Technological Development in Explosive Welding of Metals

By S. K. BANERJEE*

It has been reasonably well established that explosive welding is a form of pressure welding. To achieve a strong bond between the metal surfaces, it is essential to have the surfaces perfectly clean and the surfaces are brought together with sufficient pressure when inter-atomic repulsive and attractive forces will come into play resulting in bonding when equilibrium is reached.

Explosive welding was accidentally discovered by Philipchuk[1] who states that while explosive forming an aluminium U channel, he observed that the U channel could not be removed from the die because a circular shaped area had become welded to the metal die. Similar welding of metals to the metal die in explosive forming was also observed by Holtzman and Ruderhausen[2]. This led to the idea of using explosives for welding and it was found that explosive welding could be used to join materials which could not have been joined by other methods.

Technique and Mechanism of Explosive Welding

Pearson[3] carried out various experiments on explosive welding. He is of the opinion that explosive welding could be produced by both stand-off operation and contact operation. In stand-off operation, the explosive charge is located some distance away from the "flyer plate" (plate to be welded with the base plate) and the energy released by the explosive is transmitted through an intervening medium such as air, water or oil. Pressure at the work piece may range from a few thousand lbf/in^2 depending on the parameteis of the operation. In the contact operation, explosive is placed in direct contact with the "flyer plate" or an adjacent buffer. When the explosive is detonated, pressures of the order of several million lbf/in^2 may be developed at the contact interface. According to Pearson, the welding mechanism in these operations is the result of bringing the metal surfaces together at a high relative velocity and with a suitable geometry of impact, so that large amounts of plastic interaction occur between the surfaces to be welded. When the plates impact each other at an oblique angle of incidence, surface jetting may occur and as a result a high strength bond is produced. The experimental set-up used by them in the Michelson Laboratory is shown in Fig. 1. It is observed from the figure that two plates are oriented at some static angle and the surfaces are coated with thin layers of high energy plastic explosives which are initiated simultaneously near the apex of the plates. As the detonation waves

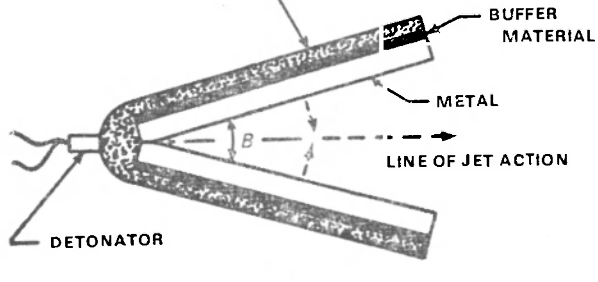

Fig.–1

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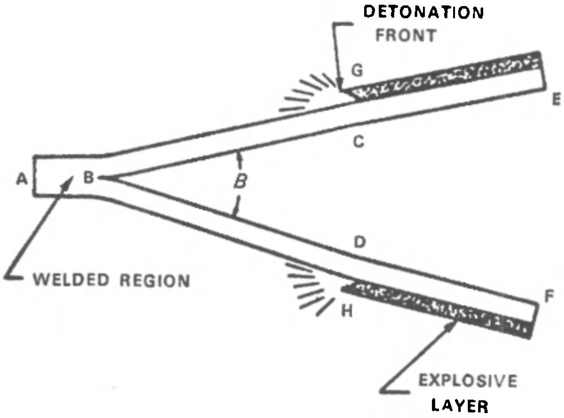


Fig.–2

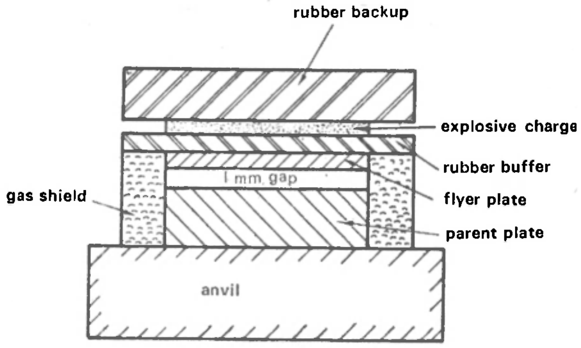


Fig.–3

propagate along the explosive, the plates are collapsed against each other with high relative velocity and this causes the metal close to the colliding surfaces to participate in the surface jetting process and produce a strong weld between the parts. Adopting this method, Pearson and Hayes could weld two or more metal plates with one explosive layer. All the welding operations are performed in air. Fig 2 shows a diagramatic sketch of a flash radiograph of a steel to steel specimen in a partially collapsed condition 18 microseconds after the initiation of detonation. Among the many metals which have been welded in similar and dissimilar combinations of from two to five layers thick are : aluminium alloys, brass, copper nickel alloys, low carbon steels, stainless steels and tantalum.

