosive load, grains/ft	gm/m	Thickness, cm	inch	Width, cm	inch
7	.138	.051	.020	.559	.220
10	.198	.051	.020	.760	.300
15	.296	.064	.025	.800	.315
20	.395	.076	.030	.927	.365
25	.494	.089	.035	.940	.370
30	.593	.089	.035	1.295	.510

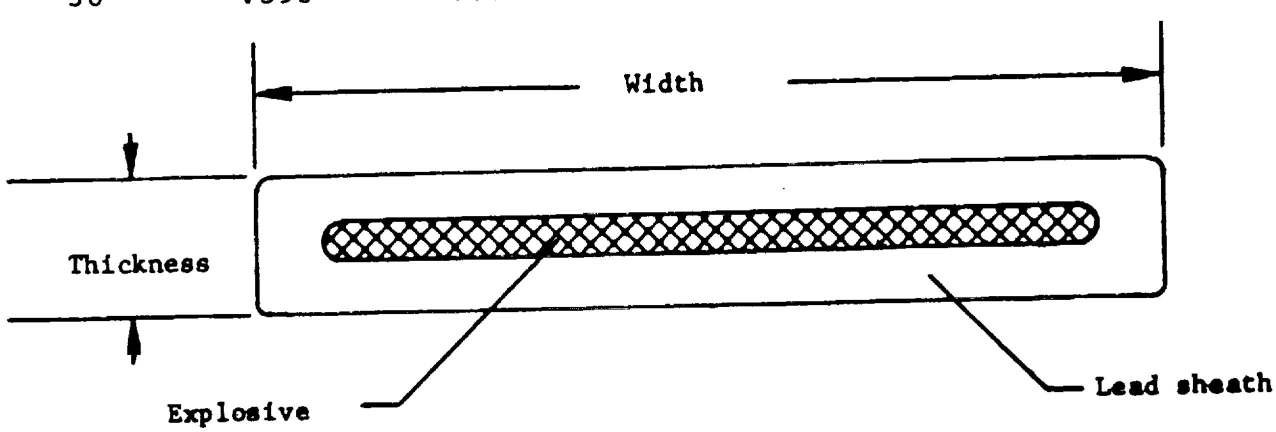

TABLE II.- LIKE METALS DEMONSTRATED JOINABLE BY EXPLOSIVE SEAM WELDING (100% STRENGTH JOINTS)

Metal	Range of Thickness cm	inch
a. Iron/steel Low-carbon, 300/400 ss	.003 - .127	.001 - .050
b. Aluminum - any fully annealed alloy and all age and work-hardened alloys, except 2024 and 6061.	.025 - .478	.010 - .188
c. Copper/brass	.025 - 0.381	.010 -.150
d. Titanium (Ti-6Al-4V)	.013 - .127	.005 -.050
e. Tantalum	.227	.090
f. Zirconium	.160	.063
g. Columbium	.081	.032

TABLE III.- METAL COMBINATIONS DEMONSTRATED JOINABLE BY EXPLOSIVE SEAM WELDING

a. Low-carbon to series 300 and 400 stainless steel 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. to 7075-T3, T6, etc.

