Kirk-Othmer Encyclopedia of Chemical Technology.

METALLIC COATINGS EXPLOSIVELY CLAD METALS

After World War II explosives began to be used in specialized metalworking operations, particularly for metal forming. Explosives provided an inexpensive source of fast-release energy and greatly reduced the need for expensive capital equipment (1, 2). Research on explosively bonding metals began during the same period (3–7) (see also Explosives and propellants).

Explosive cladding, or explosion bonding and explosion welding, is a method wherein the controlled energy of a detonating explosive is used to create a metallurgical bond between two or more similar or dissimilar metals. No intermediate filler metal, eg, a brazing compound or soldering alloy, is needed to promote bonding and no external heat is applied. Diffusion does not occur during bonding.

In 1962, the first method for welding (qv) metals in spots along a linear path by explosive detonation was patented (8). This method is not, however, used industrially. In 1963, a theory that explained how and why cladding occurs was published (9). Research efforts resulted in process patents which standardized industrial explosion cladding. Several of the patents describe the use of variables involved in parallel cladding which is the most popular form of explosion cladding (10–13). Several excellent reviews on metal cladding have been published (14–16).

The explosive cladding process provides several advantages over other metal-bonding processes:

(1) A metallurgical, high quality bond can be formed between similar metals and between dissimilar metals that are incompatible for fusion or diffusion joining. Brittle, intermetallic compounds, which form in an undesirable continuous layer at the interface during bonding by conventional methods, are minimized, isolated, and surrounded by ductile metal in explosion cladding. Examples of these systems are titanium–steel, tantalum–steel, aluminum–steel, titanium–aluminum, and copper–aluminum. Immiscible metal combinations, eg, tantalum–copper, also can be clad.

(2) Explosive cladding can be achieved over areas that are limited only by the size of the available cladding plate and by the magnitude of the explosion that can be tolerated. Areas as small as 1.3 cm^2 (17) and as large as 27.9 m^2 (18) have been bonded.

(3) Metals having tenacious surface films that make roll bonding difficult, eg, stainless steel/Cr–Mo steels, can be explosion clad.

(4) Metals having widely differing melting points, eg, aluminum (660°C) and tantalum (2996°C), can be clad.

(5) Metals having widely different properties, eg, copper or maraging steel, can be bonded readily.

(6) Large clad-to-backer ratio limits can be achieved by explosion cladding. Stainless steel-clad components as thin as 0.025 mm and as thick as 3.2 cm have been explosion clad.

(7) The thickness of the stationary or backing plate in explosion cladding is essentially unlimited. Backers $>0.5-$m thick and weighing 50 t have been clad commercially.

(8) High quality, wrought metals are clad without altering chemical composition.

(9) Different types of backers can be clad; clads can be bonded to forged members, as well as to rolled plate.

(10) Clads can be bonded to rolled plate that is strand-cast, annealed, normalized, or quench-tempered.
(11) Multilayered composite sheets and plates can be bonded in a single explosion, and cladding of both sides of a backing metal can be achieved simultaneously. When two sides are clad, the two prime or clad metals need not be of the same thickness nor of the same metal or alloy.
(12) Nonplanar metal objects can be clad, eg, the inside of a cylindrical nozzle can be clad with a corrosion-resistant liner.
(13) The majority of explosion-clad metals are less expensive than the solid metals that could be used instead of the clad systems.

Limitations of the explosive bonding process are as follows.

(1) There are both inherent hazards in storing and handling explosives and undesirable noise and blast effects from the explosion.
(2) Obtaining explosives with the proper energy, form, and detonation velocity is difficult.
(3) Metals to be explosively bonded must be somewhat ductile and resistant to impact. Brittle metals and metal alloys fracture during bonding. Alloys having as little as 5% tensile elongation in a 5.1-cm gauge length, and backing steels having as little as 13.6 J (10 ft·lbf) Charpy V-notch impact resistance can, however, be bonded.
(4) For metal systems in which one or more of the metals to be explosively clad has a high initial yield strength or a high strain-hardening rate, a high quality bonded interface may be difficult to achieve. Metal alloys of high ($>$690 MPa (10^5 psi)) yield strength, are difficult to bond. This problem increases when there is a large density difference between the metals. Such combinations often are improved by using a thin interlayer between the metals.
(5) Geometries suited to explosive bonding promote straight-line egression of the high velocity jet emanating from between the metals during bonding, eg, for the bonding of flat and cylindrical surfaces.
(6) Thin backers must be supported, thus adding to manufacturing cost.
(7) The preparation and assembly of clads is not amenable to automated production techniques, and each assembly requires considerable labor.

1. Theory and Principles

To obtain a metallurgical bond between two metals, the atoms of each metal must be brought sufficiently close so that their normal forces of interatomic attraction produce a bond. The surfaces of metals and alloys must not be covered with films of oxides, nitrides, or adsorbed gases. When such films are present, metal surfaces do not bond satisfactorily (see Metal surface treatments).

Explosive bonding is a cold pressure-welding process in which the contaminant surface films are plastically jetted from the parent metals as a result of the high pressure collision of the two metals. A jet is formed between the metal plates, if the collision angle and the collision velocity are in the range required for bonding. The contaminant surface films that are detrimental to the establishment of a metallurgical bond are swept away in the jet. The metal plates, which are cleaned of any surface films by the jet action, are joined at an internal point by the high pressure that is obtained near the collision point.

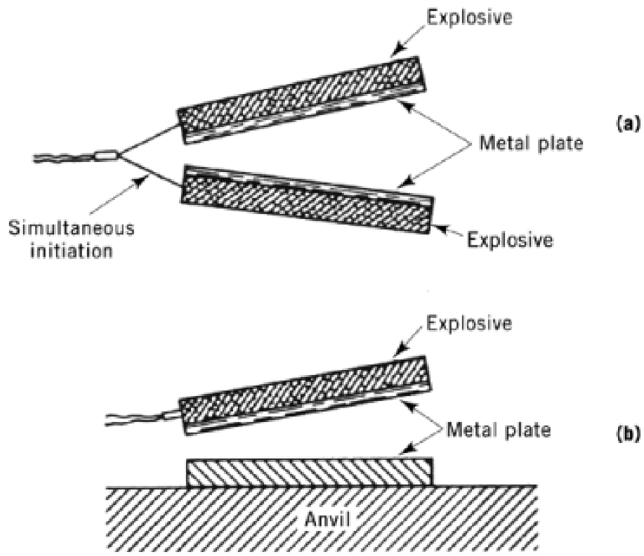


Fig. 1. Angle arrangements to produce explosion clads, where (**a**) represents symmetric angle cladding and (**b**), angle cladding.

1.1. Parallel and Angle Cladding

The arrangements shown in Figures 1 and 2 illustrate the operating principles of explosion cladding. Angle cladding (Fig. 1) is limited to cladding for relatively small pieces (19, 20). Clad plates having large areas cannot be made using this arrangement because the collision of long plates at high stand-offs, ie, the distance between the plates, on long runs is so violent that metal cracking, spalling, and fracture occur. The arrangement shown in Figure 2 is by far the simplest and most widely used (10).

1.2. Jetting

A layer of explosive is placed in contact with one surface of the prime metal plate which is maintained at a constant distance from and parallel to the backer plate, as shown in Figure 2**a**. The explosive is detonated and, as the detonation front moves across the plate, the prime metal is deflected and accelerated to plate velocity, V_P; thus an angle is established between the two plates. The ensuing collision region progresses across the plate at a velocity equal to the detonation velocity, D. When the collision velocity, V_C, and the angle are controlled within certain limits, high pressure gradients ahead of the collision region in each plate cause the metal surfaces to flow hydrodynamically as a spray of metal from the apex of the angled collision. Jetting is the flow process and expulsion of the metal surface (9). Photographic evidence of jetting during an explosion-bonding experiment is given in Figure 3 (21). The jet, which moves in the direction of detonation, is observed between the deflected prime metal and the backer metal.

