

EXPLOSIVE WELDING IN THE 1990'S

Narain S. Lalwaney and Vonne D. Linse

Battelle's Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

INTRODUCTION

Explosive bonding is a unique joining process with the serious potential to produce composite materials capable of fulfilling many of the high-performance materials needs of the 1990's. The process has the technological versatility to provide a true high-quality metallurgical bond between both metallurgically compatible and incompatible systems. Metals routinely explosively bonded include a wide variety of combinations of reactive and refractory metals, low and high density metals and their alloys, corrosion resistant and high strength alloys, and common steels. The major advantage of the process is its ability to custom design and engineer composites with physical and/or mechanical properties that meet a specific or unusual performance requirement. Explosive bonding offers the designer unique opportunities in materials selection with unique combinations of properties and high integrity bonds that cannot be achieved by any other metal joining process.

Twenty years have passed since the explosive bonding process was first commercialized. While its true potential has already been demonstrated in many instances as much as 15 years ago, it has not been extensively utilized. The explosive bonding process has simply not lived up to its expectations or technological potential. Instead of being the \$200 million/yr full-fledged high-tech, high growth industry of the 1980's as predicted, it has become a marginal industry at best with annual domestic sales stagnated at less than \$10 million and no projected breakthroughs in sight. In addition to the chemical process industry where it has found its greatest use, explosively bonded products were projected to find extensive use in the high performance aerospace and defense related materials needs of the 1970's and 1980's. These projections have not materialized. In modern times, no other industry has developed so much technological content with so little commercial success.

The failure of the explosively bonded product to live up to its expectation may be attributed to a number of reasons. It is the intent of this paper to discuss in some detail the reasons for the limited acceptance of the process and the steps that will be required for it to gain wider acceptability in the 1990's commensurate with technological capability. Initially, the process mechanism will be very briefly

reviewed and its applications to date outlined to provide an understanding of the nature of the process and its potential.

Explosive Bonding Process

In literature as well as this paper, the terms "explosive bonding", "explosive welding", and "explosive cladding" are used synonymously. The fundamentals of the process are well understood. The process is basically simple and only the rudiments are presented here. Excellent review articles⁽¹⁻⁴⁾ are available for those interested in more details.

A typical setup for explosive bonding is shown schematically in Figure 1a. The explosive is placed in a layer usually in direct contact with the upper or exposed surface of the prime or cladding component. The opposite or bonding surface of the cladding component is then placed at a specified distance above the surface of the base component to which it is to be bonded. This separation is usually known as the "standoff gap". For most explosive bonding operations, particularly large plate cladding, this gap is usually constant over the entire area being bonded.

The mechanisms that occur during the actual bonding event are shown schematically in Figure 1b. As the detonation front in the explosive passes over the surface of the cladding component, the pressure and expanding gases combine to bend and accelerate the cladding component across the standoff gap toward the base component at a high velocity. The high velocity cladding component then impacts the base component at an angle generating extreme localized pressures at the collision point which are several orders of magnitude above the yield strength of both metals being welded. Under the influence of this high pressure, angular collision, the surrounding metal surfaces act as viscous fluids around an obstacle and a few microns of the component surfaces are jetted into the standoff gap ahead of the progressing collision point. The jet consists of a combination of surface contaminants, a few microns of the metal surface layers, and compressed air. As the detonation progresses, the jet travels ahead of the collision point sweeping the contaminants from the surfaces. This enables the two cleaned metallurgical surfaces to come into intimate contact under extreme pressure at and behind the collision point and become bonded due to interatomic forces. The collision is characterized by the collision velocity (V_c) and the collision angle (θ). There is a critical collision velocity below which no bonding occurs and similarly a minimum collision angle below which no jetting will occur regardless of the collision velocity.

There is no heat associated with the process other than that generated by the plastic working near the interface and the adiabatic compression temporarily imposed on the metals. Since the process is almost instantaneous, no diffusion takes place. Therefore, explosive bonding can directly join dissimilar, metallurgically incompatible and reactive metals without the significant formation of intermetallic compounds that are harmful to the properties of the bond and the ultimate performance of the composite.

Most explosively bonded composites have a wavy bond zone that can be explained on the basis of hydrodynamics. A flat bond zone is indicative of a bond being made at the lower limits of collision energy and has the potential to display marginal and/or nonuniform properties. When properly made, the bond strength is normally equal to or slightly greater than the weaker of the two components being bonded. Figure 2 shows a typical explosively bonded interface between commercially pure titanium and steel in which the small amount of brittle iron-titanium intermetallic that exists is isolated in small areas that are surrounded by ductile direct bond. Closer examination of the bond interface usually reveals that the weld is a combination of direct weld on the crests and in the valleys of the waves, and intermittent pockets of trapped jet material on the front and back slopes (Figure 3). Figure 4 similarly shows a wavy interface in aluminum/magnesium alloy with pockets of entrapped jet material near the crests. Depending on the energy input into the bond, the trapped jet pockets will range from a mechanical mixture of the two materials being bonded to a totally melted and solidified structure. Excessive energy inputs during bonding with resultant excessively large jet pockets typically produce bonds with less than optimum properties.