c. Any combination of copper, aluminum, and brass

d. Tellurium to niobium

e. Nickel to steel

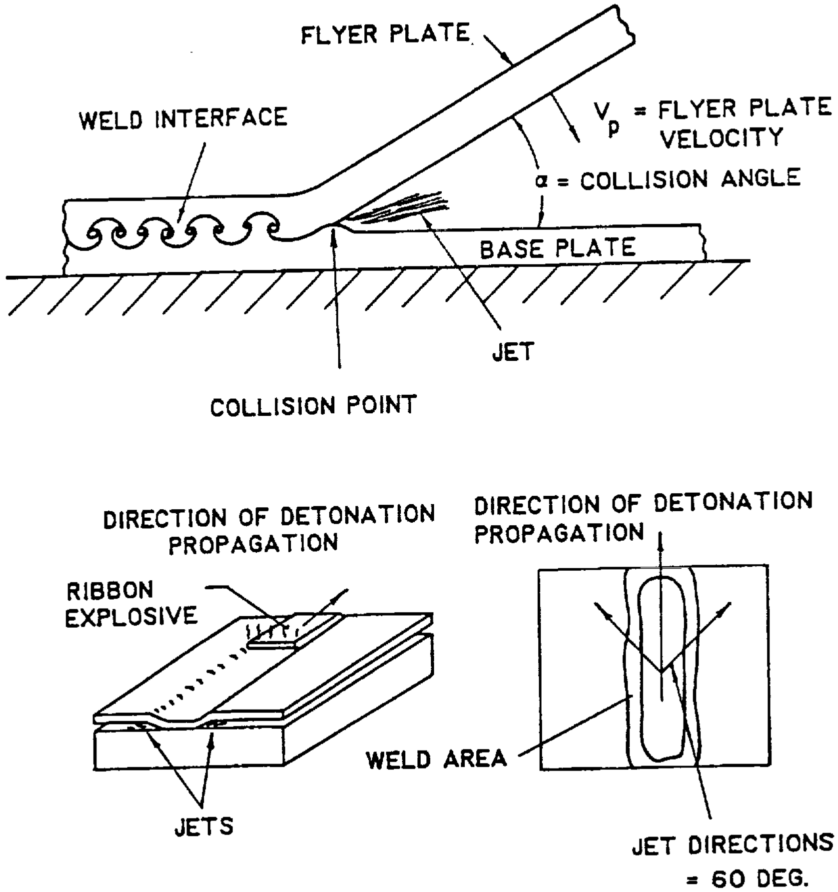

Figure 1. High-velocity, angular impacts of the two explosive joining processes: cladding in the top sketch and the NASA explosive seam welding in the bottom sketch.

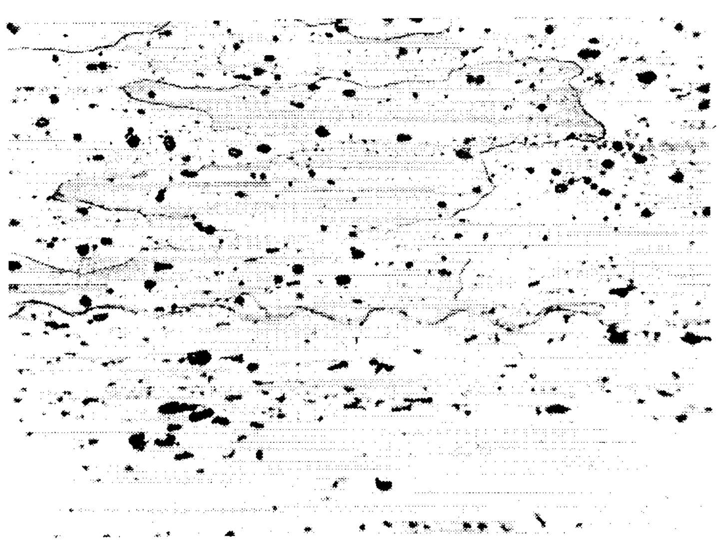

Figure 2. Microphotograph example of an explosively joined interface of 2024-T4 (top half of photograph) to 6061-T6 (lower half).