Typically, jet formation is a function of plate collision angle, collision-point velocity, cladding-plate velocity, pressure at the collision point, and the physical and mechanical properties of the plates being bonded. For jetting and subsequent cladding to occur, the collision velocity has to be substantially below the sonic velocity of the cladding plates, usually ca 4000–5000 m/s (22). There also is a minimum collision angle below which no jetting occurs regardless of the collision velocity. In the parallel-plate arrangement shown in Figure 2, this angle is determined by the stand-off. In angle cladding (see Fig. 1), the preset angle determines the stand-off and the attendant collision angle.

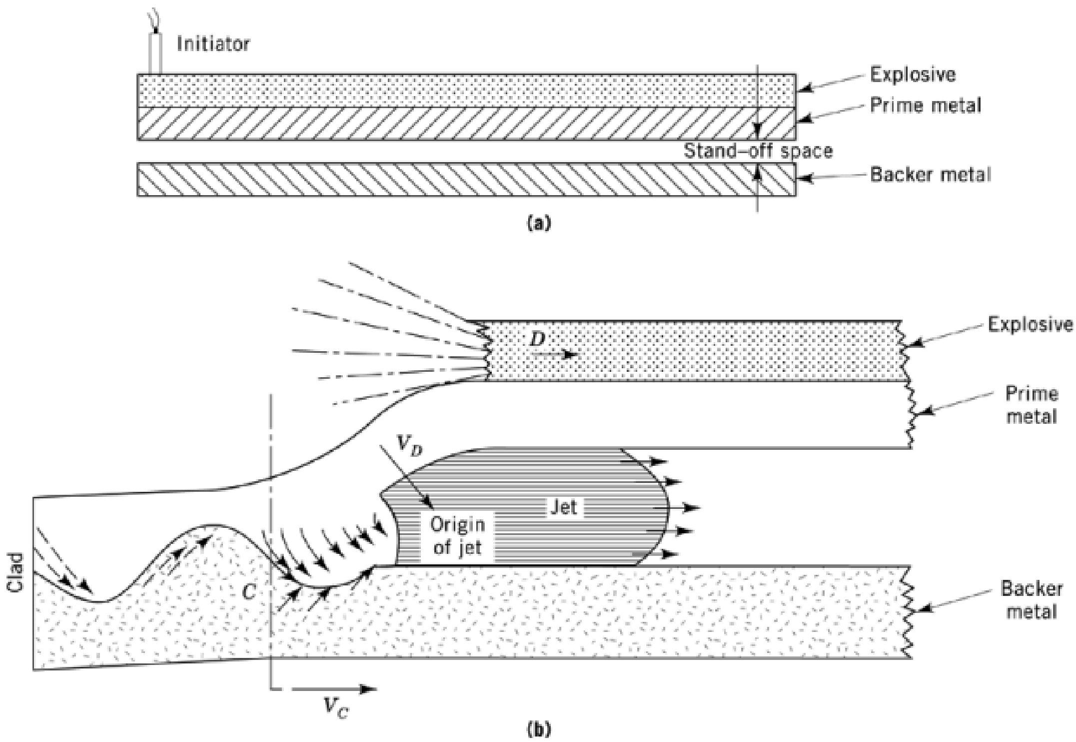


Fig. 2. Parallel arrangement for (**a**) explosion cladding and subsequent collision between the prime and backer metals that leads to (**b**) jetting and formation of the wavy bond zone, where V_D is the detonation velocity and V_C, the collosion velocity.

1.3. Nature of the Bond

Extensive metallurgical testing has determined that the best clad properties are obtained when the bond zone is wavy. It is therefore preferable that commercial, explosively bonded metals exhibit a wavy bond-zone interface. The amplitude and wavelength of the bond zone wave structure varies as a function of explosive properties and the stand-off distance, as shown in Table 1 (12). Moreover, the amplitude of the waves is proportional to the square of the collision angle. This latter finding is consistent with the fluid flow analogy theory of bond-zone wave formation (23), where bond-zone wave formation is treated as fluid flowing around an obstacle (see Flow measurement; Fluid mechanics). When the fluid velocity is low, the fluid flows smoothly around the obstacle, but above a certain fluid velocity, the flow pattern becomes turbulent, as illustrated in Figure 4. In explosion bonding, the obstacle is the point of highest pressure in the collision region. Because the pressures in this region are many times higher than the dynamic yield strength of the metals, the metals flow plastically, as evidenced by the microstructure of the metals at the bond zone. Electron microprobe analysis across such plastically deformed areas shows that no diffusion occurs because there is extremely rapid self-quenching of the metals (22).

Under optimum conditions, the metal flow around the collision point is unstable and it oscillates, thereby generating a wavy interface. Typical explosion-bonded interfaces between nickel plates made at different collision velocities are illustrated in Figure 4 (23). A typical explosion-bonded interface between titanium and steel is shown in Figure 5. Small pockets of solidified melt form under the curl of the waves; some of the kinetic energy of the driven plate is locally converted into heat as the system comes to rest. These discrete regions are

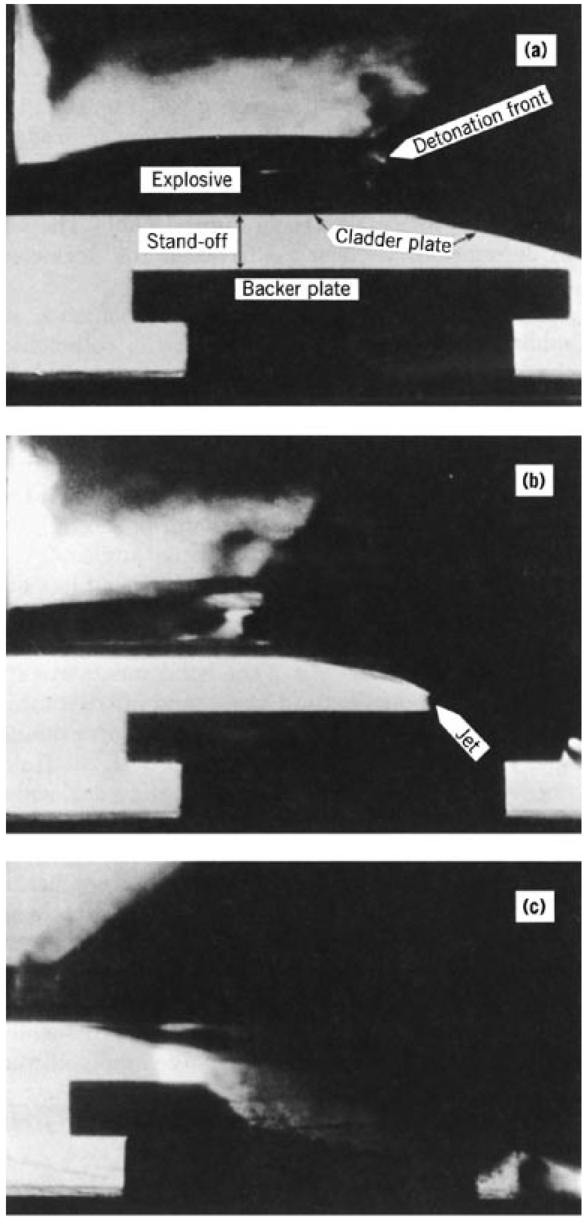


Fig. 3. (**a**–**c**) Cladding of aluminum to aluminum showing jet formation (21).

completely encapsulated by the ductile prime and base metals. The direct metal-to-metal bonding between the isolated pockets provides the ductility necessary to support stresses during routine fabrication.

