What You Can Do with Explosion Welding

BY DAVID CUTT

Lead — Arc welding of a forged steel cup-and-cross tiedown assembly into an aluminum aircraft carrier deck plate. The welding pro made possible by the application of explosion welded materials. The all-welded final assembly is extremely rugged and free of any possib points for galvanic corrosion.

DAVID CUTTER (dcutter@pacaero.com) *is vice president of R&D at Pacific Aerospace and Electronics, Inc., Wenatchee, Wash.*

The process has been continuously refined and is being applied to an ever-growing number of applications

Design engineers are often faced with a dilemma of material selection, where the material that would work the best for one specific element of a design is lacking in properties required by other elements of the design. For example, a material may exhibit good corrosion resistance, electrical conductivity, or thermal conductivity, yet be lacking in the strength, hardness, weldability, or wear resistance that may be required in the final design. A powerful tool to help resolve this dilemma is provided by the utilization of explosion welded materials.

Explosively welded materials allow design engineers to specifically place a certain material exactly where they need it in the design, without compromising other critical elements. The correct application of explosion welded materials can yield significant gains in strength, reliability, and cost-effectiveness throughout the product's lifetime.

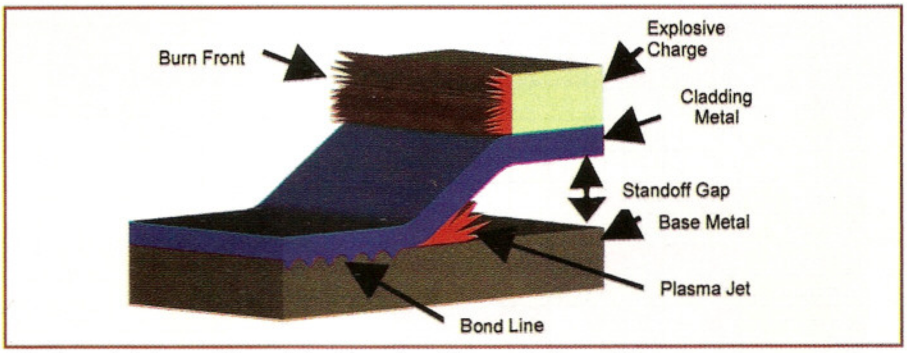

Fig. 1 — Artist's rendition of the dynamics of the explosion welding process.

The Beginnings

The explosion welding phenomenon was first observed during the early World War II years. It was noted that the force of explosions had welded bomb fragments to impacted metal objects. It was not until the early 1960s that DuPont developed a practical explosion welding process, culminating with the issuance of U.S. Patent No. 3,140,539, *Process for Bonding Metals by Explosive Means*.

Since then, the process has been continuously refined and applied to an ever-growing number of applications in many manufacturing industries. A search of U.S. patents in Classification 228.107, Metal Fusion Bonding Using Explosive Energy, lists 148 patents issued since 1976. Many of these are for refinements of the basic process, while others cover applications of explosion welded materials, for industries as diverse as hermetic electronic packaging, golf clubs, sputter targets, and cooking griddles. Whether welding lightweight materials to strong materials or noble materials to support materials, the explosion welding process has helped to achieve the "impossible" for more than 30 years.

How It Works

The explosion welding process is, at first inspection, quite straightforward. The metals to be joined are fixtured close to each other with a small separation. A layer of explosives is spread evenly over the top plate. The "sandwich" is detonated, and Bingo! Out of two separate and often totally dissimilar materials, we now have one metallically welded stack. This bimetal plate can then be machined for incorporation into a variety of products.

In reality, however, the process is much more complex. A successful weld, free of nonwelded areas or delaminations requires careful control of a number of parameters, and considerable experience is required to produce consistently high-quality welds.

The Explosives

The most common explosive material used is ANFO (ammonium nitrate-fuel oil), but other explosives are used for specialty applications where a particular detonation velocity and yield are required.

The quantity of explosive varies widely, but most welding jobs can be completed with charges ranging anywhere from 20 to more than 2000 lb. Clearly, this welding process cannot be carried out at your local welding shop. Explosion welding must be performed by licensed and experienced explosives engineers in a very remote location, where all the usual safety precautions associated with any blasting operation are enforced. There are numerous codes covering the storage and handling of explosives that must be rigorously observed.