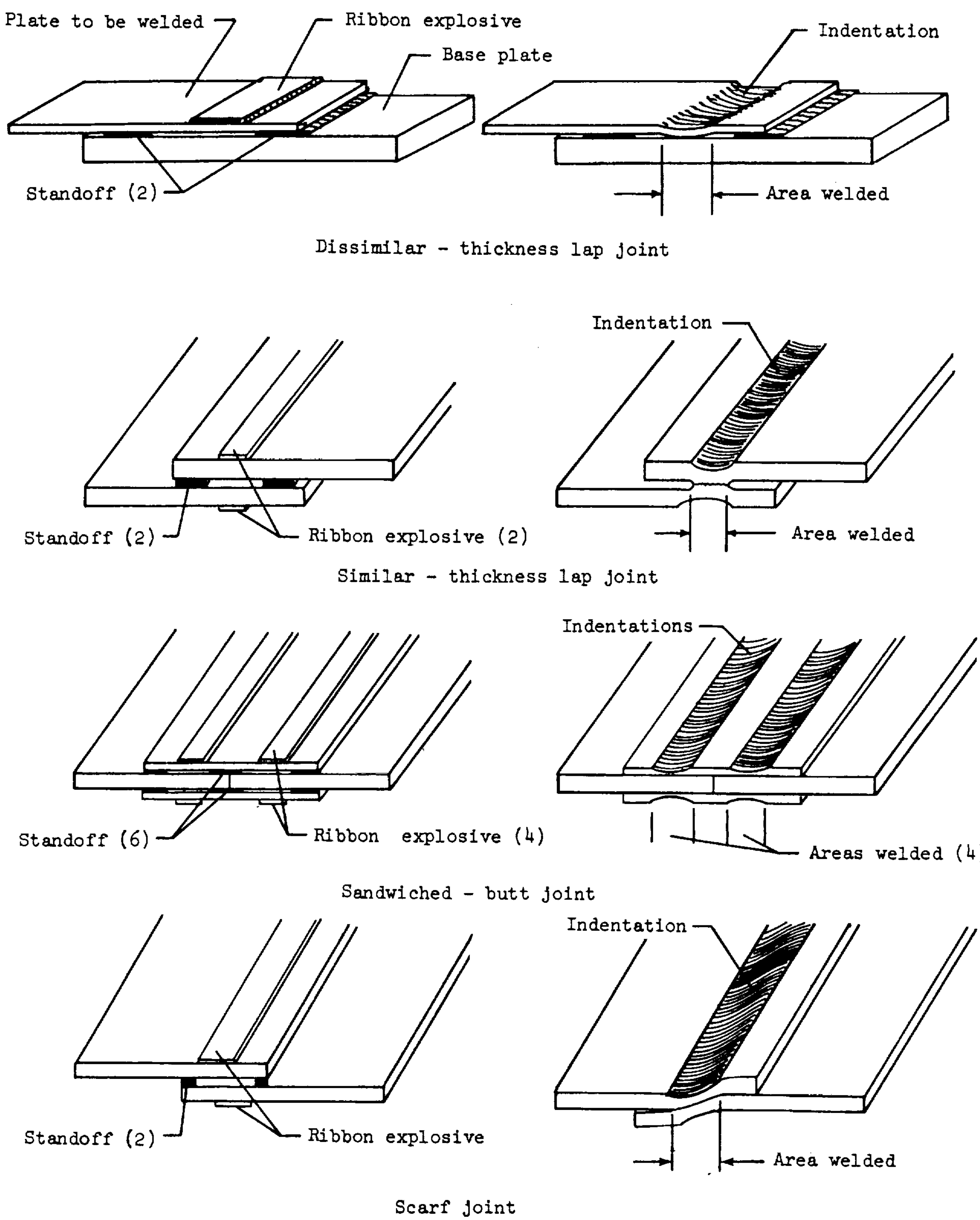

Figure 3. NASA's small-scale explosive seam welded joints.