The quality of bonding is related directly to the size and distribution of solidified melt pockets along the interface, especially for dissimilar metal systems that form intermetallic compounds. The pockets of solidified melt are brittle and contain localized defects which do not affect the composite properties. Explosion-bonding

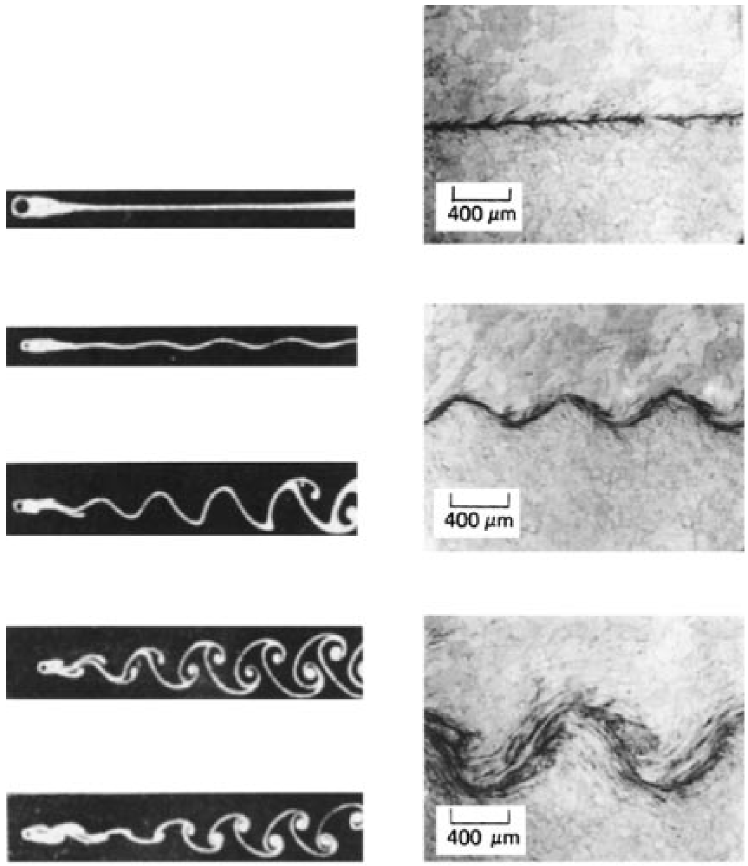
Table 1. Measured Explosion-Cladding Parameters and Bond-Zone Characteristics[a, b]

		Flyerplate		Bond-zone characteristics			
Collision velocity, m/s	Parallel stand-off, mm	Velocity, m/s	Angle, deg	Type[c]	Wave-length, μm	Ampli-tude, μm	Equivalent melt thick- ness, μm
			Grade A nickel				
1650	1.14	215	7.4	straight and wavy	112	10	<1
2000	1.14	250	7.0		103	11	<1
2500	1.14	270	6.6		236	39	1.6
3600	1.14	410	6.5		254	38	5.1
2000	2.16	310	8.7		318	41	<1
2500	2.16	337	8.2		425	76	3.9
3600	2.16	510	8.25		590	96	9.8
1650	3.96	325	11.2		520	52	<1
2000	3.96	372	10.5		567	88	<1
2500	3.96	407	9.7		671	121	6.0
3600	3.96	625	9.95		739	146	28.8
2000	6.35	420	11.8		790	132	<1
2500	6.35	462	10.8		895	171	9.0
3600	6.35	700	11.2		965	162	24.0
1650	10.54	425	14.8		1018	169	<1
2000	10.54	460	13.0		623	97	<1
3600	10.54	775	12.5		1333	284	59.2
1650	17.78	465	16.5	straight			[d]
			Grade 1 titanium				
2000	1.14	330	9.9		103	8	<1
2500	1.14	400	9.7		254	19	1.2
3600	1.14	580	9.3	MLW	250	23	14.0
2000	2.16	420	12.2	MLW	215	17	<1
2500	2.16	465	11.0	MLW	482	47	3.0
3600	2.16	710	11.3	MLW	468	59	11.6
2000	3.96	495	14.2	MLW	373	31	<1
2500	3.96	520	12.1	MLW	768	89	3.1
3600	3.96	845	13.4	MLW	868	122	9.2
2000	6.35	530	15.2	MLW	610	53	<1
2500	6.35	565	13.0	MLW	1009	130	8.2
3600	6.35	945	15.0	MLW	1228	189	18.5
2000	10.54	560	15.5	MLW	1013	96	<1
2500	10.54	600	14.0	MLW	1300	167	3.6
3600	10.54	1040	16.5	MLW	1360	230	21.8

[a]Ref. 12.
[b]For cladding 3.2-mm metal to 12.7-mm AISI 1008 Carbon Steel.
[c]Wavy unless otherwise noted. MLW = melted layer and waves.
[d]Not detectable.

parameters for dissimilar metal systems normally are chosen to minimize the pockets of melt associated with the interface.

When cladding conditions are such that the metallic jet is trapped between the prime metal and the backer, the energy of the jet causes surface melting between the colliding plates. In this type of clad, alloying through melting is responsible for the metallurgical bond. As shown in Figure 6, solidification defects can occur and, for this reason, this type of bond is not desirable.



(a) (b)

Fig. 4. (**a**) Photographs of fluid flow behind cylinders at increasing flow velocities top to bottom. (**b**) Photomicrographs of nickel–nickel bond zones made at increasing collision velocities; top, ~1600 m/s; middle, ~1900 m/s; bottom, ~2500 m/s (23).

The industrially useful combinations of explosively clad metals that are available in commercial sizes are listed in Figure 7. The list does not include triclads or possible combinations not yet explored. The combinations that explosion cladding can provide are virtually limitless (24).

2. Processing

2.1. Explosives

The pressure, P, generated by the detonating explosive that propels the prime plate is directly proportional to its density, ρ, and the square of the detonation velocity, V_D^2 (25):

$$P = \frac{1}{4}\rho V_D^2$$

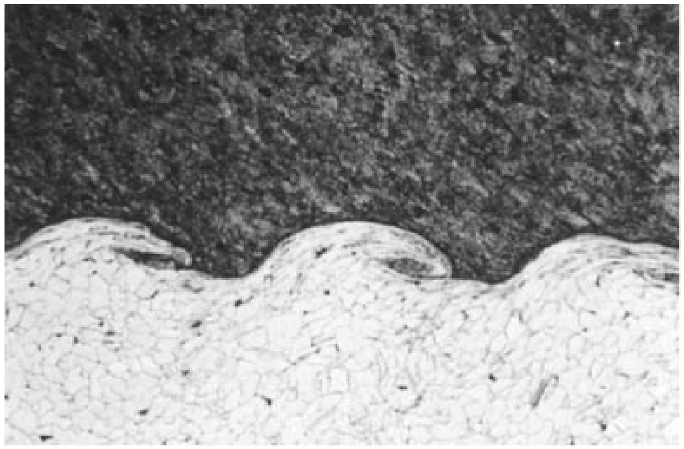


Fig. 5. Photomicrograph of titanium, top, to carbon steel, bottom, explosion clad ($_{100x}$).

The detonation velocity is controlled by adjusting thepacking density or the amount of added inert material (26).

The types of explosives that have been used include both high (4500–7600 m/s) and low to medium (1500–4500 m/s) velocity materials (24, 26).

High velocity	Low–medium velocity
trinitrotoluene (TNT)	ammonium nitrate
cyclotrimethylenetrinitramine (RDX)	ammonium nitrate prills sensitized with fuel oil
pentaerythritol tetranitrate (PETN)	
composition B	ammonium perchlorate
composition C_4	amatol
plasticized PETN-based rolled sheet and extruded cord	amatol and sodatol diluted with rock salt to 30–35%
	dynamites
primacord	nitroguanidine
	diluted PETN

In commercial practice, powdered explosives on an ammonium nitrate basis are used in most cases. Typical detonation velocities are between 1800 and 3500 m/s depending on the metal system to be bonded. The lower detonation velocity range is preferred for many metal systems in order to minimize the quantity of solidified melt associated with the bond-zone waves (12). In addition, subsonic detonation velocity explosives are required for the parallel cladding technique in order to avoid attached shock waves in the collision region, which preclude formation of a good bond.

2.2. Metal Preparation

Preparation of the metal surfaces to be bonded usually is required because most metals contain surface imperfections or contaminants that undesirably affect bond properties. The cladding faces usually are surface ground, using an abrasive machine, and then are degreased with a solvent to ensure consistent bond strength (26). In general, a surface finish that is $\geq 3.8\ \mu m$ deep is needed to produce consistent, high quality bonds.

