The Fundamentals of Explosion Welding

BY COLIN MERRIMAN

No heat-affected zones or problems with differences in thermalexpansions make explosion welding an alternative process worth learning about

In the postwar years of the 1950s, many companies and research institutions considered explosives as an energy source for metalworking. Since that time there has been much experimentation in swaging, forming, cutting, hardening, powder compaction, and welding.

The application of explosive welding has unique advantages in joining metals that would frequently be incompatible, such as titanium or zirconium and steel. These clad materials are commonly used today in chemical process vessel construction. Intuitively, it may be assumed that the great pressures produced by various types of explosives used in bonding and forming processes could bring the metal plates together so forcefully that welding would naturally occur. However, it has been shown that high pressure alone is not sufficient to form a satisfactory metallic bond.

To achieve a metallic bond, atoms of one metal must come into intimate contact with atoms of the other metal. However, metals are generally coated with surface films including oxides (e.g., Al_2O_3), nitrides (e.g., AlN), and adsorbed gases (such as H_2), which prevent sufficiently close contact.

These surface films must be removed by effacement or dispersion before welding can be achieved. Once the films have been removed, the underlying metal can be brought together by high pressure to form the metallic weld. The surface film may also be dissipated in a melted region so that the weld is formed via a solidified zone.

Characteristics of Explosions

An explosion is a rapid increase in volume and release of energy in a violent manner that propagates with a wavelike nature. There are two types of explosive waves — deflagrations and detonations.

Deflagrations travel at subsonic velocities, which depend on the rates of chemical reaction, thermal, and mass diffusion. The deflagration velocity can vary wildly during its progression, especially if it is confined. Typical deflagrations are gas-air mixtures in a gas stove, fuel-air mixtures in an internal combustion engine, and gunpowder in a firearm or pyrotechnic device.

In contrast, a detonation travels at supersonic velocity, far exceeding the sonic velocity of the undetonated explosive. The detonation wave consists of a shock front that compresses and heats the explosive, followed by a region of rapid chemical reaction. The detonation velocity (V_D) is dependent upon the compressibility and density ($_e$) of the explosive products and on the effective energy release per unit weight of explosive.

The velocity of an explosive, such as ammonium nitrate-fuel oil (ANFO), will vary typically with the depth, run length of the explosive used, and confinement. This must be accounted for and compensated for in a welding operation. By taking the product of the explosive density ( ) and the square of the detonation velocity (V_D), it is possible to attain approximately the pressure developed at the detonation front:

$$P_D = 0.25 \quad V_D^2 \quad 10^{-6}$$

Two Views of the Process

The explosive welding process is considered both a solid-phase and a fusion welding process depending upon the literature reviewed. The classical view of explosive welding is that when the effaced metal surfaces are brought into sufficiently close contact, the valence electrons can overcome the repulsive forces and result in sharing of their orbits (Ref. 1). This would result in a cold weld through metallurgical bonding from a solid-phase process.

The second view is that a microscopic layer of molten metal is created followed by rapid cooling (10^5 K/s) at the metal collision line (Ref. 2). Upon rapid cooling, a 0.05–0.2 m amorphous zone is created surrounded by a thin region of very fine

COLIN MERRIMAN (cmerriman@pacaero.com) *is an applications engineer at Pacific Aerospace & Electronics, Inc., Wenatchee, Wash.*

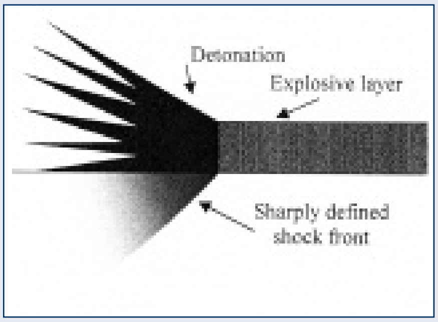

Fig. 1 — A shock wave develops when the sonic velocity of the explosive is greater than 120% of the sonic velocity of the faster metal.

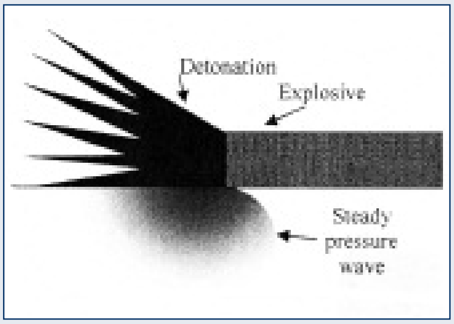

Fig. 2 — No shock wave is produced when the detonation velocity is less than the sonic velocity of the metal.

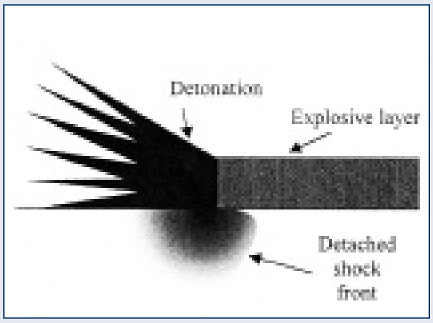

Fig. 3 — A detached shock wave results when the detonation velocity is between 100% and 120% of the sonic velocity of the metal.

grains. This would be included under a fusion-type weld.

Advantages of Explosive Welding

Regardless of whether or not the bond is a solid-phase or a fusion weld, explosive welding has several advantages over competing processes. Notable are no heat-affected zone (HAZ), no diffusion, and only minor melting; and material melting temperatures and coefficients of thermal expansion differences do not affect the final product.