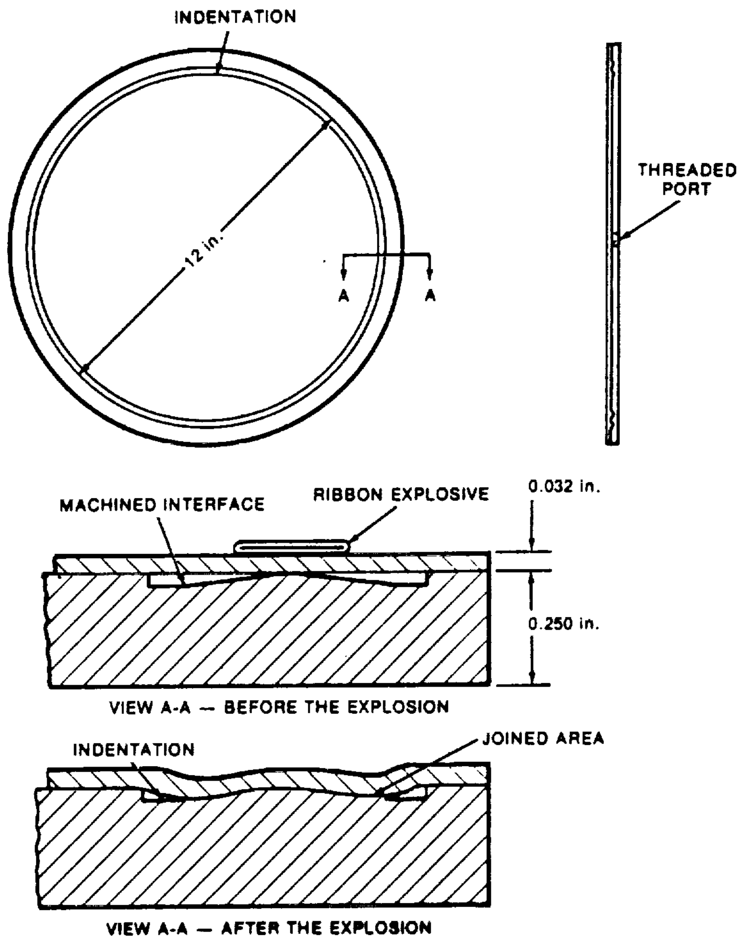

Figure 4. Approach for closing and hermetically sealing a vessel.

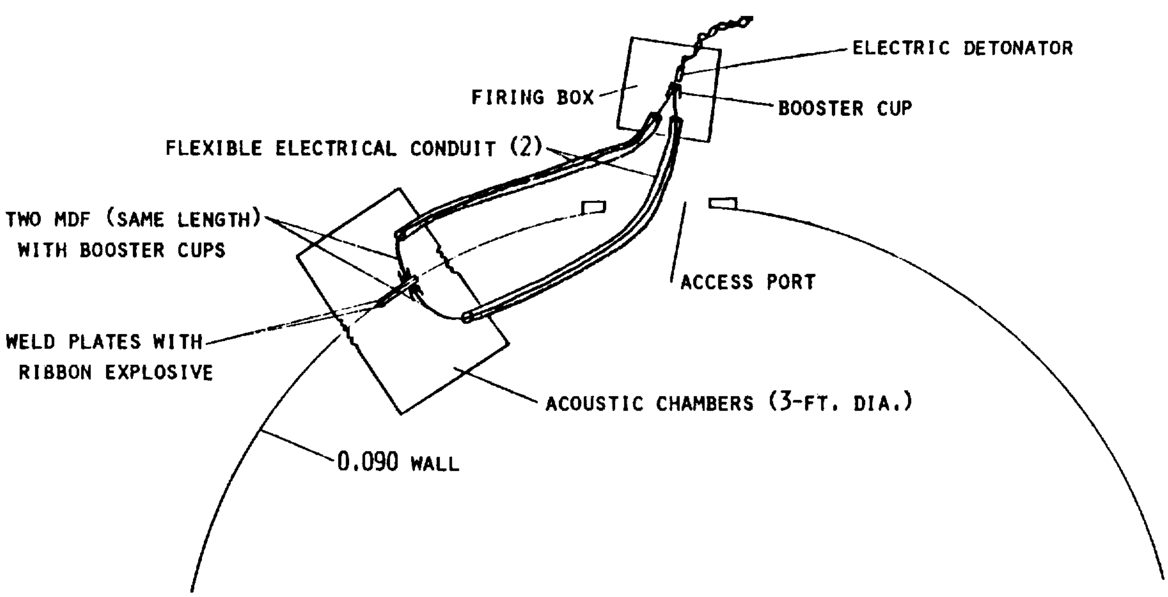

Figure 5. Approach for repairing a puncture in a pressure vessel.