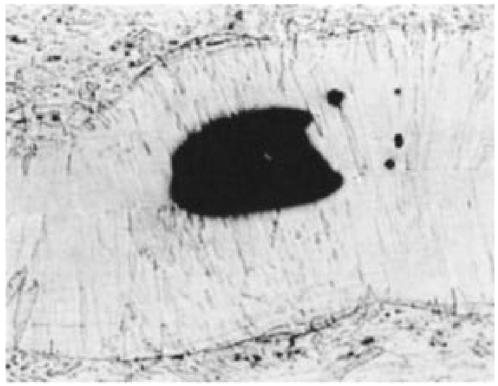


Fig. 6. Solidification defects in the copper–copper explosion-clad evidence the occurrence of melting at the interface ($_{100x}$) (9).

Fabrication techniques must take into account the metallurgical properties of the metals to be joined and the possibility of undesirable diffusion at the interface during hot forming, heat treating, and welding. Compatible alloys, ie, those that do not form intermetallic compounds upon alloying, eg, nickel and nickel alloys (qv), copper and copper alloys (qv), and stainless steel alloys clad to steel, may be treated by the traditional techniques developed for clads produced by other processes. On the other hand, incompatible combinations, eg, titanium, zirconium, or aluminum to steel, require special techniques designed to limit the production at the interface of undesirable intermetallics which would jeopardize bond ductility.

2.3. Assembly, Stand-Off

The air gap present in parallel explosion cladding can be maintained by metallic supports that are tack-welded to the prime and backer plates or by metallic inserts that are placed between the prime and backer (26–28). The inserts usually are made of a metal that is compatible with one of the cladding metals. If the prime metal is so thin that it sags when supported by its edges, other materials, eg, rigid foam, can be placed between the edges to provide additional support; the rigid foam is consumed by the hot egressing jet during bonding (26–29) (see Foamed plastics). A moderating layer or buffer, eg, polyethylene sheet, water, rubber, paints, and pressure-sensitive tapes, may be placed between the explosive and prime metal surface to attenuate the explosive pressure or to protect the metal surface from explosion effects (24).

2.4. Facilities

The preset, assembled composite is placed on an anvil of appropriate thickness to minimize distortion of the clad product. For thick composites, a bed of sand usually is a satisfactory anvil. Thin composites may require a support made of steel, wood, or other appropriate materials. The problems of noise, air blast, and air pollution (qv) are inherent in explosion cladding, and clad-composite size is restricted by these problems. Thus the cladding facilities should be in areas that are remote from population centers. Using barricades and burying the explosives and components under water or sand lessens both noise and air pollution (24). An attractive method for making small-area clads using light explosive loads employs a low vacuum, noiseless chamber (24). Underground missile silos and mines also have been used as cladding chambers (see Insulation, acoustic).

	Zirconium	Magnesium	Stellite	Platinum	Gold	Silver	Niobium	Tantalum	Hastelloy	Titanium	Nickel alloys	Copper alloys	Aluminum	Stainless steels	Alloy steels	Carbon steels
Carbon steels	●	●			●	●	●	●	●	●	●	●	●	●	●	●
Alloy steels	●	●	●					●	●	●	●	●	●	●	●	
Stainless steels			●		●	●	●	●		●	●	●	●	●		
Aluminum [*7429-90-5*]		●				●	●	●		●	●	●	●			
Copper alloys						●	●	●		●	●	●				
Nickel alloys		●		●	●			●		●	●					
Titanium [*7440-30-6*]	●	●				●	●	●		●						
Hastelloy									●							
Tantalum [*7440-25-7*]					●		●	●								
Niobium [*7440-03-1*]				●			●									
Silver [*7440-22-5*]						●										
Gold [*7440-57-4*]																
Platinum [*7440-06-4*]				●												
Stellite 6B																
Magnesium [*7440-95-4*]		●														
Zirconium [*7440-67-7*]	●															

Fig. 7. Commercially available explosion-clad metal combinations.

3. Analytical and Test Methods

When the explosion-bonding process distorts the composite so that its flatness does not meet standard flatness specifications, it is reflattened on a press or roller leveler (ASME SA20). However, press-flattened plates sometimes contain localized irregularities which do not exceed the specified limits but which, generally, do not occur in roll-flattened products.

3.1. Nondestructive Testing

Nondestructive inspection of an explosion-welded composite is almost totally restricted to ultrasonic and visual inspection. Radiographic inspection is applicable only to special types of composites consisting of two metals having a significant mismatch in density and a large wave pattern in the bond interface (see Nondestructive evaluation).

3.1.1. Ultrasonics

The most widely used nondestructive test method for explosion-welded composites is ultrasonic inspection. Pulse-echo procedures (ASTM A435) are applicable for inspection of explosion-welded composites used in pressure applications.

The acceptable amount of nonbond depends on the application. In clad plates for heat exchangers, $>98\%$ bond usually is required. Other applications may require only 95% of the total area to be bonded. Configurations of a nonbond sometimes are specified, eg, in heat exchangers where a nonbond area may not be $>19.4\ \mathrm{cm}^2$ or 7.6 cm long. The number of areas of nonbond generally is specified. Ultrasonic testing can be used on seam welds, tubular transition joints, clad pipe and tubing, and in structural and special applications.

3.1.2. Radiographic

Radiography is an excellent nondestructive test (NDT) method for evaluating the bond of Al–steel electrical and Al–Al–steel structural transition joints. It provides the capability of precisely and accurately defining all nonbond and flat-bond areas of the Al–steel interface, regardless of size or location (see Surface and interface analysis).

The clad plate is x-rayed perpendicular from the steel side and the film contacts the aluminum. Radiography reveals the wavy interface of explosion-welded, aluminum-clad steel as uniformly spaced, light and dark lines with a frequency of one to three lines per centimeter. The waves characterize a strong and ductile transition joint and represent the acceptable condition. The clad is interpreted to be nonbonded when the x-ray shows complete loss of the wavy interface (see X-ray technology).

3.2. Destructive Testing

Destructive testing is used to determine the strength of the weld and the effect of the explosion-welding process on the parent metals. Standard testing techniques can be utilized on many composites; however, nonstandard or specially designed tests often are required to provide meaningful data for specific applications.

3.2.1. Pressure-Vessel Standards

Explosion-clad plates for pressure vessels are tested according to the applicable ASME Boiler and Pressure Vessel Code Specifications. Unfired pressure vessels using clads are covered by ASTM A263, A264, and A265; these include tensile, bend, and shear tests (see Tanks and pressure vessels).

Tensile tests of a composite plate having a thickness of <3.8 cm require testing of the joined base metal and clad. Strengthening does occur during cladding and tensile strengths generally are greater than for the original materials. Some typical shear-strength values obtained for explosion-clad composites covered by ASTM A263, A264, A265, which specify 138 MPa (20,000 psi) minimum, and B432, which specifies 83 MPa (12,000 psi) minimum, are listed in Table 2 (see High pressure technology).

3.2.2. Chisel

Chisel testing is a quick, qualitative technique that is widely used to determine the soundness of explosion-welded metal interfaces. A chisel is driven into and along the weld interface, and the ability of the interface to resist the separating force of the chisel provides an excellent qualitative measure of weld ductility and strength.

3.2.3. Ram Tensile

A ram tensile test has been developed to evaluate the bond-zone tensile strength of explosion-bonded composites. The specimen is designed to subject the bonded interface to a pure tensile load. The cross-section area of the specimen is the area of the annulus between the outer and inner diameters of the specimen. The specimen typically has a very short tensile gauge length and is constructed so as to cause failure at the bonded interface.

Table 2. Shear Strengths of Explosively Clad Metals

Cladding metal on carbon steel backers	Shear strength,[a] MPa[b]
stainless steels	448
nickel and nickel alloys	379
Hastelloy alloys	391
zirconium	269
titanium[c]	241
cupronickel	251
copper	152
aluminum (1100-Ah4)	96

[a]See ASTM A263, A264, A265, and B432.
[b]To convert MPa to psi, multiply by 145.
[c]Stress relief annealed at 621 °C.

The ultimate tensile strength and relative ductility of the explosion-bonded interface can be obtained by this technique.

3.2.4. Mechanical Fatigue

Some mechanical fatigue tests have been conducted on explosion-clad composites where the plane of maximum tensile stress is placed near the bond zone (30).