Present Applications

Since its initial commercialization in the mid 1960's, the flat-plate cladding applications grew rapidly until the early 1970's and then leveled off. From 1970 onward, most new applications were in the area of specialty products other than flat plate configurations.

Flat-Plate Clads

The largest and most extensive commercialization to date of explosively bonded products has been in the form of flat-plate clads which are subsequently fabricated into a structure. The most important application has been in chemical process pressure vessels. Commercial applications can be broadly divided into the following three categories:

1. Pressure Vessels

Products: Ti/steel, Zr/steel, Ta/steel, Inconel/steel, Hastelloy/steel (Figures 5 and 6)

Industry: Chemical process industry

2. Tube Sheets for Heat Exchangers

Products: Ti/steel, Inconel/steel, stainless steel /steel, bronze/steel (Figure 7)

Industry: Chemical process industry

3. Transition Joints

Products: Al/Al/steel (Figure 8)

Industry: Shipbuilding-structural transition joints for both new construction and repair work

Products: Cu/Al

Industry: Electrorefining industry

In the chemical process related industries, the major applications have been for corrosion resistant clads in pressure vessels and tube sheets for heat exchangers. The corrosion resistant clad is almost always bonded onto a steel backer which becomes the pressure carrying component of the vessel or tube sheet for these applications. This process has made it possible to economically use expensive, high-density metals such as tantalum for a tantalum/copper clad steel pressure vessel in the recovery of chlorine from HCl at higher temperature and pressure.

In the shipbuilding industry, aluminum alloy/aluminum/steel structural transition joints replace bolted or riveted aluminum/steel joints thus avoiding crevice corrosion. The aluminum part of the joint is then conventionally welded to the aluminum superstructure and the steel part is welded to the steel decking/coaming. Similarly copper/aluminum and aluminum/steel transition joints are used in the electrorefining industry to replace bolted /riveted joints in high current density systems.

Other applications of explosively bonded flat plate product have been for stainless steel clad steel boiler plates in the nuclear industry and helium leakproof tubular transition joints of aluminum/stainless steel with either titanium or silver interlayers for cryogenic applications.

Cylindrical Products

Up to now the use of explosively clad cylindrical products has been customized and not widespread. Several industries have used both small and large diameter explosively clad titanium/steel, stainless steel/steel, and Inconel/steel concentric cylinders. In other cylindrical configuration applications, direct explosively bonded aluminum/steel tubular transition joints in various diameters such as shown in Figure 9 are made by overlap cylindrical bonding techniques and being used in significant numbers in the nuclear industry. The joining of large sections of oil and gas pipelines, 36, 42, and 48 inches in diameter, by explosive welding has been successfully developed and placed into commercial application.⁽⁵⁾

Specialty Products

Multilayer laminates of three or more layers of metals explosively bonded together have been used for various applications such as coinage stock, condensers, electrodes, etc. Figure 10 shows one such configuration of thirteen explosively bonded 1/8-inch-thick layers of Alclad aluminum. With the explosive bonding process, laminate structures can be designed with specific combinations of metals and layer thicknesses to modify or control heat/electrical conduction properties or to improve fracture toughness or fatigue crack arresting capabilities.

The repair and buildup of worn flat and cylindrical components is another specialty area of explosive bonding that has not been utilized to its full potential. Figure 11 shows an explosively welded repair buildup sleeve over the remachined worn area of a high speed turbine shaft.⁽⁶⁾

In Europe, explosive bonding is used to simultaneously bond tubes into tubesheets in the fabrication and retubing of heat exchangers, in lieu of conventional welding where seal welds are required. This application has not yet gained wide acceptance in the United States where the use of explosives to expand but not weld tubes into tubesheets has been used successfully for quite some time. Explosive bonding is used for plugging leaky tubes during heat exchanger repairs in both the United States and Europe.

Present Status

The entire explosive metalworking or fabrication area (bonding, forming, powder compaction, etc) has experienced relatively little commercialization of its products with respect to its overall potential. The reasons for this lack of use vary depending on the process. The most serious lack of use with respect to its overall potential in the technological and manufacturing community to date however is explosive bonding. The basic understanding of process fundamentals and manufacturing procedures for making high quality explosively clad product has been thoroughly established and is available. Well over 300 similar and dissimilar combinations of metal and their alloys have been explosively bonded and many more are capable of being bonded if the need arises. Yet, explosive bonded materials are seemingly used only as a last resort, with those systems that have been commercialized being ones that cannot be produced by any other joining technique.

The major reason for the lack of use of explosively bonded products is graphically illustrated in Figure 12. Large engineering/informational gaps exist between the three major components that are involved with the explosively bonded product throughout its life. As a result the growth potential of the product has not been realized.