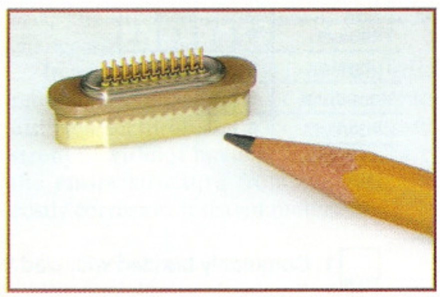

Fig. 2 — The wavy weld line on this electronic component reveals that it was machined from an explosively welded block (6061 aluminum to 4047 aluminum).

Weld Characteristics

During the welding process, very high forces at the impact area (estimated at

Table 1 — Metals Compatibility for Explosion Welding

	Zirconium	Vanadium	Tungsten	Titanium	Tantalum	Steel alloy	Steel, mild	Steel, Stain	Silver	Rhenium	Platinum	Palladium	Niobium	Ni alloy	Nickel	Molly alloy	Molybdenum	Magnesium	Kovar	Indium	Hafnium	Gold	Copper alloy	Copper	Beryllium Cu	Al Bronze	Al alloy	Aluminum
Aluminum	8	8	4	1	1,3	6,3	1	6,3	1	8	8	7	1	6	6	8	8	7	6,3	7	8	1	5	5	7	6	1	1
Al alloy	8	8	4	1	1,3	6	6,3	6,3	1	8	8	7	1	6	6	8	8	7	6,3	7	8	8	5	5	7	6	1	
Al Bronze	7	8	7	7	8	8	1	7	7	7	8	7	8	7	7	8	8	7	8	8	7	8	8	8	7	8		
Beryllium Cu	7	8	7	7	8	7	1	7	8	7	8	7	8	7	7	8	8	7	7	7	7	8	1	1	7			
Copper	8	8	4	1,3	1,3	1	1,3	1,3	1	8	1	1	1	1	1	8	1	7	1,3	1	8	1	1	1				
Copper alloy	8	8	8	8	8	1	1	1	8	8	8	8	1	1	8	8	1	7	1,3	8	8	8	1					
Gold	8	8	8	8	8	8	8	8	1	8	1	8	8	8	8	8	8	7	8	8	8	1						
Hafnium	7	1	8	7	8	8	8	1	8	8	8	8	8	7	7	1	1	6	8	7	8							
Indium	8	8	8	7	8	7	7	7	8	7	7	7	8	7	7	8	8	6	8	8								
Kovar	7	8	8	7	8	1	1	1	8	7	8	7	8	8	8	8	8	6	1									
Magnesium	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	8										
Molybdenum	8	1	4	8	1	1	1	1	8	1	8	8	8	8	8	1	8											
Molly alloy	8	1	4	8	8	8	8	8	8	1	8	8	8	8	8	8												
Nickel	8	8	8	1	1	1	1	1	7	8	7	7	8	1	1													
Ni alloy	7	8	8	7	8	1	1	1	8	7	8	7	8	8														
Niobium	8	1	4	8	8	8	8	1	8	1	1	8	1															
Palladium	7	7	7	7	7	1	7	7	7	7	7	8																
Platinum	8	8	8	8	8	1	8	1	8	8	8																	
Rhenium	7	1	8	7	1	7	7	7	7	8																		
Silver	8	8	8	8	8	1	1	1	1																			
Steel, Stain	2,5	1	4	2,5	1,3	1	1	1																				
Steel, mild	2,5	8	8	2,5	1,3	1	1																					
Steel alloy	8	8	8	2,5	1,3	1																						
Tantalum	8	1	4	1	1																							
Titanium	8	1	8	1																								
Tungsten	8	1	4																									
Vanadium	8	8																										
Zirconium	8																											

METAL COMPATIBILITY

1. Commonly bonded with clad layer of 1/8" to 3/4". [A]
2. Can be done with increases edge affect and scrape.
3. Proven hermetic bonds. [B]
4. Common with small thin clads. [C]
5. Commonly bonded but the bond is below the strength of the weaker material.
6. Commonly bonded with inner layer (no direct bonds). [D]
7. Unknown system may require inner layer. [D]
8. Unknown system with high probability of direct bonding. [E]

A. The thickness restraints normally only apply to the cladding layer. There are no thickness restraints to the base layer. The above mentioned thickness values are common not absolute limits. Clads as thin as 0.005" and as thick as 2.00" have been bonded.
B. These bonds have been proven to be hermetic at PA&E. Many other bonds are probably hermetic.
C. These bi-metal systems require that the less ductile metal be the clad.
D. These are tri-metal inner layer systems that have been developed at PA&E. The Tantalum layer is typically 0.010" thick. Titanium has also been used as an inner layer in specific systems. Many other inner layers possibly exist. Any metal that has compatibility with two other metals that require bonding will make a good inner layer for that particular system. This allows any combination of metals to be bonded as long as they have enough ductility to tolerate the explosive process (approx. 8% elongation). Tantalum displays a general compatibility with many metals. Other metals that potentially have a general compatibility with several other metals are: Molybdenum, Vanadium and Niobium.
E. Probability of success is a judgment based on the chemical activity and diffusion rate of the metals.