3.2.5. Thermal Fatigue and Stability

Explosion-welded plates have performed satisfactorily in several types of thermal tests (18). In thermal fatigue tests, samples from bonded plate are alternately heated to 454–538°C at the surface and are quenched in cold water to less than 38°C. The three-minute cycles consist of 168 s of heating and 12 s of cooling. Weld-shear tests are performed on samples before and after thermal cycling. Stainless steel clads have survived 2000 such thermal cycles without significant loss in strength (18). Similarly welded and tested Grade 1 titanium–carbon steel samples performed in a similarly satisfactory fashion.

3.2.6. Metallographic

The interface is inspected on a plane parallel to the detonation front and normal to the surface. A well-formed wave pattern without porosity generally is indicative of a good bond. The amplitude of the wave pattern for a good weld can vary from small to large without a large influence on the strength, and small pockets of melt can exist without being detrimental to the quality of the bond. However, a continuous layer of melted material indicates that welding parameters were incorrect and should be adjusted. A line-type interface with few waves indicates that the collision velocity of the plate was not great enough and/or that the collision angle was too high for jetting to occur. A well-defined wave pattern in which the crest of the wave is bent over to form a large melt pocket with a void in the swirl is indicative of a poor bond. In this case, the plate velocity is too high as is the collision angle.

In some materials, eg, titanium and martensitic steels, shear bands are adjacent to the weld interface if the cladding variables are excessive. This is the result of thermal adiabatic shear developed from excessive overshooting energy, and a heat treatment is required to eliminate the hardened-band effect. When the cladding variables and the system energy are optimum, thermal shear bands are minimized or eliminated and heat treatment after cladding is not required. Several types of metal composites require heat treatment after cladding to relieve stress, but intermetallic compounds can form as a result of the treatment. A metallographic examination indicates if the heat treatment of the explosion-bonded composite has resulted in the formation of intermetallic compounds.

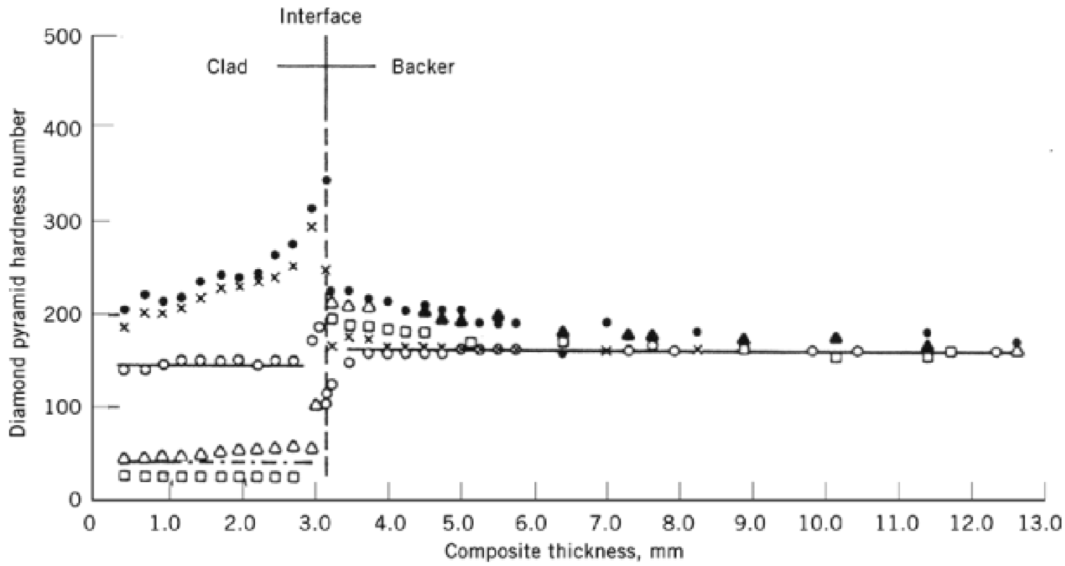


Fig. 8. Microhardness profile across interfaces of two types of explosion clads that show widely divergent response resulting from the inherent cold-work hardening characteristics where () represents the 3.2-mm type 304L stainless/28.6-mm, A 516-70 control (before cladding); (•)=clad+flat; (×)=clad+stress relief annealed at 621°C+flat; (○)=clad+normalize at 954°C. (—.) represents 3.2-mm 1100-H14 aluminum/25.4-mm, A 516-70 control (before cladding); (△)=clad+flat; (□)=clad+flat+stress relief annealed at 593°C (31).

3.2.7. Hardness, Impact Strength

Microhardness profiles on sections from explosion-bonded materials show the effect of strain hardening on the metals in the composite (see Hardness). Figure 8 illustrates the effect of cladding a strain-hardening austenitic stainless steel to a carbon steel. The austenitic stainless steel is hardened adjacent to the weld interface by explosion welding, whereas the carbon steel is not hardened to a great extent. Similarly, aluminum does not strain harden significantly.

Impact strengths also can be reduced by the presence of the hardened zone at the interface. A low temperature stress-relief anneal decreases the hardness and restores impact strength (30). Alloys that are sensitive to low temperature heat treatments also show differences in hardness traverses that are related to the explosion-welding parameters, as illustrated in Figure 9 (16). Low welding impact velocities do not develop as much adiabatic heating as higher impact velocities. The effect of the adiabatic heating is to anneal and further age the alloys. Hardness traverses indicate the degree of hardening during welding and what, if any, subsequent heat treatment is required after explosion bonding. Explosion-bonding parameters also can be adjusted to prevent softening at the interface, as shown in Figure 9.

4. Safety Aspects

All explosive materials should be handled and used following approved safety procedures in compliance with applicable federal, state, and local laws, regulations, and ordinances. The Bureau of Alcohol, Tobacco, and Firearms (BATF), the Hazardous Materials Regulation Board (HMRB) of the Department of Transportation (DOT), the Occupational Safety and Health Agency (OSHA), and the Environmental Protection Agency (EPA) in Washington, D.C., have federal jurisdiction on the sale, transport, storage, and use of explosives. Many

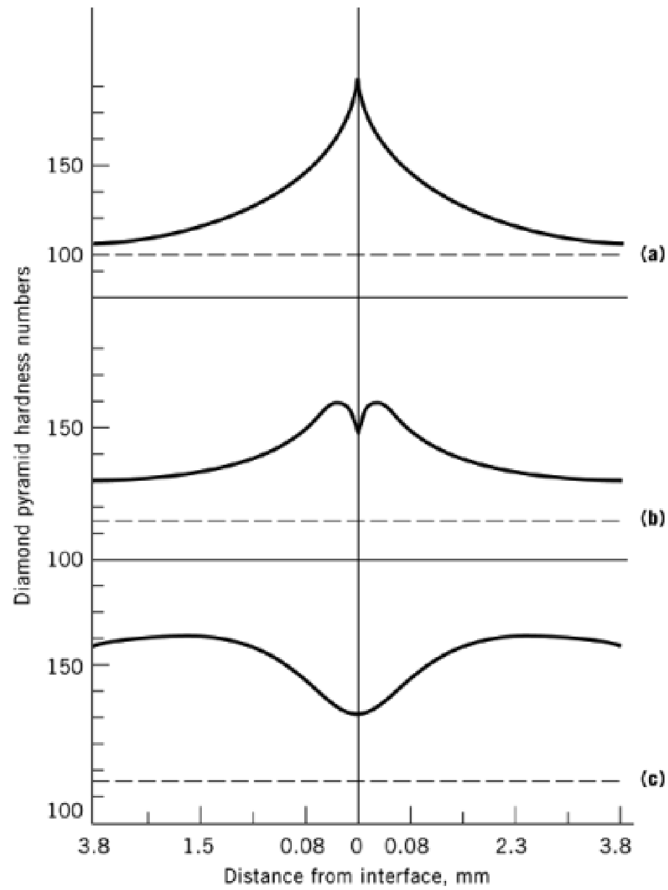


Fig. 9. Microhardness profiles across interface of explosion-clad age-hardenable aluminum alloy 2014-T3 where the initial hardness is shown as () (**a**) low, (**b**) medium, and (**c**) high impact velocity (16).

states and local counties have special explosive requirements. The Institute of Makers of Explosives (IME) in New York provides educational publications to promote the safe handling, storage, and use of explosives. The National Fire Protective Association (NFPA) in Boston, Mass., similarly provides recommendations for safe explosives manufacture, storage, handling, and use.