The user typically specifies the material in terms of type, properties, sizes, etc that he desires for his end product based on his need and the available information and design data for the material. The greatest area of deficiency is the almost total lack of good

design support data and information on explosively bonded product that are universally available for the end user to input to his design and materials selection. As a result, only a few large repetitive end users are cognizant of the product and its capability and have consistently utilized the product.

The large chemical companies in the U.S. and abroad have treated explosive bonding and its product as an extension of their explosive product lines rather than treating it as an entity of its own. They have incorporated these products into their own designs only after expending large engineering efforts to evaluate clad materials, establish their own user criteria, and work out fabrication and repair procedures for use by the fabricators. The information created thus becomes proprietary and not available for general use by industry.

Fabricators in the past have had little or no information made available to them from either the end user or the material manufacturer on how to fabricate explosively bonded product into an end product such as a pressure vessel. The responsibility for developing these fabrication procedures has thus fallen to a few custom fabricators who do little process designing. Once again the fabrication procedures developed become very specialized and proprietary and not always technically and economically the most effective.

The materials/clad manufacturers provide guidance/information only as to the bond integrity and strength of the product which they manufacture. None possess the facilities for intermediary processing of the clad product such as hot/cold conversion rolling, extrusion, etc., to enhance its technical quality and/or its economical attractiveness. The intermediary processing requires a much higher level of technology than the simple forming of plates during standard fabrication. The availability of this technology is very restricted and supplied mostly through the clad manufacturer. It is therefore either very expensive or oftentimes unavailable because the technology does not exist. Again much of the property data and secondary processing information on explosively bonded products has become proprietary to the materials manufacturer and is not available on a general basis.

Until recently, there has been no attempt to bridge these engineering/informational gaps between the three major components so the potential end user can select and utilize explosively bonded products to their fullest potential.

Future Opportunities

Mechanistically and parametrically, the explosive bonding process is well understood; therefore, the basic, fundamental research and development on the process is primarily behind us. Likewise the previous restrictions to market entry into the field imposed by basic patent protection or any other barriers have now disappeared. Urgently needed is market development via new thrusts into application areas where the need for composite materials having unique properties or performance capabilities is present. The development of process technology and material data and information that will be readily

available to all who need it for these new markets will be the overriding factor is the future implementation of explosive bonding.

There are several areas of opportunity for explosively bonded products that hold considerable promise and need to be addressed:

- Very lightweight/high strength composites for application in both aircraft frame and engine components and land vehicles.

Examples: aluminum/titanium, beryllium/titanium, aluminum/magnesium

- Thin composite foils for the electronic and aerospace industries.

Examples: multilayer composites of a number of metals having the combined desired properties explosively bonded and subsequently conversion rolled to the desired foil thickness.

- Multilayer composites that provide the proper combination of densities and strengths, with the added benefit of significantly improved fatigue and fracture toughness properties.
- Advanced composite materials for neutron capture/impermeability in managing nuclear wastes.
- Remote joining of metals in hostile, hazardous, or inaccessible areas such as nuclear reactor repairs, underwater welding, or assembly of structures in earth orbit or space. Such an application with seam welding has been demonstrated. (7)
- Repair and renovation of worn or damaged parts or components especially in situ will become more popular as materials and new replacement parts become more expensive. The costs of critical materials, although stable at present, are subject to significant increases in the future depending on the world political situation. An example is such as those in Africa where the major supplies of the raw materials for many of our critical metals are located.

Needs of the 1990's

A number of critical aspects of the explosive bonding area must be addressed in the remaining years of the 1980's in order that the process and its products will be ready to meet the high tech materials requirements of the 1990's. These aspects include:

- Create reliable design data that is readily available and easy to disseminate to those who need it. The data base should include representative mechanical and physical properties for each material system along with typical applications, fabrication methods, repair procedures, etc. This will help the designing engineer to consider and employ new materials. The data base should be continuously expanded to include new materials which can be produced but are not presently being commercialized.
- Develop more meaningful product specifications and testing methods (user friendly) so that potential users can easily establish their own criteria to better meet their needs. Present specifications like shear tests, etc., as standards for acceptance in many cases are not realistic from the user's viewpoint.
- Provide innovation into high tech, high performance materials through innovations in the explosive bonding process. One potential area is in the welding of very high strength, low impact materials which are susceptible to fracture during bonding at room temperature. The basic feasibility of using elevated temperature bonding has already been demonstrated as one solution to this problem.
- Reduce the costs to the end user. Not only is the explosive bonding process presently expensive but the cost of subsequently fabricating the product is also expensive. From the explosive bonding viewpoint, the cost of the bonded product is proportional to the area clad. The cost of bonding can be considerably reduced in many instances by cladding thicker components and subsequently rolling flat-plate clads or extruding clad cylinders to increase the bond area and thus reduce its unit cost.