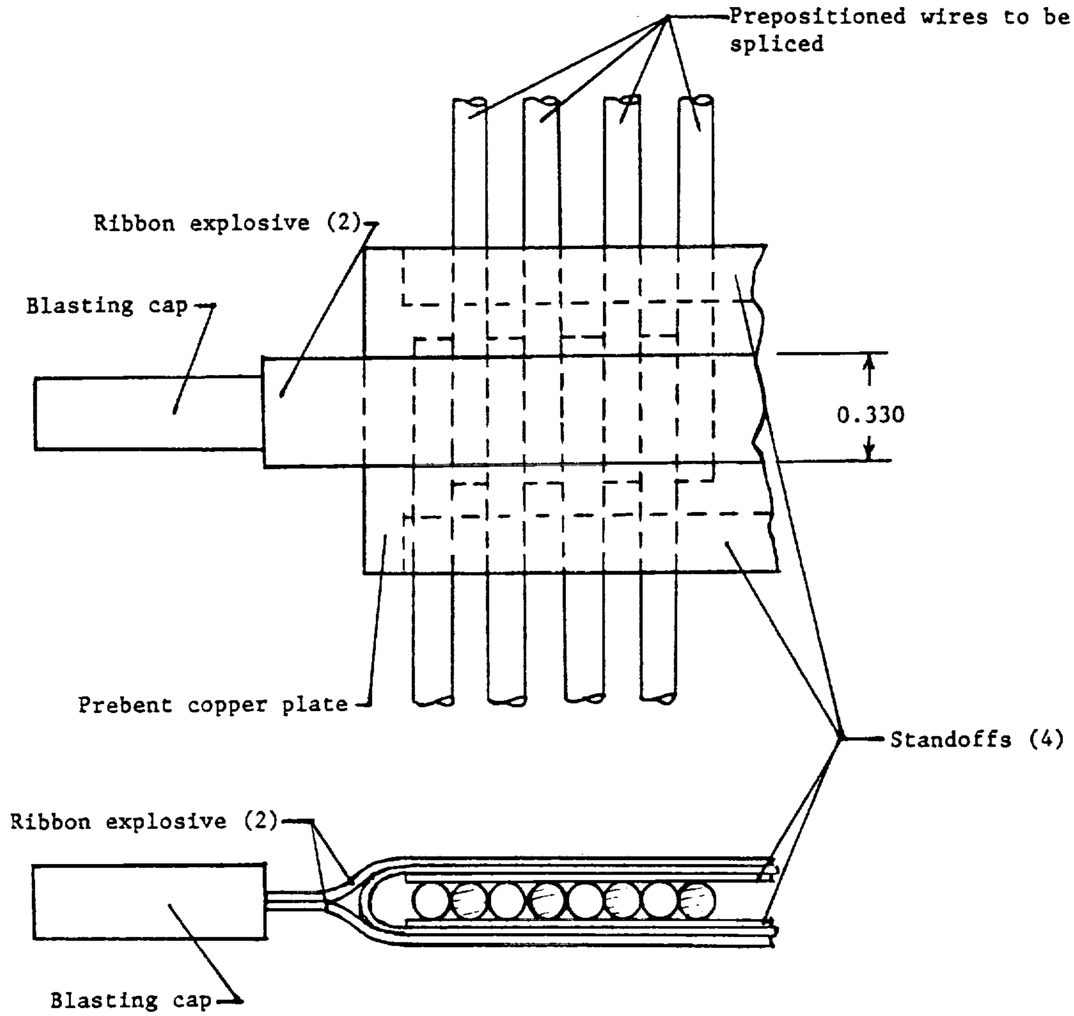

Figure 6. Explosive joining setup for splicing wires.