5. Uses

Cladding and backing metals are purchased in the appropriately heat-treated condition because corrosion resistance is retained through bonding. It is customary to supply the composites in the as-bonded condition because hardening usually does not affect the engineering properties. Occasionally, a post-bonding heat treatment is used to achieve properties required for specific combinations.

Vessel heads can be made from explosion-bonded clads, either by conventional cold- or by hot-forming techniques. The latter involves thermal exposure and is equivalent in effect to a heat treatment. The backing metal properties, bond continuity, and bond strength are guaranteed to the same specifications as the composite

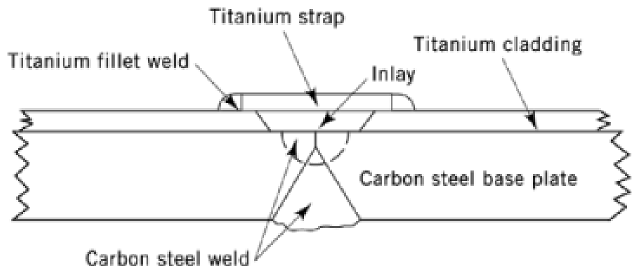


Fig. 10. Double-v inlay, batten-strap technique for fusion welding of an explosion-clad plate containing titanium and zirconium.

from which the head is formed. Applications such as chemical-process vessels and transition joints represent approximately 90% of the industrial use of explosion cladding.

5.1. Chemical-Process Vessels

Explosion-bonded products are used in the manufacture of process equipment for the chemical, petrochemical, and petroleum industries where the corrosion resistance of an expensive metal is combined with the strength and economy of another metal. Applications include explosion cladding of titanium tubesheet to Monel, hot fabrication of an explosion clad to form an elbow for pipes in nuclear power plants, and explosion cladding titanium and steel for use in a vessel intended for terephthalic acid manufacture.

Precautions must be taken when welding incompatibly clad systems, eg, hot forming of titanium-clad steel plates must be conducted at 788°C or less. The preferred technique for butt welding involves a batten-strap technique using a silver, copper, or steel inlay (Fig. 10). Precautions must be taken to avoid iron contamination of the weld either from the backer steel or from outside sources. Stress relieving is achieved at normal steel stress-relieving temperatures, and special welding techniques must be used in joining tantalum–copper–steel clads (32, 33).

5.2. Conversion-Rolling Billets

Much clad plate and strip have been made by hot and cold rolling of explosion-bonded slabs and billets. Explosion bonding is economically attractive for conversion rolling because the capital investment for plating and welding equipment needed for conventional bonding methods is avoided. Highly alloyed stainless steels and some copper alloys, which are difficult to clad by roll bonding, are used for plates made by converting explosion-bonded slabs and billets. Conventional hot-rolling and heat-treatment practices are used when stainless steels, nickel, and copper alloys are converted. Hot rolling of explosion-bonded titanium, however, must be performed below ca 843°C to avoid diffusion and the attendant formation of undesirable intermetallic compounds at the bond interface. Hot-rolling titanium also requires a stiff rolling mill because of the large separation forces required for reduction.

Perhaps the most extensive application for conversion-rolled, explosion-bonded clads was for U.S. coinage in the 1960s (34) when over 15,900 metric tons of explosion-clad strip that was supplied to the U.S. Mint helped alleviate the national silver coin shortage. The triclad composites consist of 70–30 cupronickel/Cu/70–30 cupronickel.

5.3. Transition Joints

Use of explosion-clad transition joints avoids the limitations involved in joining two incompatible materials by bolting or riveting. Many transition joints can be cut from a single large-area flat-plate clad and delivered to limit the temperature at the bond interface so as to avoid undesirable diffusion. Conventional welding practices may be used for both similar metal welds.

5.3.1. Electrical

Aluminum, copper, and steel are the most common metals used in high current–low voltage conductor systems. Use of these metals in dissimilar metal systems often maximizes the effects of the special properties of each material. However, junctions between these incompatible metals must be electrically efficient to minimize power losses. Mechanical connections involving aluminum offer high resistance because of the presence of the self-healing oxide skin on the aluminum member. Because this oxide layer is removed by the jet, the interface of an explosion clad essentially offers no resistance to the current. Thus welded transition joints, which are cut from thick composite plates of aluminum–carbon steel, permit highly efficient electrical conduction between dissimilar metal conductors. Sections can be added by conventional welding. This concept is routinely employed by the primary aluminum reduction industry in anode-rod fabrication. The connection is free of the aging effects that are characteristic of mechanical connections and requires no maintenance. The mechanical properties of the explosion weld, ie, shear, tensile, and impact strength, exceed those of the parent-type 1100 aluminum alloy.

Usually, copper surfaces are mated when joints must be periodically disconnected because copper offers low resistance and good wear. Junctions between copper and aluminum bus bars are improved by using a copper–aluminum transition joint that is welded to the aluminum member. Deterioration of aluminum shunt connections by arcing is eliminated when a transition joint is welded to both the primary bar and the shunting bar.

The same intermetallic compounds that prevent conventional welding between aluminum and copper or steel can be developed in an explosion clad by heat treatment at elevated temperature. Diffusion can be avoided if the long-term service temperature is kept below 260°C for aluminum–steel and 177°C for copper–aluminum combinations. Under short-term conditions, as during welding, peak temperatures of 316 and 232°C, respectively, are permissible. Bond ductility is maintained, although there is a reduction in bond strength as the aluminum is annealed. Bond strength, however, never falls below that of the parent aluminum; therefore nominal handbook values for type 1100 alloy aluminum may be used in design considerations. The bond is unaffected by thermal cycling within the recommended temperature range.

5.3.2. Marine

In the presence of an electrolyte, eg, seawater, aluminum and steel form a galvanic cell and corrosion takes place at the interface. Because the aluminum superstructure is bolted to the steel bulkhead in a lap joint, crevice corrosion is masked and may remain unnoticed until replacement is required. By using transition-joint strips cut from explosion-welded clads, the corrosion problem can be eliminated. Because the transition is metallurgically bonded, there is no crevice in which the electrolyte can act and galvanic action cannot take place. Steel corrosion is confined to external surfaces where it can be detected easily and corrected by simple wire brushing and painting.

Explosion-welded construction has equivalent or better properties than the more complicated riveted systems. Peripheral benefits include weight savings and perfect electrical grounding. In addition to lower initial installation costs, the welded system requires little or no maintenance and, therefore minimizes life-cycle costs. Applications of structural transition joints include aluminum superstructures that are welded to decks of naval vessels and commercial ships as illustrated in Figure 11.