In fabrication, the cost can be considerably reduced by developing better and more economical techniques for joining or welding clad components. For example, the cost for joining titanium/steel clads in the fabrication of pressure vessels can run as much as \$150/linear foot while that for joining tantalum/copper clad steel may run to \$300/foot. Reducing the amount of welding by simply increasing the initial overall size of the bonded plate would bring significant fabrication savings. Oftentimes the thickness of the composite bonded plate, both clad and base, is significantly greater than necessary. Reduction of the thickness along with improved fusion welding techniques to handle it would also help to further reduce the overall costs of the process. In many instances such as titanium/steel composite, the clad may be as much as three to five times as thick as necessary for corrosion protection

only because the technology for fusion welding it in thinner layers does not exist.

NEW DEVELOPMENTS

There are several recent developments that suggest the industry may be undergoing some change in the near future.

For example:

1. Several large metallurgical companies, both domestic and foreign, are looking seriously at the potential U.S. explosive metalworking market with several captive inhouse and export applications in mind now that there are no market barriers.
2. Serious and increasing Soviet effort in the high energy rate fabrication field is under way in several institutions. Some of these are solely devoted to explosive metalworking with potential military applications. Our own defense needs will have to keep these developments under scrutiny.
3. Battelle recently announced the opening of an explosive metalworking application center at Columbus, Ohio to bridge the information/engineering gaps discussed above.
4. The Center for Explosive Technology recently opened at the New Mexico Institute of Mining and Technology.

These activities suggest a new era of activity in the explosive fabrication field. If successful, these developments could lead to new commercial applications that will once again produce growth within the industry.

ACKNOWLEDGEMENTS

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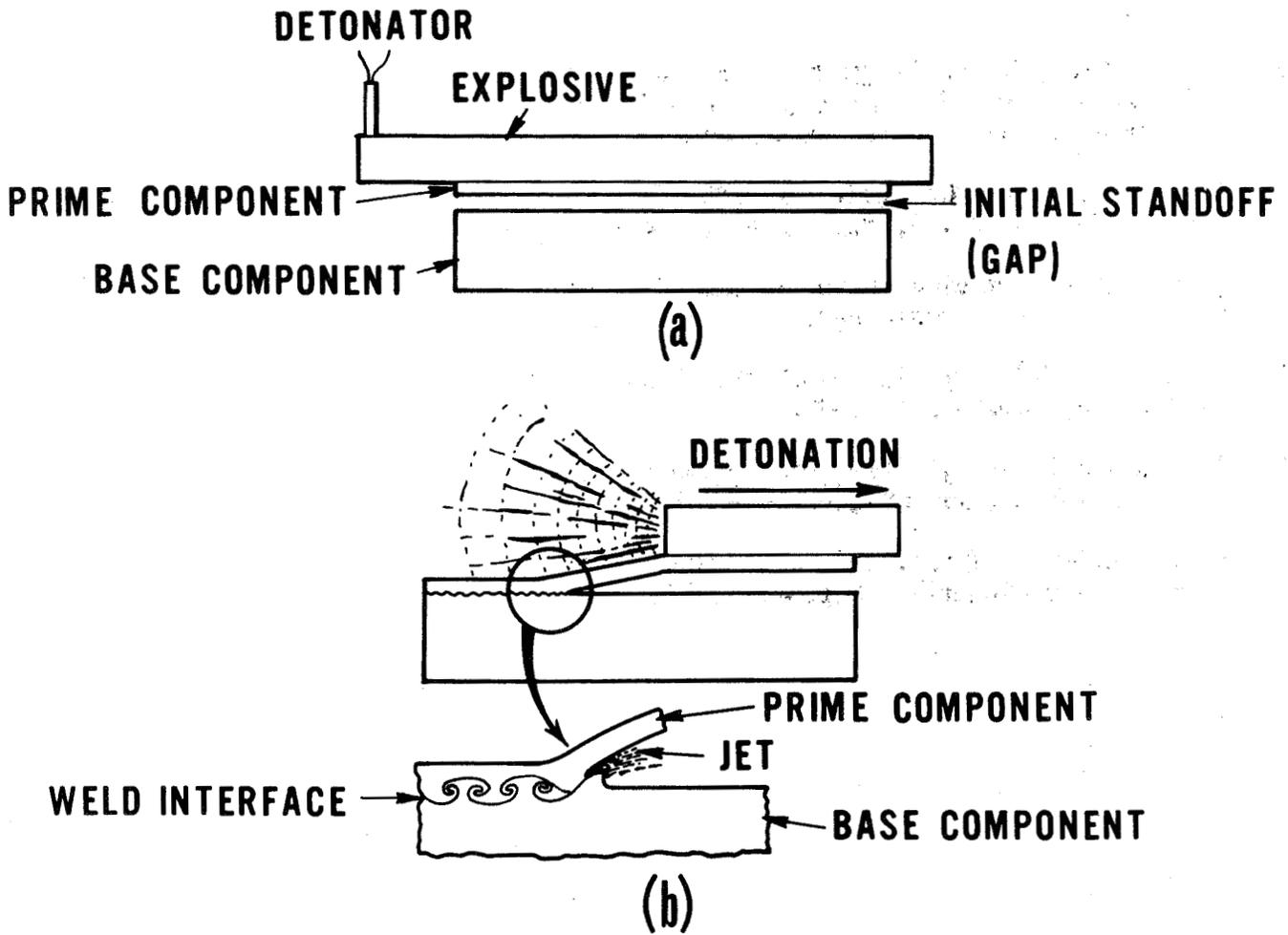