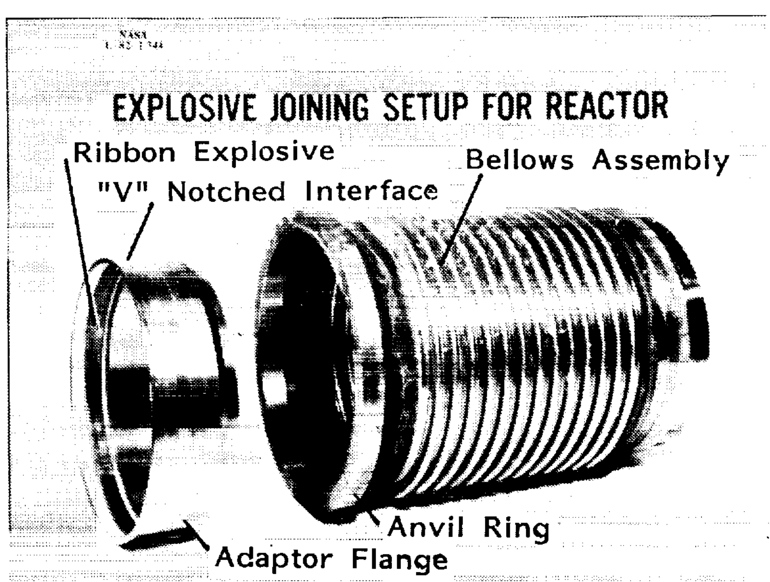

Figure 7. Setup for explosive joining adaptor flange to bellows assembly for Candu reactor.

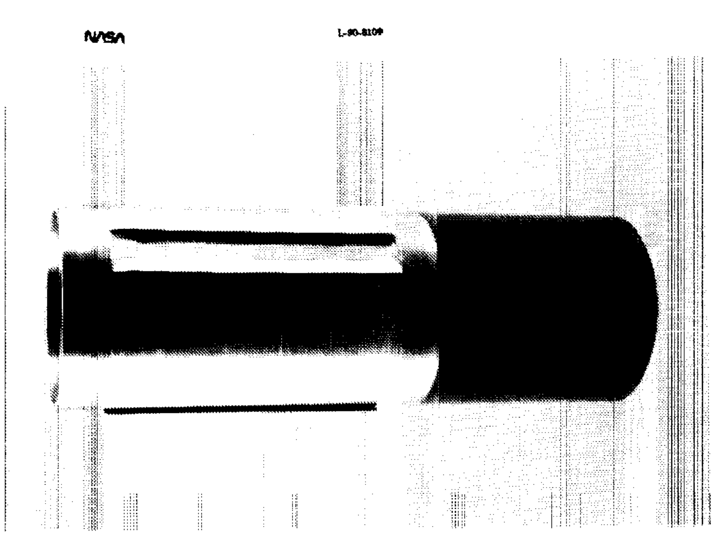

Figure 8. Cooling fins explosively bonded to Candu pressure tube.

