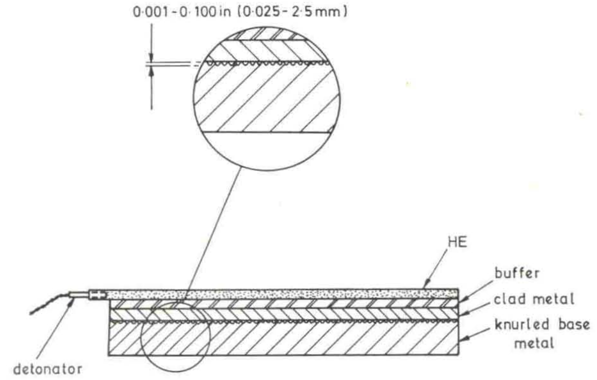
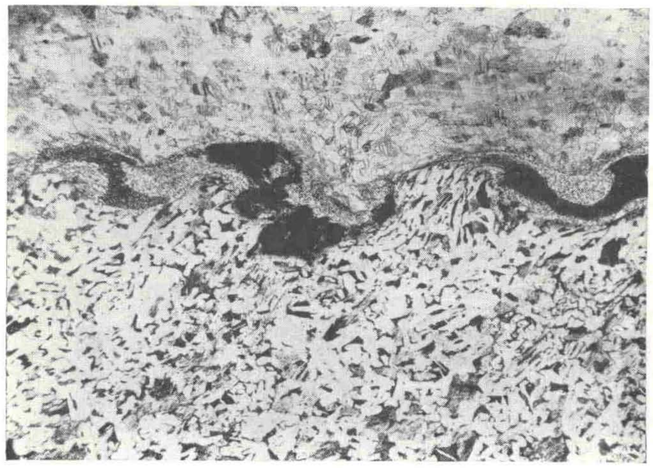
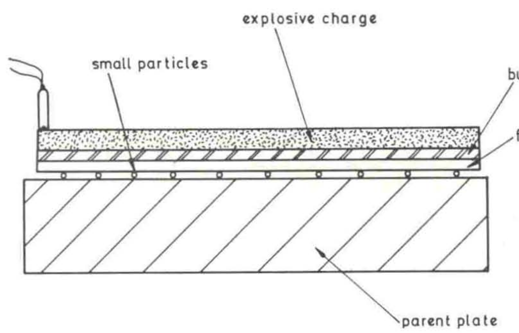


[Courtesy *Amer. Soc. Tool Manuf. Eng.*

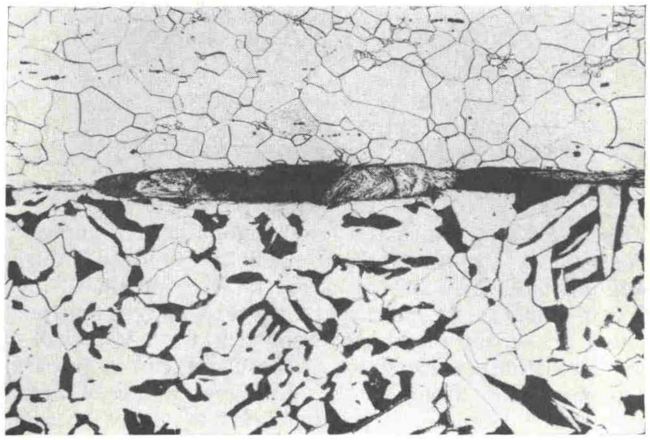
18 Flat-plate cladding. (*Philipchuk.*[1])



19 Micrograph of a steel weld made by using a knurled base plate. × 45.



20 Separating the flyer plate from the parent plate by small particles.



21 Micrograph of a steel weld made by supporting the flyer plate on metal particles. × 150.

The process thus continues in a zip-fastener manner. Bahrani *et al.* have suggested a mechanism of wave generation which appears to most readily agree with general metallographic observations of explosive welds. Figure 17 shows the basic steps as suggested by them. However, it would appear that this mechanism defies analysis at the present time. Hunt considers that the waves can be explained by Helmholtz instability. The main difficulty in providing a satisfactory explanation is that the properties of the metals at the interface during this process cannot be measured or even estimated.