FIGURE 1. SCHEMATIC OF EXPLOSIVE BONDING PROCESS
 (a) SETUP (b) PROCESS MECHANISM

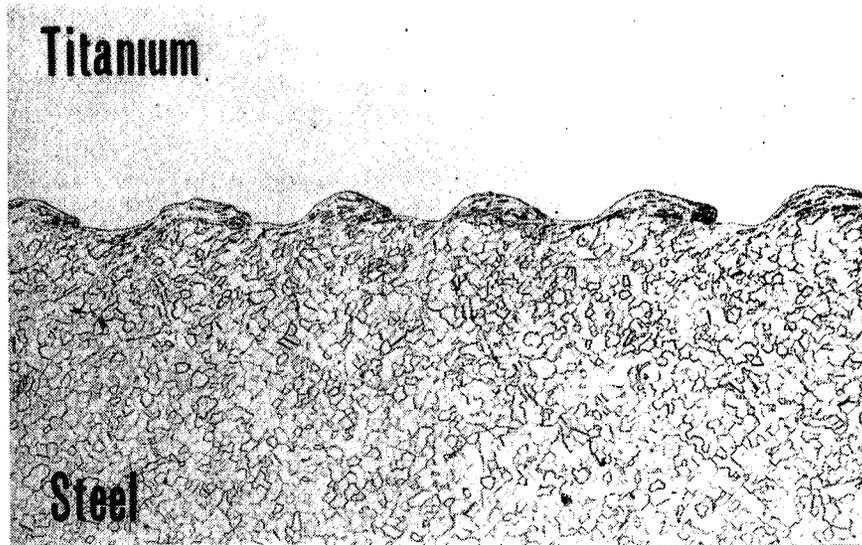


FIGURE 2. PHOTOMICROGRAPH OF A SKEWED WAVE PATTERN IN MISMATCHED SYSTEM OF TITANIUM (TOP) TO LOW CARBON STEEL (BOTTOM). 100 x. (LOW DENSITY/HIGH DENSITY) SYSTEM

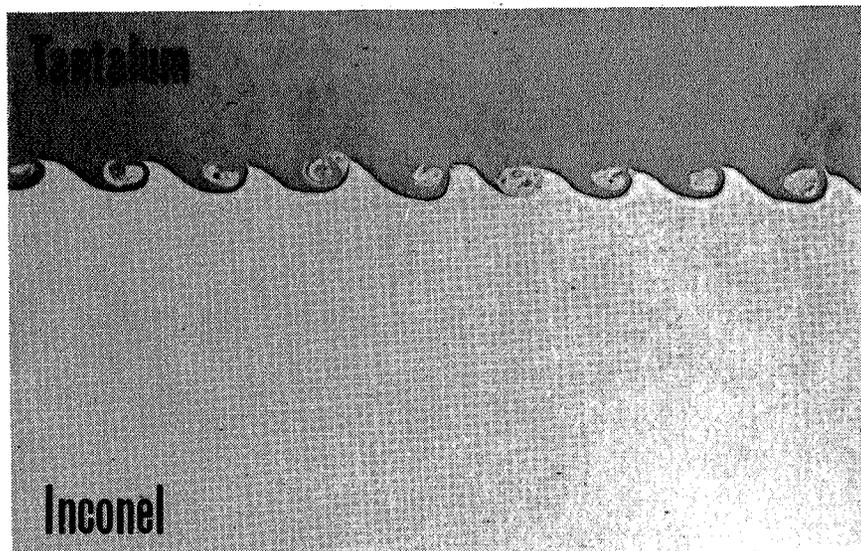


FIGURE 3. EXPLOSIVE WELD BETWEEN TANTALUM AND INCONEL SHOWING POCKETS OF ENTRAPPED JET MATERIAL (50 x)