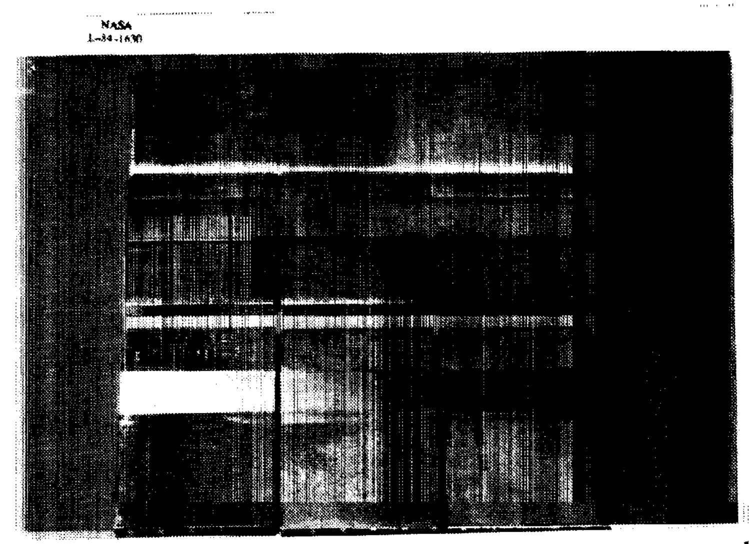

Figure 9. Preliminary evaluation of joining 316L sheet stock to (left to right) Inconel 625, Incoloy 903 and Haynes 188 with a V-notched interface.

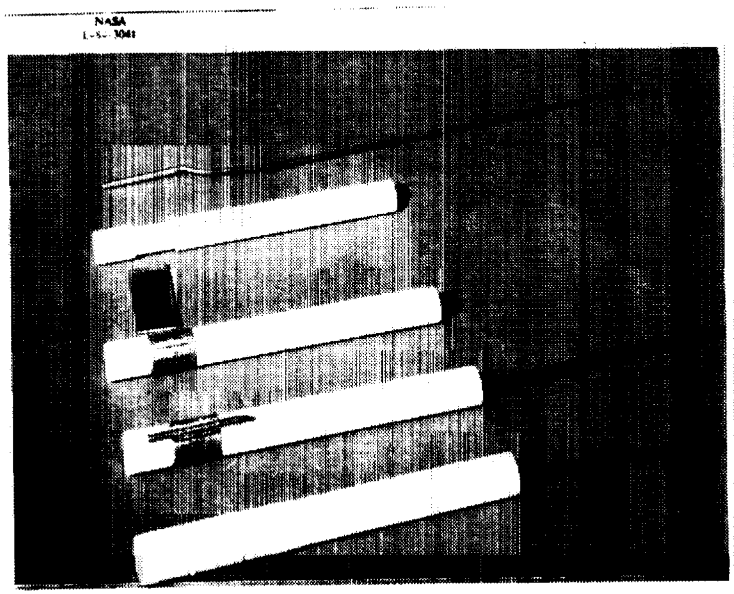

Figure 10. Assembly of the tool used for joining of tubes to fittings.

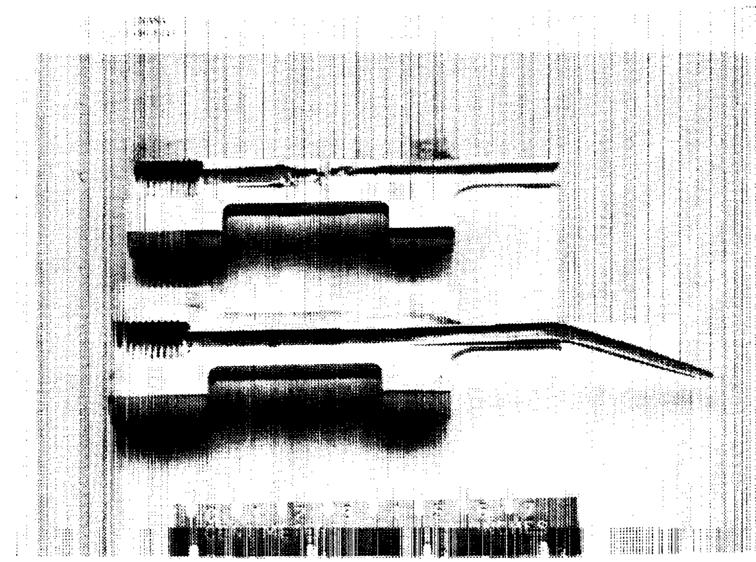

Figure 11. Explosively welded, 0.260 OD, 0.026-inch wall, 316L tube to Haynes 188 fitting with a V-notched interface. Top figure shows attempt to peel weld.