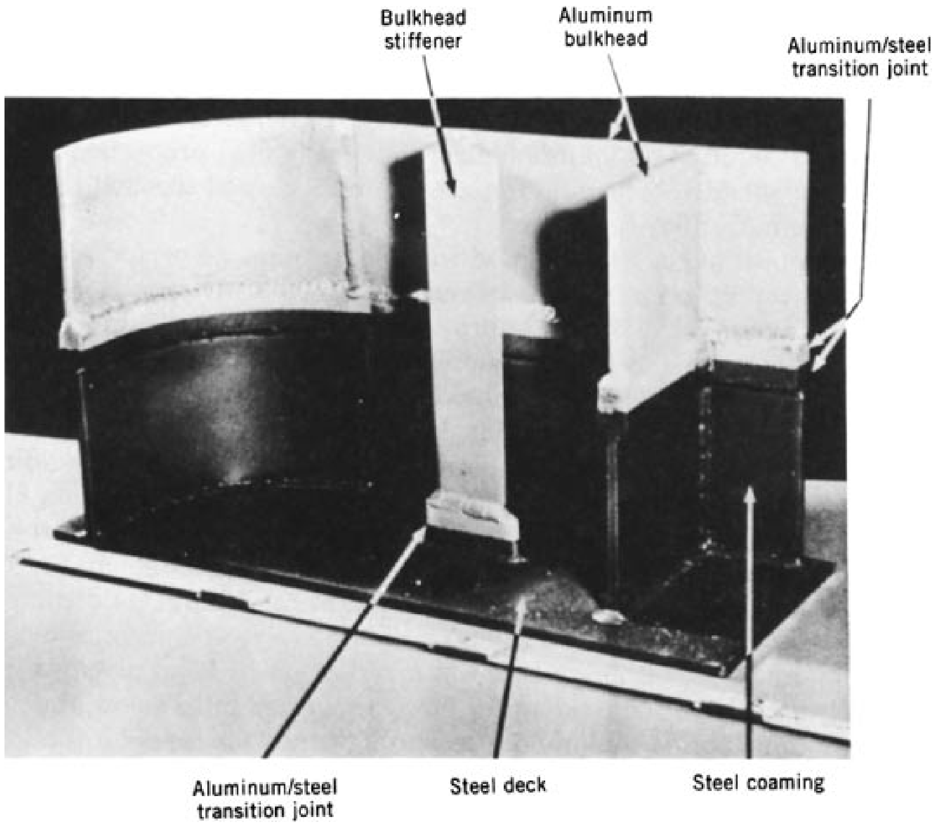


Fig. 11. Sample showing typical aluminum superstructure and deck connection made possible by use of explosion-clad aluminum–carbon steel transition joint.

5.3.3. Tubular

Explosion welding is a practical method for providing the means to join dissimilar metal pipes, eg, aluminum, titanium, or zirconium, to steel or stainless steel, using standard welding equipment and techniques. The process provides a strong metallurgical bond which assures that the transition joints provide maintenance-free service throughout years of thermal and pressure/vacuum cycling. Explosion-welded tubular transition joints are being used in many diverse applications in aerospace, nuclear, and cryogenic industries. These operate reliably through the full range of temperatures, pressures, and stresses that normally are encountered in piping systems. Tubular transition joints in various configurations can be cut and machined from explosion-welded plate, or made by joining tubes by overlap cladding. Standard welding practices are used to make the final joints.

5.4. Nonplanar Specialty Products

The inside walls of hollow forgings that are used for connections to heavy walled pressure vessels have been metallurgically bonded with stainless steel. These bonded forgings, or nozzles, range from 50 to 610 mm in inner diameter and are up to 1 m long. Large-clad cylinders and internally clad, heavy-walled tubes have been extruded using conventional equipment. Other welding applications have been demonstrated, including those shown in Figure 12.

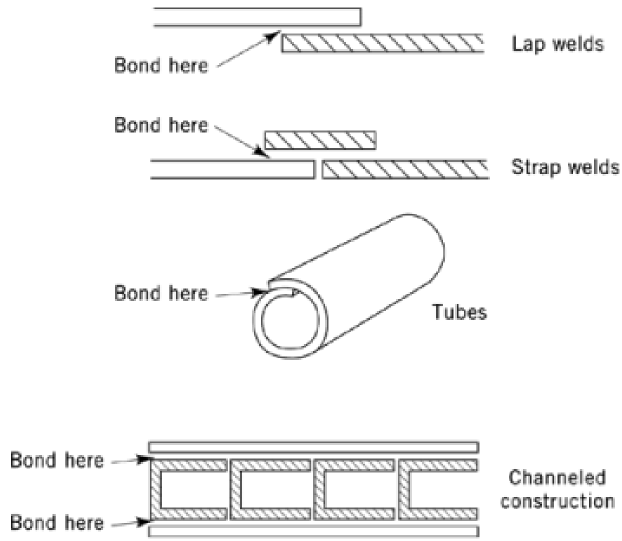


Fig. 12. Explosion-clad welding applications (7).

5.5. Tube Welding and Plugging

Explosion-bonding principles are used to bond tubes and tube plugs to tube sheets. The commercial process resembles the cladding of internal surfaces of thick-walled cylinders or pressure vessel nozzles, as shown in Figure 13; angle cladding is used (35). Countersink machining at the tube entrance provides the angled surface of 10–20° at a depth of 1.3–1.6 cm. The exploding detonator propels the tube or tube plug against the face of the tube-sheet to form the proper collision angle which in turn provides the required jetting and attendant metallurgical bond. Tubes may be welded individually or in groups. Metal combinations that are welded commercially include carbon steel–carbon steel, titanium–stainless steel, and 90–10 cupronickel–carbon steel.

5.6. Refractory Metals and Alloys

Special modifications of the explosion-bonding process have been developed to successfully produce clads of refractory metals on steel and other backer metals. Among the refractory metals that have received particular attention for specialized chemical process equipment are tantalum, molybdenum, and molybdenum–rhenium alloys. In the case of tantalum, thin interlayers of copper are usually clad simultaneously with the tantalum sheet onto steel or stainless steel backers. This facilitates production of reliable welds when several explosion-clad plates are joined along their edges to form a larger clad plate for fabrication into large commercial chemical reactors. In the case of molybdenum, and certain molybdenum alloys that have a high brittle-to-ductile transition temperature, it is necessary to use specialized heating techniques during the explosion cladding operation to produce well-bonded clads having good ductility for subsequent forming operations (36–41).

6. Production and Markets

Explosion-bonded metals are produced by several manufacturers in the United States, Europe, and Japan. The chemical industry is the principal consumer of explosion-bonded metals which are used in the construction of clad reaction vessels and heat-exchanger tube sheets for corrosion-resistant service. The primary market

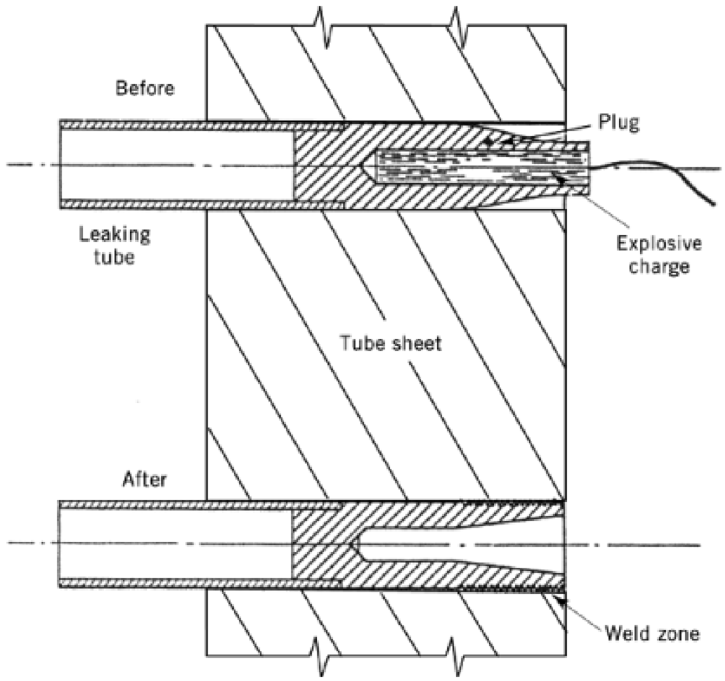


Fig. 13. Tube-to-tubesheet plugging (35).

segments for explosion-bonded metals are for corrosion-resistant pressure vessels, tube sheets for heat exchangers, electrical transition joints, and structural transition joints. Total world markets for explosion-clad metals are estimated to fluctuate between $\$30 \times 10^6$ to $\$60 \times 10^6$ annually.

BIBLIOGRAPHY

"Metallic Coatings (Explosively Clad)" in *ECT* 3rd ed., Vol. 15, pp. 275–296, by A. Pocalyko, E. I. du Pont de Nemours & Co., Inc.