The following terms are commonly used in the explosive welding industry.

Cladding metal or **cladder** is the thinner plate that is either in direct contact with the explosive, or is shielded by a flyer plate from the explosive.

Flyer plate is a sacrificial plate placed between the cladder and the explosive to protect the cladder metal.

Interlayer is a thin (typically 0.01–0.03 in.) metal layer that is sometimes placed between the cladder and base plate to enhance joining.

Base plate or **backer** is the plate that the cladder is being joined to.

Anvil is the surface on which backer rests during the joining operation.

Standoff is the distance between the cladder and base plate prior to the joining operation.

Bond window is the range of process variables, such as velocity, dynamic bend ( ), and standoff distance that result in a successful weld.

Bonding operation is the detonation of the explosive resulting in a weld.

Assuring a Good Weld

With the welding operation taking only a few microseconds, there is no time for in-process adaptive control of welding parameters or conditions. Therefore, high-quality welds are attained through careful preparation of the materials before the joining operation is carried out, including material preparation, assembly, and setup.

The first step in material preparation is to clean the surfaces to be joined by grinding them to a predetermined surface finish. This varies from material to material, and is determined by the size of the bond window. The smaller the bond window, the finer the required surface finish. Once the surface has been prepared, the plates are joined together and held at a predetermined standoff distance by a shim. There are many different types of shims for different types of welding operations. Shims are designed to be consumed by the jet so as to not adversely affect the weld.

The standoff distance is unique to the material combination, and is selected to ensure the cladder reaches a specific collision velocity (critical velocity) before impacting the backer plate. The standoff distance typically ranges between ½ and 2 times the thickness of the cladder. It should be noted that for multilayer joining operations (three or more layers), the process variables change significantly. An explosive containment box is placed around the edges of the cladder metal. The height of this box is selected to contain a specific amount of explosive material, resulting in a specific energy release per unit area.

The explosive type and composition are selected to achieve a specific detonation velocity (V_D) and energy release per unit area. The detonation velocity of the explosive must be less than about 120% of the sonic velocity of the material V_S:

$$V_S = \sqrt{\frac{k}{\ }}$$

$$k = \frac{E}{(1-2\ )}$$

Where k is the adiabatic bulk (dynes/cm^2), is the material density (g/cm^3), E is Young's modulus, and is Poisson's ratio.

If the sonic velocity of the explosive is greater than 120% of the sonic velocity of the faster material, a shock wave develops. This results in an extremely steep rise to maximum pressure as shown in Fig. 1.

The material just in front of the shock wave experiences no pressure, while the material just behind the shock wave is compressed to peak pressure and density. The shock wave travels through the material at a supersonic velocity and accelerates the metal rapidly to a large fraction of the shock velocity. This form of shock wave creates significant plastic deformation locally and results in considerable hardening, known as shock hardening.

When the detonation velocity is less than the sonic velocity of the metal, the pressure generated by the expanding gasses that is imparted to the metal moves faster than the detonation. A shock wave is not produced, resulting in a steady rise to peak pressure — Fig. 2.

The maximum pressure at the interface is equal to the detonation pressure of the explosive. The third type of detonation is the intermediate region where the detonation velocity is between about 100% and 120% of the sonic velocity of the metal. This results in a detached shock wave that travels slightly ahead of the detonation — Fig. 3 (Ref. 3).

In the detached shock wave and no shock wave cases, pressure is generated ahead of the collision point of the metal plates. If a sufficiently large pressure is generated, it will cause the metal just ahead of the collision to flow into the space between the plates. This flow takes the form of a high-velocity jet that effaces the material, removing unwanted oxides and other surface films. At the collision point, the newly cleaned metal surfaces impact at high pressures (typically between 0.5 and 6 GPa). Upon detonation of the explosive, there is a significant amount of heat generated within the explosive. Fortunately, however, the detonation is complete within a few hundred microseconds, and there is very little heat transferred to the metal. This results in no bulk diffusion and a weld with only localized melting.

The impact parameters for a specific metal combination are dependent upon metal type, thickness, and properties making them unique to each metal combination. Selection of these parameters is critical to attaining a high-quality weld with the desired properties. The impact conditions for a parallel plate setup are related by the following equation.

$$V_P = 2V_C \sin \frac{\quad}{2}$$

where V_C is the impact point velocity, which is equal to the detonation velocity of the explosive (V_D). is referred to as the dynamic bend angle. It is the angle created between the cladder and backer at the impact point, while V_P is the plate collision velocity at the point of impact. Typically, the detonation velocity, which is an independent variable selected to attain the desired impact properties, ranges between 1200 and 3800 m/s depending upon the metals to be welded. The standoff distance, which is not included in this equation, is also an independent variable and is selected to achieve a specific bend angle and velocity at impact.

The dynamic bend angle is a dependent variable that is controlled by the detonation velocity and the standoff distance. Typical values for are between 2 and 25 deg. This results in a plate collision velocity at the impact point (V_P) of about 200–500 m/s.

Once these parameters have been considered and accounted for, it is possible to select an explosive and standoff gap to achieve the desired properties. The assembly of the two metal plates and explosive containment box, along with the explosives, are transported to a safe remote site where they are detonated. Once the welding operation is complete, it may be necessary to trim and flatten the welded pieces before any further processing is done. The sale of explosively clad products to diverse manufacturers has resulted in the use of this product in nearly every industry.

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