II. Explosive cladding

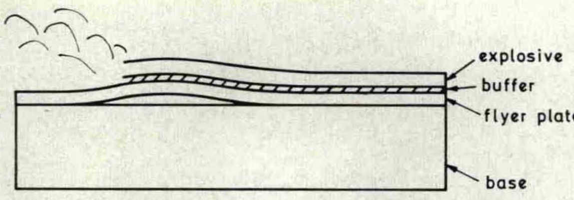
The inclined-angle set-up shown in Fig. 2 is strictly needed only if a high-detonating-velocity explosive is being used, to bring the collision-point velocity down to an acceptable value. However, the use of such an explosive gives rise to problems of spalling and surface damage. There is, in addition, the problem of supporting a large flyer plate with the minimum of constraint to prevent excessive deformation of the plate under its own weight, thus changing the value of the initial angle of obliquity. If, however, the flyer plate is fairly thick it can be adequately supported at the edges. The problem remains that the clearance between the flyer and parent plate in this arrangement does not remain constant, and at the large-clearance end of the plate it is probable that the flyer-plate velocity at impact is below the maximum or terminal velocity that is reached at smaller clearances. This becomes more serious the larger the plate. However, the technique can be used satisfactorily for areas of a few square feet.

There are considerable advantages in using a lower-detonation-velocity explosive and a parallel or only slightly inclined plate technique, but there is still the problem of how to support the flyer plate at a fixed clearance above the parent plate without providing excessive constraint. The plates might be arranged in the vertical position, but this gives rise to practical problems in placing a uniform explosive charge in juxtaposition with the flyer plate.

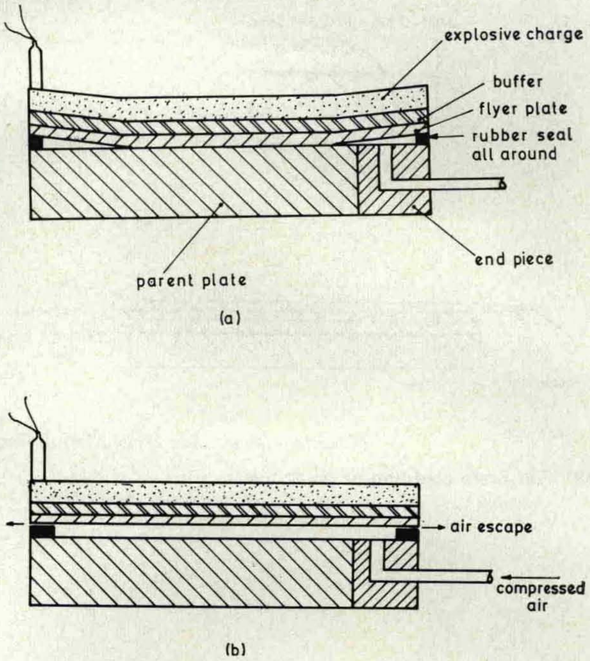
Philipchuk[1] suggested supporting the flyer plate on a knurled or grooved parent plate, as shown in Fig. 18, but Shribman *et al.*[39] showed that this produced a weld with voids and excessive melting (see Fig. 19). As a consequence, this would seem to be an unacceptable method for high-quality welds.

Cowan *et al.*[40] proposed that the necessary clearance between the flyer and parent plate could be achieved by placing metallic particles of a suitable size between the two plates, as in Fig. 20. This certainly provides an adequate weld but, as shown by Crossland and Bahrani[4] or Shribman *et al.*,[39] the jet is apparently trapped behind the particle and a void is formed in front (see Fig. 21). Also, with fairly thin flyer plates the impression of the particles is visible on the top surface.

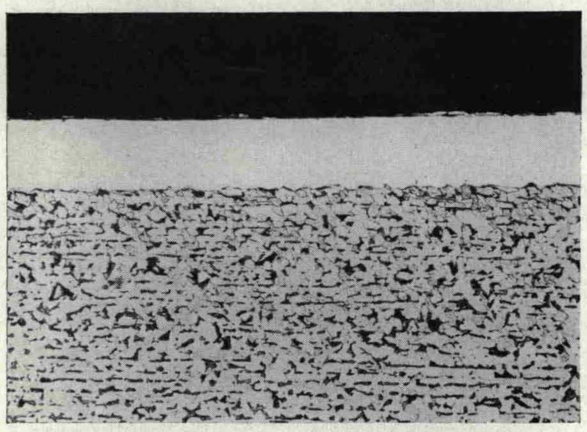
Otto[14] suggested that welding could be achieved with plates in contact using a high-detonation-velocity explosive, but attempts by Crossland and Bahrani[4] to repeat this work with *Metabel* sheet explosive proved abortive. However, using