Cited Publications

1. J. Pearson, *J. Met.* **12**, 673 (1960).
2. R. S. Rinehart and J. Pearson, *Explosive Working of Metals*, MacMillan, New York, 1963.
3. J. J. Douglass, *New England Regional Conference of AIME*, Boston, Mass., May 26, 1960.
4. *Ryan Reporter*, Vol. **21**, No. 3, Ryan Aeronautical Co., San Diego, Calif., 1960, 6–8.
5. C. P. Williams, *J. Met.*, 33 (1960).
6. "High Energy Rate Forming" in *Product Engineering and American Machinist/Metalworking Manufacturing*, McGraw Hill, New York, 1961 and 1962.
7. A. H. Holtzman and C. G. Rudershansen, *Sheet Met. Ind.* **39**, 401 (1961).
8. U.S. Pat. 3,024,526 (Mar. 13, 1962), V. Philipchuk and F. Le Roy Bois (to Atlantic Research Corp.).
9. G. R. Cowan and A. H. Holtzman, *J. Appl. Phys.* **34**(Pt. 1), 928 (1962).
10. U.S. Pat. 3,137,937 (June 23, 1964), G. R. Cowan, J. J. Douglass, and A. H. Holtzman (to E. I. du Pont de Nemours & Co., Inc.).

11. U.S. Pat. 3,233,312 (Feb. 8, 1966), G. R. Cowan and A. H. Holtzman (to E. I. du Pont de Nemours & Co., Inc.).
12. U.S. Pat. 3,397,444 (Aug. 20, 1968), O. R. Bergmann, G. R. Cowan, and A. H. Holtzman (to E. I. du Pont de Nemours & Co., Inc.).
13. U.S. Pat. 3,493,353 (Feb. 3, 1970), O. R. Bergmann, G. R. Cowan, and A. H. Holtzman (to E. I. du Pont de Nemours & Co., Inc.).
14. B. Crossland and A. S. Bahrani, *Proceedings of the First International Conference on Center High Energy Forming*, University of Denver, Denver, Colo., 1967.
15. A. A. Ezra, *Principles and Practices of Explosives Metal Working*, Industrial Newspapers, Ltd., London, 1973.
16. S. H. Carpenter and R. H. Wittman, *Ann. Rev. Mater. Sci.* **5**, 177 (1975).
17. J. L. Edwards, B. H. Cranston, and G. Krauss, *Metallic Effects at High Strain Rates*, Plenum Press, New York, 1973.
18. A. Pocalyko, *Mater. Prot.* **4**(6), 10 (1965).
19. U.S. Pat. 3,264,731 (Aug. 9, 1966), B. Chudzik (to E. I. du Pont de Nemours & Co., Inc.).
20. U.S. Pat. 3,263,324 (Aug. 2, 1966), A. A. Popoff (to E. I. du Pont de Nemours & Co., Inc.).
21. O. R. Bergmann, G. R. Cowan, and A. H. Holtzman, *Trans. Met. Soc. AIME* **236**, 646 (1966).
22. A. H. Holtzman and G. R. Cowan, *Weld. Res. Counc. Bull. No. 104*, Engineering Foundation, New York, Apr. 1965.
23. G. R. Cowan, O. R. Bergmann, and A. H. Holtzman, *Met. Trans.* **2**, 3145 (1971).
24. V. D. Linse, R. H. Wittman, and R. J. Carlson, *Defense Metals Information Center, Memo 225*, Columbus, Ohio, Sept. 1967.
25. M. A. Cook, *The Science of High Explosives*, Reinhold Publishing Corp., New York, 1966, p. 274.
26. A. A. Popoff, *Mech. Eng.* **100**(5), 28 (1978).
27. U.S. Pat. 3,140,539 (July 14, 1964), A. H. Holtzman (to E. I. du Pont de Nemours & Co., Inc.).
28. U.S. Pat. 3,205,574 (Sept. 14, 1965), H. M. Brennecke (to E. I. du Pont de Nemours & Co., Inc.).
29. U.S. Pat. 3,360,848 (Jan. 2, 1968), J. J. Saia (to E. I. du Pont de Nemours & Co., Inc.).
30. J. L. DeMaris and A. Pocalyko, *American Society of Tool and Manufacturing Engineers*, *Paper AD66-113*, Dearborn, Mich., 1966.
31. A. Pocalyko and C. P. Williams, *Weld. J.* **43**, 854 (1964).
32. U.S. Pat. 3,464,802 (Sept. 2, 1969), J. J. Meyer (to Nooter Corp.).
33. U.S. Pat. 4,073,427 (Feb. 14, 1978), H. G. Keifert and E. R. Jenstrom (to Fansteel, Inc.).
34. J. M. Stone, paper presented at *Select Conference on Explosive Welding*, Hove, U.K., Sept. 1968, 29–34.
35. R. Hardwick, *Weld. J.* **54**(4), 238 (1975).
36. U.S. Pat. 5,226,579 (July 13, 1993), O. R. Bergmann, V. M. Felix, W. J. Simmons, and R. H. Tietzen (to E. I. Du Pont de Nemours & Co., Inc.).
37. U.S. Pat. 4,264,029 (Apr. 28, 1981), R. Henne and R. Pruemmer (to Deutsche Forschungs und Versuchsanstalt Fuer Luft und Raumfahrt).
38. Ger. Pat. 1,934,104 (Jan. 21, 1971), A. A. Deribas and V. M. Kudinov (to Institute of Hydrodynamics, Novosibirsk, Russia).
39. R. Koecher, *Chem. Ing. Tech.* **55**(10), 752–762 (1983).
40. U. Gramberg, E. M. Horn, and K. O. Cavalar, "Explosionsplattierte Bleche in Anlagen, Erfahrungen aus der Chemietechnik," VDI Meeting, *Explosionsplattieren-ein modernes Verfahren zur Herstellung von Hochleistungsvebundsystemen*, Duesseldorf, Germany, Dec. 1, 1983, 29–35.
41. U.S. Pat. 5,323,955 (June 28, 1994) O. R. Bergmann, V. M. Felix, W. J. Simmons, and R. H. Tietjen (to E. I. du Pont de Nemours & Co.).

General References

42. *The Joining of Dissimilar Metals*, DMIC Report S-16, Battelle Memorial Institute, Columbus, Ohio, Jan. 1968.
43. S. H. Carpenter, *Nat. Tech. Info. Ser. Rept. No. AMMRC CTR74-69*, Dec. 1978.
44. C. Birkhoff, D. P. MacDougall, E. M. Pugh, and G. Taylor, *J. Appl. Phys.* **19**, 563 (1948).
45. L. Zernow, I. Lieberman, and W. L. Kincheloe, *American Society of Tool and Manufacturing Engineers, Technical Paper SP60-141*, Dearborn, Mich., 1961.
46. R. H. Wittman, *Metallurgical Effects at High Strain Rates*, Plenum Press, New York, 1973.
47. R. H. Wittman, *American Society of Tool and Manufacturing Engineers, Technical Paper AD-67-177*, Dearborn, Mich.

48. G. Bechtold, I. Michael, and R. Prummer, *Gold Bull. Chamber Mines S. Afr.* **10**(2), 34 (1977).
49. B. H. Cranston, D. A. Machusak, and M. E. Skinkle, *West Electr. Eng.*, 26 (Oct. 1978).
50. A. A. Popoff, *American Society of Manufacturing Engineers, Technical Paper AD77-236*, Dearborn, Mich., 1977.
51. T. Z. Blazynski, *International Conference on Welding and Fabrication of Non-Ferrous Metals*, *Eastbourne, May 2 and May 3, 1972, Cambridge, U.K.*, The Welding Institute, 1972.
52. J. K. Kowalick and D. R. Hay, *Second International Conference of the Center For High Energy Forming*, Estes Park, Colo., June 23–27, 1969.
53. J. Ramesam, S. R. Sahay, P. C. Angelo, and R. V. Tamhankar, *Weld Res. Suppl.*, 23s (1972).
54. L. F. Trueb, *Trans. Met. Soc. AIME* **2**, 147 (1971).
55. *Metals Handbook*, 9th ed., Vol. **6**, American Society for Metals, Metals Park, Ohio, 1983, 705–718.
56. *ASM Handbook*, Vol. **6**, ASM International, Metals Park, Ohio, 160–164, 303–305, 896–900.

OSWALD R. BERGMANN
E. I. du Pont de Nemours & Co., Inc.

Related Articles

Metallic Coatings, Survey; Explosives; Nondestructive testing; Welding; Metal treatments