Davenport and Duval[4] used the "parallel plate technique" shown in Fig. 3, at which the flyer plate is maintained at a specific distance parallel to the lower plate and the whole plate impacts directly with the lower plate. They observed that where the impact was normal no welding resulted whereas the places where the impact was oblique a good bonding is achieved. However, finally they adopted the oblique impact technique and varied the angle of incidence between flyer plate and parent plate in the range from 0°-4° and successfully welded aluminium to aluminium and copper to copper, but failed to weld copper to aluminium or aluminium to copper.

Holtzman and Ruderhansen[2] used a similar type of set-up as that of Pearson shown in Fig. 1 for their experiments on explosive welding at the E.I. du Pont deNemours & Co. According to them, when two plates collide, metal from each plate is forced out into the included space in the form of 'metallic jet'. The jet materials subsequently melt and form the bond. In their conclusion, they have justified the process of explosive cladding on the grounds of the following advantages : (a) the process is versatile and a wide variety of metals can be welded, (b) the quality of bond is excellent and the shear strength of the bond often exceeds that of the metal bonded and (c) the process is economical.

Boes[5] mentioned some contact explosive technique developed for explosive welding at the Technical Centre for Metal Working (T.N.O.) Holland. The set-ups used for contact explosive welding are shown in Fig. 5, in which the surfaces to be welded are kept in contact with each other, on a rigid support which is usually a steel anvil. The surfaces should be smooth and uncontaminated A rubber buffer is laid on the upper plate and the sheet explosive placed on top of it Boes[5] emphasized the desirability of a rubber buffer since a very heavy deformation and damage of the surface were observed when the charge was placed directly on the parts to be welded. The thickness of the rubber buffer depends on the metals to be welded and on the type and thickness of explosive used. When the explosive charge is detonated, the rubber deforms and causes a modification to the shock wave front as shown in fig. 6. Thus the pressure wave subjects the inter-face of the two plates to a high pressure and a small relative velocity.