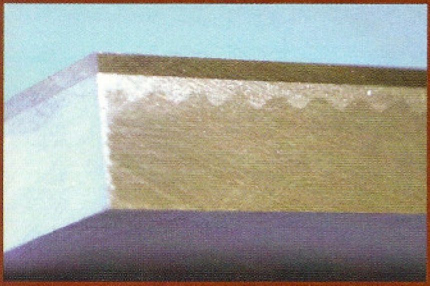

Fig. 3 — The characteristic wavy explosive weld appearance is clearly visible in this cross section.

Fig. 4 — Tensile testing of this Al-stainless steel-Al specimen displays the strength of the explosion welds exceeded that of the aluminum.

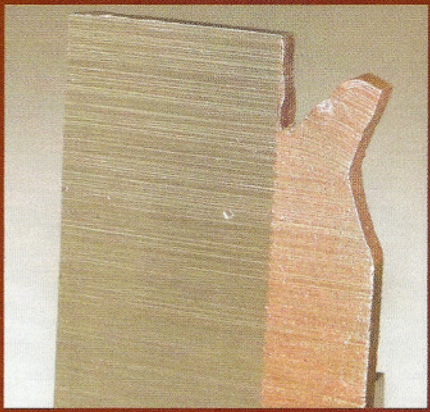

Fig. 5 — The chisel test showed no separation at the weld in this stainless steel-copper specimen.

several hundred thousand lb/in.^{2}) cause the first few atomic layers of each material to form a plasma jet that in turn propagates out of the impact zone, taking with it any contamination and unwanted oxide layers — Fig. 1. The impact causes the metals to form a true metallic bond, where the metals share valence electrons.

Due to the extreme cooling rate at the bond transition, the formation of intermetallics is largely suppressed. On a more macroscopic level, an explosion welded stack usually displays a characteristic waviness along the weld line — Figs. 2, 3. This waviness is a function of the different material properties and the welding parameters used. The amplitude of the waviness can be influenced by the impact angle and the detonation velocity. In extreme cases, it can be so high that unwanted voids or inclusions form under crests of the waves.

Weld Quality

Generally speaking, an explosion welded joint exhibits weld strength at least as great as the weaker of the two base metals. The welded product is routinely tested using pull tests for ultimate tensile strength, and ultrasonic inspection to reveal interior non-bonded areas — Figs. 4–6. The U.S. Navy has adopted a specification MIL-J-24445 for joining aluminum to steel. In addition, ASME publishes specifications detailing clad products.

What Can Be Welded?

The explosion welding process has been proven to work on a wide range of materials, and new combinations are being tried. In certain cases, the weld quality can be improved by inserting a thin layer of a third material between the two dissimilar layers. Stacks of four or more layers are not uncommon — Fig. 7.

Table 1 displays a chart of the various combinations of materials that Pacific Aerospace has successfully welded. Other suppliers will have encountered additional material combinations.

Some Applications for the Process

Weld Transitions

Explosively welded bimetal sheets can be used as weldable transitions between two dissimilar metals. For example, an explosively bonded strip of aluminum and stainless steel can be inserted between an aluminum structure and a stainless steel structure. This allows for direct conventional welding of the stainless steel structure to the stainless steel side of the bimetallic strip, and then direct conventional welding of the aluminum structure to the aluminum side of the bimetallic strip. The resulting joint is a fully welded aluminum-to-stainless steel structure. This application allows designers and fabricators to apply specific materials to the location or function that they are best suited for without having to make the entire structure out of one of the metals, thereby limiting the design's potential.

Precious Metal Conservation

Thin layers of precious metals, refractory metals, and other expensive alloys can be explosively welded to the specific area of a part where it is needed. This not only significantly reduces the cost of the manufactured part, but allows for the use of more structurally sound materials to be used where strength is required.

Galvanic Corrosion Prevention

Explosively welded dissimilar metals act as a significant inhibitor to galvanic activity that would occur between mechanically fastened dissimilar metals. Maritime applications benefit from the use of explosively welded metals by allowing for weldable transitions between dissimilar metals that significantly reduce or eliminate galvanic corrosion.