Aluminum

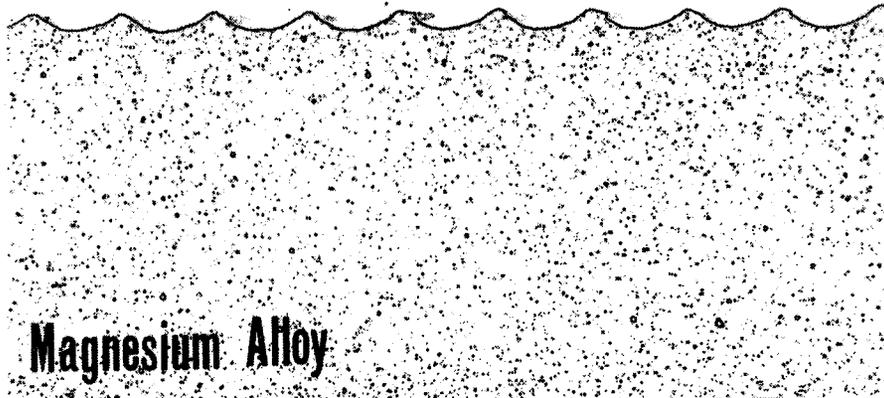


FIGURE 4. EXPLOSIVE WELD BETWEEN ALUMINUM 1100 (TOP) AND MAGNESIUM ALLOY SHOWING POCKETS OF ENTRAPPED JET MATERIAL. (VERY LOW/VERY LOW DENSITY) (20 x)