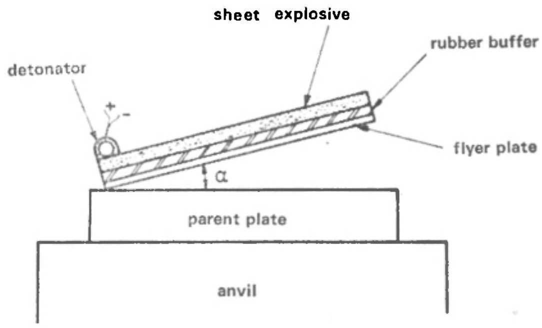


Fig.–4

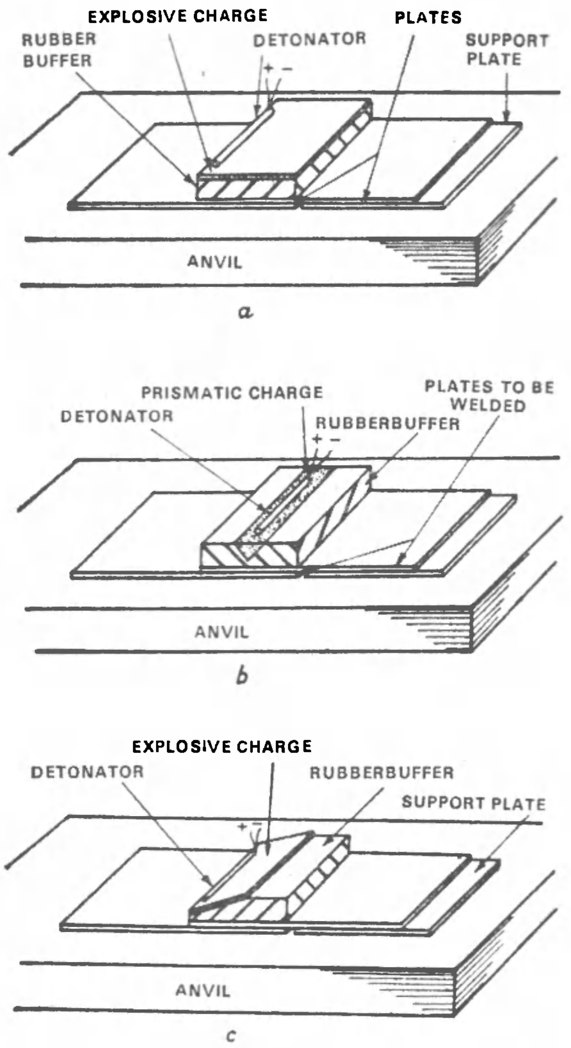


Fig.–5

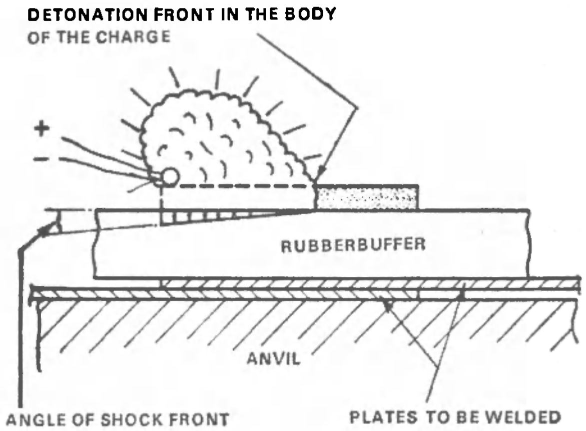
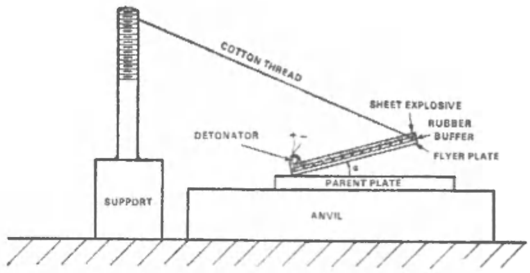


Fig.–6



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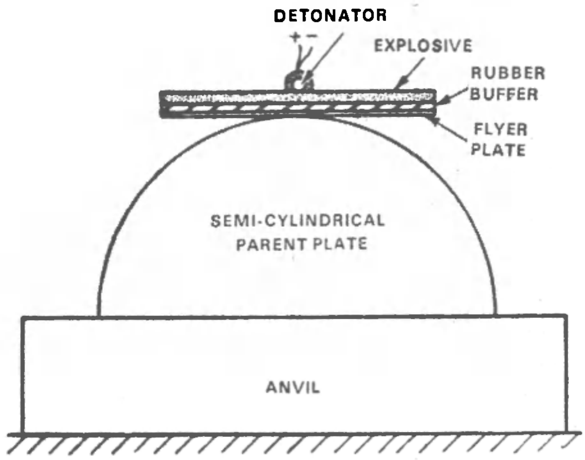

Fig.–8

Bahrani and Crossland[6] used various experimental techniques of explosive welding to obtain satisfactory bond and reproducible results. From their experiments, they have concluded that, to obtain a good bond, there should be the minimum of restraint on the flyer plate. The set-up shown in fig. 7 achieves this requirement and produced good bonding. Another technique used by them is shown in fig. 8. In this experimental set-up a semi-cylindrical parent plate is used with a flat flyer plate, so that the flyer plate impacts the parent plate with a gradually increasing angle of incidence.

It was reported that, using this set-up, it was possible for them to establish the influence of the angle of impact on wave action at the inter-face, and the limits of angle within which a bond is produced. They have also established a theory of jet formation while explaining the mechanism of welding[7]. A summary of this theory is given as under.