Corrosion-Resistant Linings

A common application for explosively welded (or clad) metals is as corrosion- or erosion-resistant linings for pressure vessels, chemical process tanks, heat exchangers, and tube sheets — Fig. 8.

In addition, there is a significant cost reduction afforded by the opportunity to utilize structural steels to improve wall strength without having to manufacture the entire structure from the typically costly corrosion-resistant metals.

Bearing Surfaces

Similar to corrosion-resistant linings, bearing materials can be explosively bonded to sheets of metal. This allows a structurally sound component to have a bearing surface clad directly to it, significantly reducing the wear of the part and improving its operation.

Radiation Shielding

Thin layers of shielding materials can be bonded to other structural metals or components. This has been a cost-effective method of providing radiation shielding to satellites.

Examples

Marine Shipbuilding Components

Because of the galvanic corrosion-prevention characteristics referred to previously, explosion welded transition materials have become prevalent throughout the shipbuilding industry. Cylindrically bonded aluminum-to-steel transition

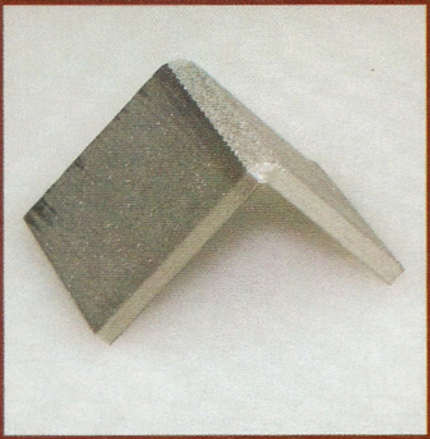

Fig. 6 — This stainless steel-aluminum sample was subjected to a 90-deg bend test. The part yielded in the aluminum away from the weld line.

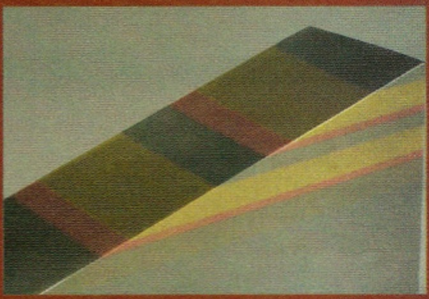

Fig. 7 — Eight metallic layers were explosively welded in multiple operations to produce this colorful ornamental stack.

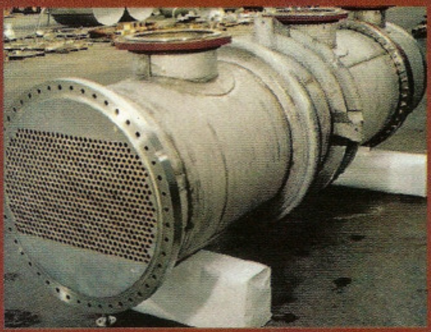

Fig. 8 — This shell and tube heat exchanger was manufactured from zirconium-clad steel for use in the chemical industry. (Courtesy of Dynamic Materials Corp., Boulder, Colo.)

Fig. 9 — Explosion welded aircraft tie-down fittings welded into aluminum aircraft carrier decks never need replacing. See lead photo.

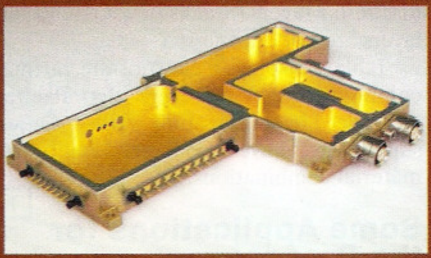

Fig. 10 — This aluminum electronics package features steel connectors in an all-welded construction.

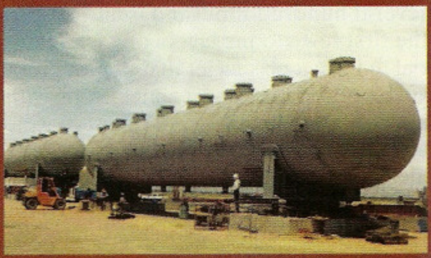

Fig. 11 — This large high-pressure autoclave is used to leach laterite nickel ore in hot sulfuric acid. The vessel is constructed from corrosion-resistant titanium clad to 4-in.-thick steel for strength. (Courtesy of Dynamic Materials Corp., Boulder, Colo.)

rings enable shipbuilders to securely weld forged steel cup-and-cross tie-down elements into the aluminum deck of aircraft carriers — Lead photo and Fig. 9.