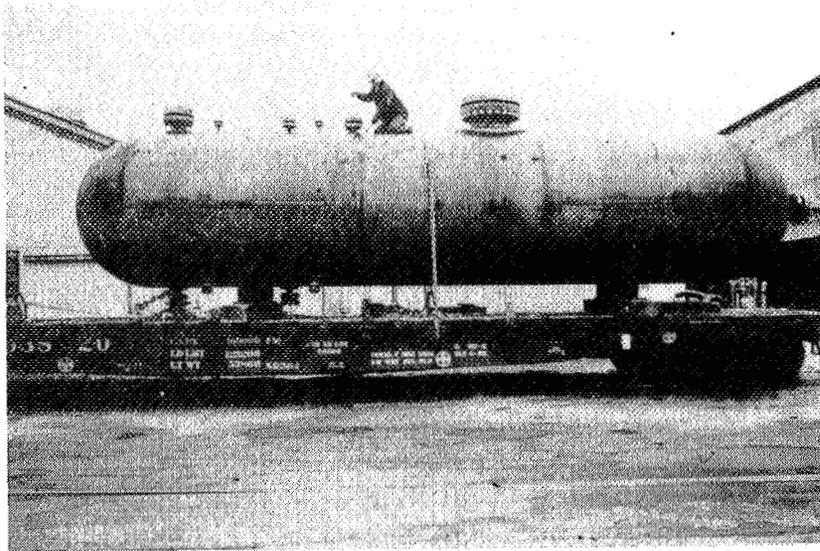


FIGURE 5. TITANIUM/STEEL PRESSURE VESSEL MADE FROM EXPLOSIVELY BONDED CLAD PLATE

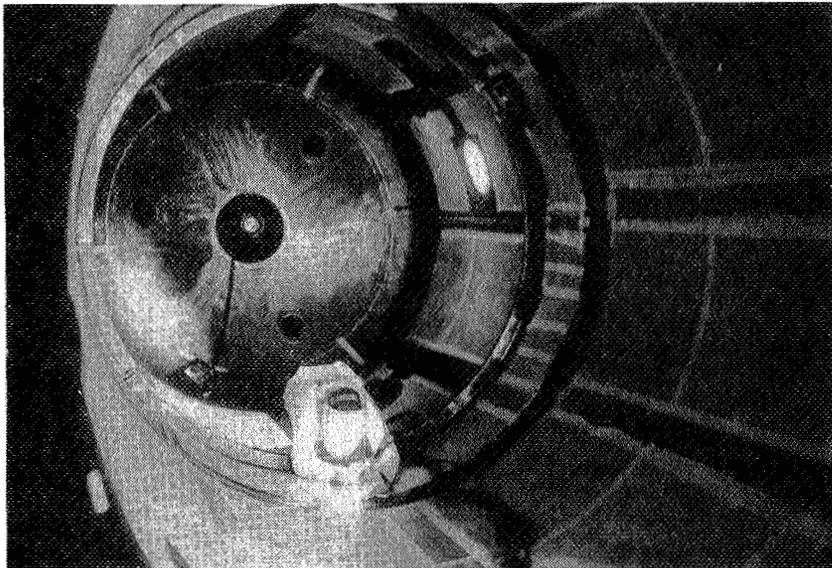


FIGURE 6. INTERIOR OF 8 BY 60 FT. DIAMETER VESSEL FABRICATED FROM EXPLOSION-CLAD TANTALUM TO COPPER TO CARBON STEEL

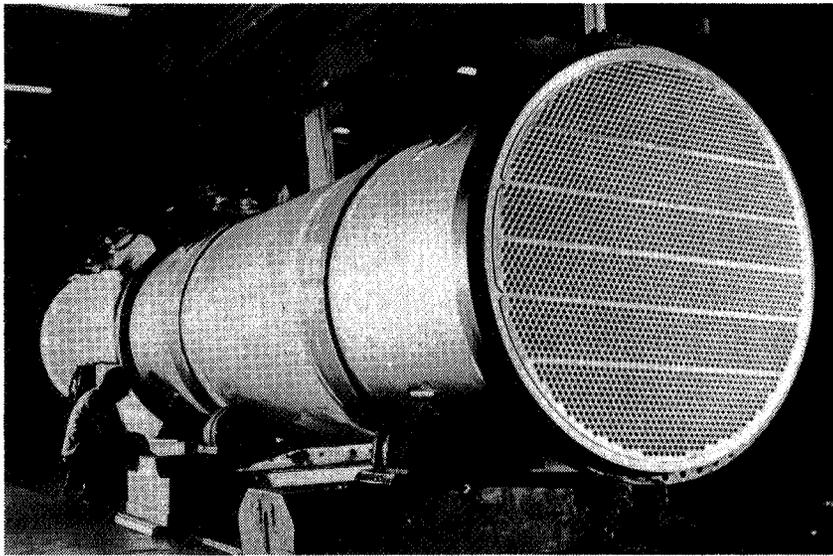


FIGURE 7. TITANIUM TUBE SHEET EXPLOSIVELY BONDED TO MONEL 400

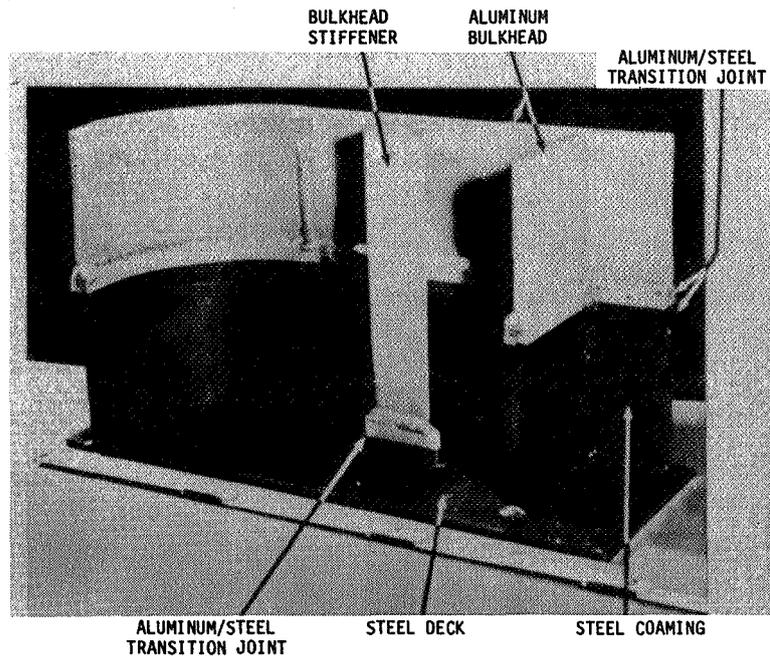


FIGURE 8. ALUMINUM SUPERSTRUCTURE AND STEEL DECK CONNECTION USING A1/A1 STEEL TRANSITION JOINT

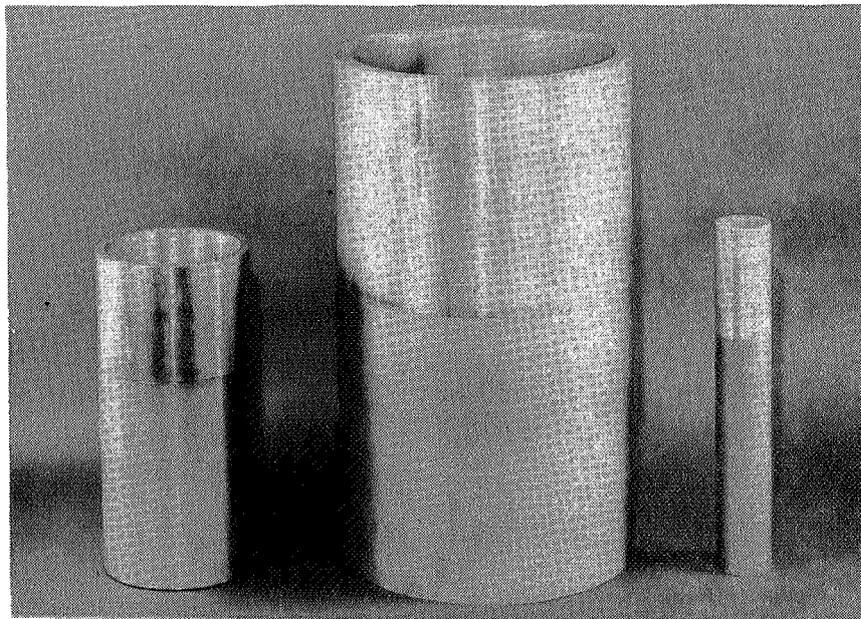


FIGURE 9. EXPLOSIVELY WELDED ALUMINUM-STEEL TUBULAR TRANSITION JOINTS (NOMINAL DIAMETERS LEFT TO RIGHT, 6, 12, AND 2 IN.)