As the detonation wave moves down the charge shown in fig. 9, it subjects the outside of the wedge (formed between two plates at any instant), to a high pressure causing the walls to collapse on each other at a high velocity. As a result of the high pressure generated in the region of impact, high shear stresses are produced in the material which greatly exceed the shear strength of the material so that the material in the region

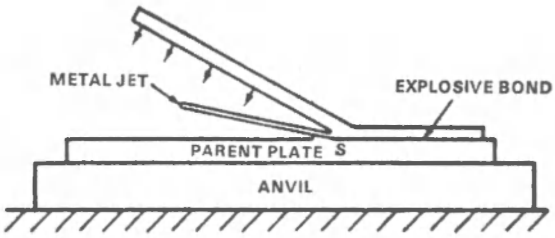

Fig. 9

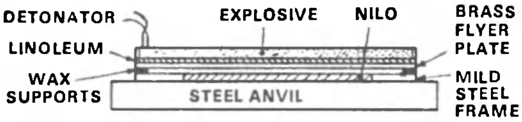

Fig. 10

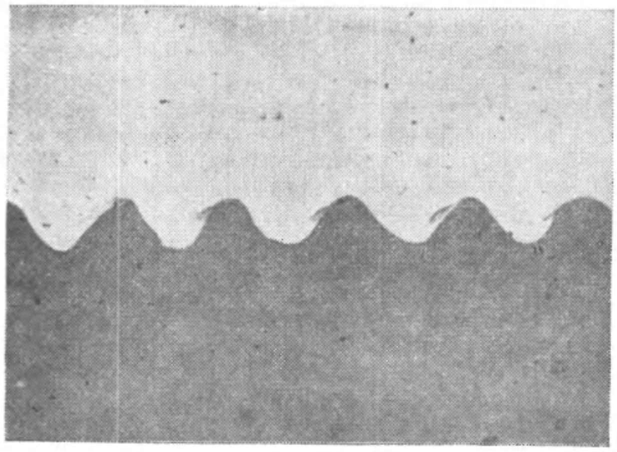

Fig. 11

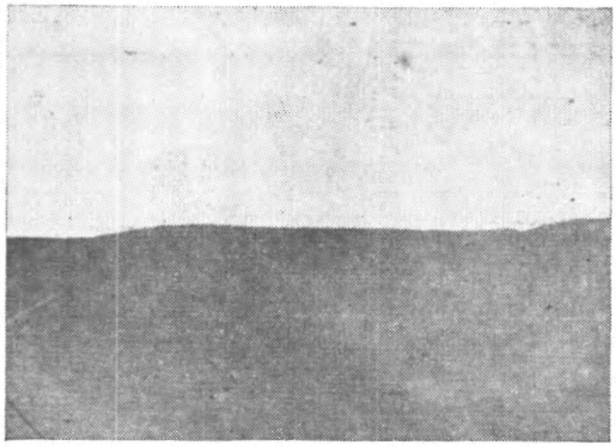

Fig. 12

of impact behaves like a liquid of low viscosity. Under the circumstances, the material in this region forms a very fast moving "metallic jet" which contains the original surfaces of both plates which meet at "S" (in fig. 9) to form the bond. If the speed of explosive and angle of incidence are chosen correctly, wave formation occurs in addition to jetting; this increases the bonded area and therefore the strength of the bond.

Banerjee, Williams & Crossland[8] developed a new set-up shown in fig. 10 for explosive welding of bimetallic strip for use in thermostat. This method is particularly suitable for those combinations which might prove difficult to bond by conventional hot-roll bonding or fusion cladding method. A highly sensitive thermal bimetal is produced when d brass with a linear co-efficient of expansion of $19.9 \times 10^{-6}/°C$ is bonded to Invar whose co-efficient of thermal expansion is considered to be minimum. This combination is difficult to bond by hot rolling and it is normally produced by casting brass on to the Invar. However, this method of production has the disadvantage of fusion strip cladding such as brittle intermediate alloy formation, porosity etc. and consequently scrap losses are high. These problems can be avoided by explosive welding. Figs. 11 and 12 are the photomicrographs of interface of the explosively bonded brass-invar composite and the interface of the same composite after 76% reduction by cold rolling.