Hermetic Electronic Packaging

Electronics packages used for modern military and aerospace applications invariably require the use of lightweight materials while simultaneously providing the utmost in reliability. In the past, connectors made from steel or Kovar™ were gold plated then soldered into a gold-plated aluminum housing. With prolonged usage and temperature swings, the solder joints were prone to fail. This allowed moisture to enter the housing and cause the entire unit to fail. By utilizing precision-machined aluminum-to-steel explosively welded transitions, the assembly can be laser beam welded, eliminating solder joints entirely — Fig. 10. As an added benefit, should a connector fail, the damaged part can be machined out and a new connector welded in its place, without affecting the rest of the package. With solder technology, connector removal requires heating the entire package, which could destroy the housing.

Chemical Process Vessels

On the other dimensional scale, explosion welding can be used to create some rather large structures. Dynamic Materials Corp. explosively clads large plates of hot-rolled carbon steel with corrosion-resistant materials such as titanium or stainless steel. The plates are rolled into cylinders then welded together to form large process and pressure vessels. Plates 40 ft long and ten ft wide are routinely bonded — Fig. 11.

Sputter Targets

Cathodic sputtering targets used in semiconductor manufacturing are made from expensive, high-purity materials to minimize contamination during the sputtering process. In order to reduce the quantity consumed of these materials, the target plate is usually welded to a lower-cost backing plate, which provides mechanical support and enables cooling through the back side. This bond must provide very good thermal and electrical conductivity between the carrier and backer plates, as well as maintain these properties as the target erodes through normal operation and becomes thinner. During operation, thermal stresses develop that could lead to a debonding of soldered or brazed assemblies. Explosion welding provides superior weld strength compared with these other technologies, resulting in a more reliable interface that will extend the effective lifetime of the target.

Summary

Explosion welded materials offer designers unique possibilities to design and manufacture devices and systems that exhibit superior performance and reliability characteristics, and significantly extend the useful lifetimes of their products. The added cost associated with these materials is often paid back several times through the life cycle of the product. Composite-welded materials are available in a very wide range of sizes and material combinations. The physical properties of the constituent base materials in the bonded system do not differ substantially from those of the individual base metals. In particular, the density of the bonded materials is essentially 100% of the theoretical density. Other cladding technologies such as thermal spray generally exhibit higher porosity.

Many conventional designs that specify soldering, brazing, or other attachment technologies could benefit when converted to explosion welding technology. ♦

Suggested Reading

1. Jaramillo, D. V., Szecket, A., and Inal, O. T. 1987. *Materials Science and Engineering* 91: 217–222.

2. Jaramillo, D. V., Inal, O. T., and Szecket, A. 1987. *Journal of Materials Science* 22: 3143–3147.

3. Linse, V. D., and Lalwaney, N. S. May 1984. *Journal of Metals:* 62–65.

4. Gerland, M., Presles, H. N., Guin, J. P., and Bertheau, D. 2000. *Materials Science and Engineering* A280: 311–319.

5. Leedy, K. D., and Stubbins, J. F. 2001. *Materials Science and Engineering* A297: 19–25.

6. Acarer, M., Gülenc, B., and Findik, F. 2003. *Materials and Design* 24: 659–664.

7. Cowan, G. R., Bergmann, O. R., and Holtzman, A. H. 1971. *Metallurgical Transactions* 2: 3145–3155.

8. Bergmann, O. R., Cowan, G. R., and Holtzman, A. H. 1966. *Transactions of the Metallurgical Society of AIME* 236: 646–653.

9. Cowan, G. R., and Holtzman, A. H. 1963. *Journal of Applied Physics* 34: 928–939.

10. Kowalick, J. F., and Hay, D. R. 1971. *Metallurgical Transactions* 2: 1953–1958.

11. Reid, S. R., and Sherif, N. H. S. 1976. *Journal Mechanical Engineering Science* 18: 87–93.

12. Blazynski, T .Z. 1983. *Explosive Welding, Forming, and Compaction,* Applied Science Publishers, London, U.K.

13. Crossland, B. 1982. *Explosive Welding of Metals and Its Application,* Oxford Science Publications, Oxford, U.K.

14. Murr, L. E. 1988. *Shock Waves for Indutrial Applications.* Noyes Publications.

15. U.S. Patent 3,137,937.

16. U.S. Patent 3,233,312.

17. U.S. Patent 3,397,444.

18. U.S. Patent 6,554,927.

Note: To view an up-to-date list of recent U.S. patents related to explosion welding, visit http://www.uspto.gov/patft/, *click Published Patents, Advanced Search, then enter* CCL/"228/107" *into the query box.*