22 Welding of plates that are initially in contact.



23 Air-supported flyer plate.



24 Micrograph of mild steel clad with a 0·005 in-(0·127 mm) layer of brass. × 70.

Trimonite No. 3, which is a lower-detonation-velocity explosive, they noted that welding could be achieved except for the first 1–2 in (25–50 mm), and they attributed this to the plates separating before the detonation wave arrived as a result of deformation in front of the detonation wave being possible, as demonstrated in Fig. 22. Crossland and Bahrani prevented this separation by means of mechanical constraint, and they then found that even with *Trimonite No.* 3, no welding was achieved. They concluded that separation between the parent and flyer plate is necessary to achieve welding.

Another arrangement proposed by Crossland *et al.*[41] has been provisionally patented by Crossland, Bahrani, and Shribman.[42] The method consists of supporting the flyer plate by gas pressure. Figure 23(a) shows the arrangement in the absence of gas pressure, as a consequence of which the plate is sagging. Figure 23(b) shows the pressure applied and the flyer plate lifting, rather like a flap valve, to relieve the gas pressure. There is some advantage in having a small angle of obliquity and this can be accommodated by the correct arrangement of the sealing strips. If necessary, an inert gas can be used as the pressurising medium. This method has been adopted successfully with *Trimonite* explosive.

Yet another arrangement has been proposed by Williams *et al.*[32] using polystyrene particles to separate the flyer and parent plate. They note that a slight initial angle of obliquity, with an explosive with a detonation velocity less than the sonic velocity, gives a better wave form and reduces the chance of forming a continuous cast interlayer, particularly towards the end of the weld. A slight initial angle of obliquity can be achieved by selecting polystyrene particles of different sizes, small particles at one end increasing to large particles at the other end. In the case of *Trimonite No.* 3, no signs of voids have been observed at the weld interface, though very slight defects which may be associated with the particles have been noted.

For thick flyer plates it is adequate to support the flyer plate on blocks of polystyrene placed at its edges and a slight taper can be readily accommodated by introducing different heights of blocks.

To summarise, if a very thin flyer plate, such as the 0·005 in- (6·127 mm) thick brass flyer plate shown in Fig. 24, which was studied by Shribman,[35] is to be welded, then a contact method should be used even though a small area of no bonding will be found near the detonator. For plates of up to $\frac{1}{16}$ in (1·6 mm) thickness the gas-supported principle appears to be satisfactory, and with even thicker plates, up to $\frac{1}{4}$ in (6 mm), the polystyrene-particle technique can be adopted. With much thicker plates the edge-support technique is adequate.

Du Pont have clad areas up to 300 ft^2 (28 m^2) and used flyer-plate thicknesses up to 1·3 in (33 mm), while thicknesses of 2 in (51 mm) have been used experimentally according to Stone.[43] At the Queen's University of Belfast, the largest plates clad have been 3 ft × 3 ft (900 × 900 mm), with a mild-steel parent plate $2\frac{1}{2}$ in (64 mm) thick clad with a $\frac{1}{2}$ in (13 mm) thick flyer plate of aluminium bronze. The set-up is shown in Fig. 25 and the product in Fig. 26. The problem with large plates is the weight of charge employed and the resulting noise and associated pressure pulse, which makes it necessary to have a site remote from human habitation. Stone[43] shows a photograph of the entrance to a tunnel used by Du Pont for carrying out explosive cladding. Apparently after a few blasts the tunnel roof became stabilised. Shribman[35] has reported tests using a vacuum tank which is claimed considerably to reduce the noise level, but whether this is a practical or economic proposition for large plates must be questioned. Another possibility is to bury the plates and explosive charge under a large heap of earth, but this requires earth-handling equipment as a very considerable thickness of soil would be required. For instance, from a private communication with Dr. Nemitz, a charge of 40–60 kg used in direct-contact forming operations required a mound of sand 3–4 m thick.

The strength of the bonds formed in explosive cladding has been extensively studied by Philipchuk,[7] Hayes and Pearson,[17] Boes,[13] Addison *et al.*,[44] Bahrani and Crossland,[24,45] De Maris,[46] Gelman *et al.*,[47] Rowden,[48] and Banerjee.[49] Static tests have included shear tests (Fig. 27), side shear tests (Fig. 28), tension tests (Fig. 29), and bend tests (Fig. 30), with the cladding on the top or bottom or side. Briefly, 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,