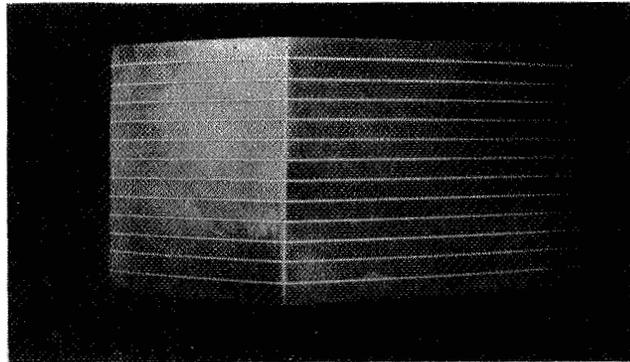


FIGURE 10. MULTILAYER LAMINATE OF
EXPLOSIVELY WELDED
ALCLAD 6061-T6 ALUMINUM
LAYERS (TOTAL THICKNESS
4.1 cm)

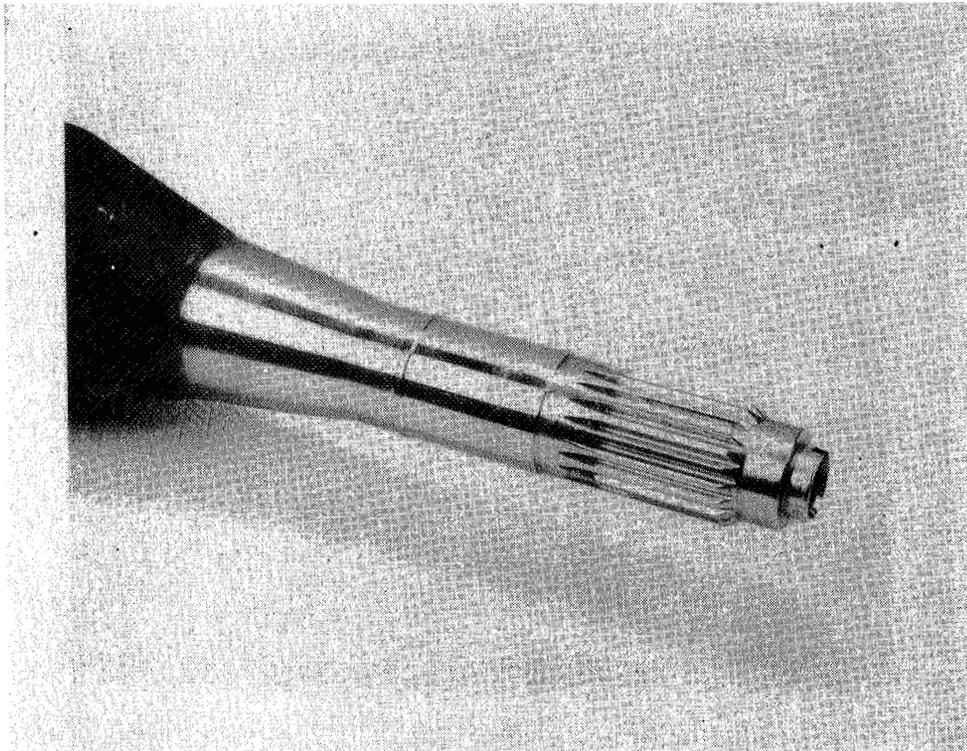


FIGURE 11. EXPLOSIVE WELD REPAIRED BEARING JOURNAL
ON HIGH-SPEED TURBINE SHAFT

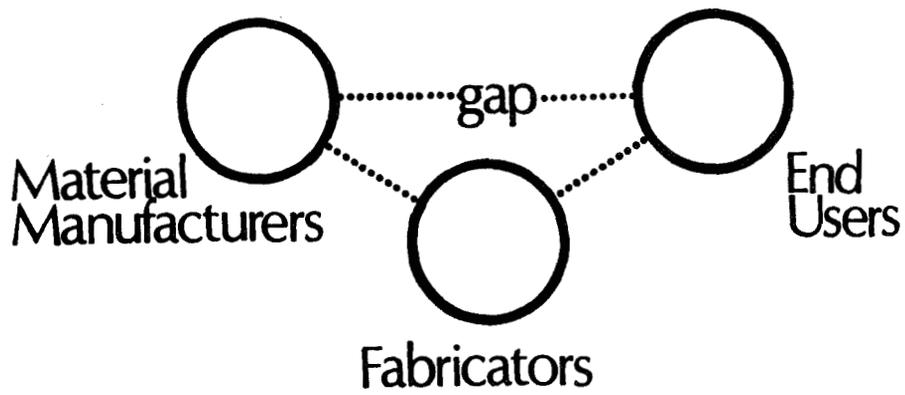


FIGURE 12. ENGINEERING/INFORMATIONAL GAPS BETWEEN ALL COMPONENTS OF EXPLOSIVE METALWORKING INDUSTRY