It had been observed especially with larger plates that while explosive welding, the weld at the end remote from the point of initiation of the detonation showed excess melting at the interface, whereas the weld immediately adjacent to the point of initiation was poor or non-existent. In the region of excess melting there was either no bond formed or the plates had separated after the melted layer had solidified suggesting that the cast interlayer leads to a weak bond. Banerjee and Crossland[9] designed a set-up which is shown in fig. 13. It can be seen from the figure that the charge (explosive) was tapered from the point of initiation to the remote end of the plate. This enabled a large charge per unit area to be used close to the point of initiation to obtain the required impact velocity, while giving a reduced charge remote from the point of detonation so that the velocity of impact was not so great as to cause excessive melting.

Properties of the Bond

The strength of the bonds formed in explosive cladding has been extensively studied by Philipchuk[1], Hayes & Pearson[10], Boes[5], Addison[11] et al, Bahrani & Crossland[6], De Maris[12], Gelman[13] et al & Banerjee[14]. Static tests have included shear, tension and bend tests with cladding on the top or bottom or side. Briefly

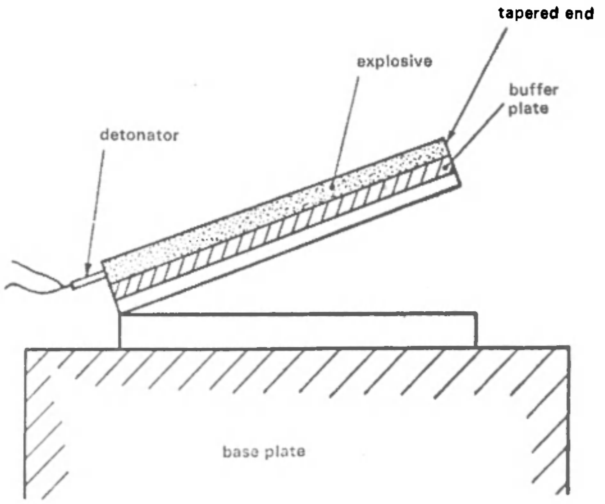

Fig. 13

under ideal welding conditions and in the absence of unfavourable metallurgical conditions at the interface such as a cast interlayer or brittle intermetallic compound, the strength of the bond is greater than the strength of the weaker of the two materials, and with the bend tests, even with the cladding on the side, the specimen will bend through 180° without failure of the bond. De Maris[12] gives data for fatigue tests on cantilever specimens of inconel welded to steel ; the fatigue results lay between the S/N curves for the two materials before cladding, and the fracture did not initiate at the interface. Gelman et al[13] clad constructional steels and in general found a reduction of fatigue strength which was however improved by a subsequent heat treatment. Banerjee[14] carried out repeated tension fatigue tests on stainless steel clad to mild steel ; results are shown in fig. 14 where it will be seen that the fatigue strength of the clad plate is marginally greater than that of either stainless steel or mild steel. He obtained similar results for brass clad to mild steel. Banerjee[14] also considered thermal fatigue by subjecting clad plates of stainless and mild steel and brass and steel to 10 cycles of heating and cooling. Each specimen was cycled to a different maximum temperature and then shear tests were carried out. A very slight reduction in shear strength of the specimen subjected to 10 cycles of 15° to 700°C was noted, but this could have been attributed to recrystallisation.

Very few references are available for non-destructive testing of the clad plates to establish the weld integrity. Perhaps the only readily available one is the ultrasonic test. Addison[11] et al concluded that ultrasonic inspection is the most promising method ; they submerged the plate in water between the transmitter and receiver rather than adopting the more normal reflection technique in which the crystal operates

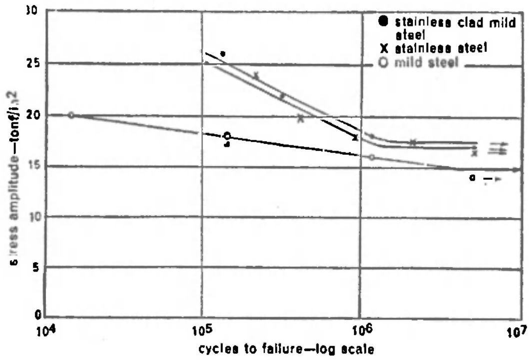

Fig. 14

as a transmitter and receiver. Banerjee[14] carried out ultrasonic testing of plates and showed that it was possible to detect areas of poor bond or no bond. He could not detect a cast interlayer or an undesirable intermetallic compound at the interface. It must be concluded that the inspection of either roll clad or explosively clad plate can only reveal areas of no bond, but not areas of weak bonding caused by unfavourable metallurgical condition.

Metallurgical aspects of the explosively welded clad plates has not been discussed in this paper, as a paper on this subject written by one of the authors[15] has been published recently in the transactions I.I.M., September 1970. However, a few photomicrographs of the interface of the explosively cladded plates are shown in figs. 15 & 16.

Applications

The most general and useful application of explosive welding to date has been in cladding flat plates or cylindrical, spherical and elliptical shapes to give a uniform and high quality bond. It can be useful in joining boiler tubes to the tube plates to give a pressure tight seal. Explosive welding could be the most convenient way of welding in space since no atmosphere is needed, bulky equipment is not required and explosives function reliably in vacuum. Explosive bonding is almost uniquely suited to joining those metal or alloy combinations that form brittle inter-metallic compound when exposed to elevated temperature. Explosively bonded clad can be effectively used for the manufacture of vessels and heat exchangers for the chemical industry and related users. A Titanium clad steel vessel made for the American Oil Company has been in use for over three years now and no clad problems have been encountered. This process could also be used for joining aluminium alloys to stainless steel and zirconium and many other magnesium alloys which are difficult to weld because of reactions which set in at the welding temperature. Recently it has been

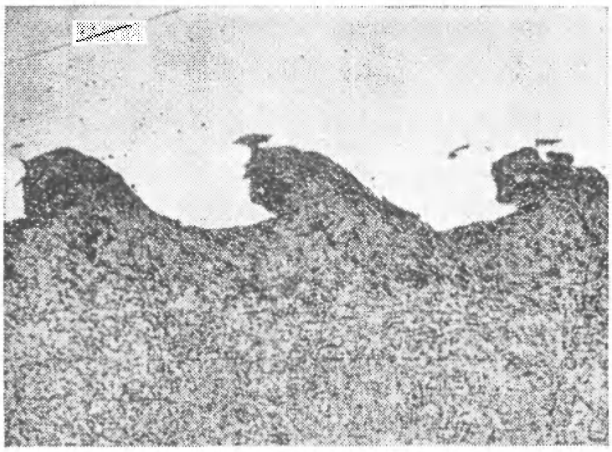

Fig. 15

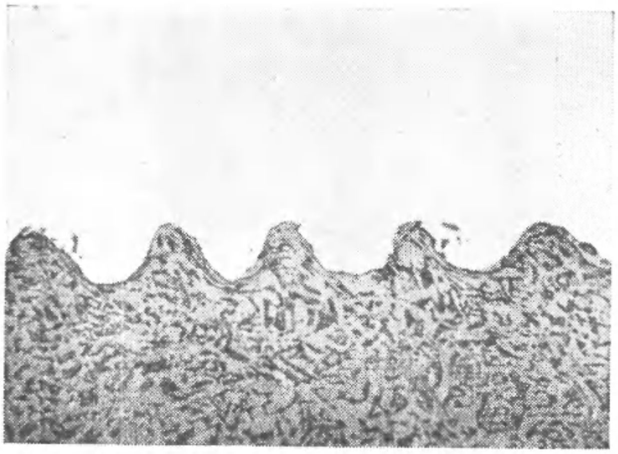

Fig. 16

reported that explosive welding offers an attractive method for producing bimetallic strip for use in thermostat[8]. This method is particularly suitable for those combinations which might prove difficult to bond by conventional hot-roll bonding or fusion bonding.

The National Metallurgical Laboratory is working for a considerable period in the field of thermostat metal and various types of clad metal. Introduction of explosive welding technique will solve many of the problems encountered in bonding difficult combinations. Already it has been applied successfully in bonding thermostat metal incorporating Cu-base alloys such as brass/invar bimetal. Other difficult combinations such as Manganese alloy-Invar thermo-bimetal, copper clad aluminium etc. can be conveniently clad by explosive welding.

The explosive welding technique is sure to find increasing use in the future in our country for developing material science and to solve the increasing demand of the industries for producing joints between a wide range of metals and alloys.

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