IV. Other explosive-welding processes

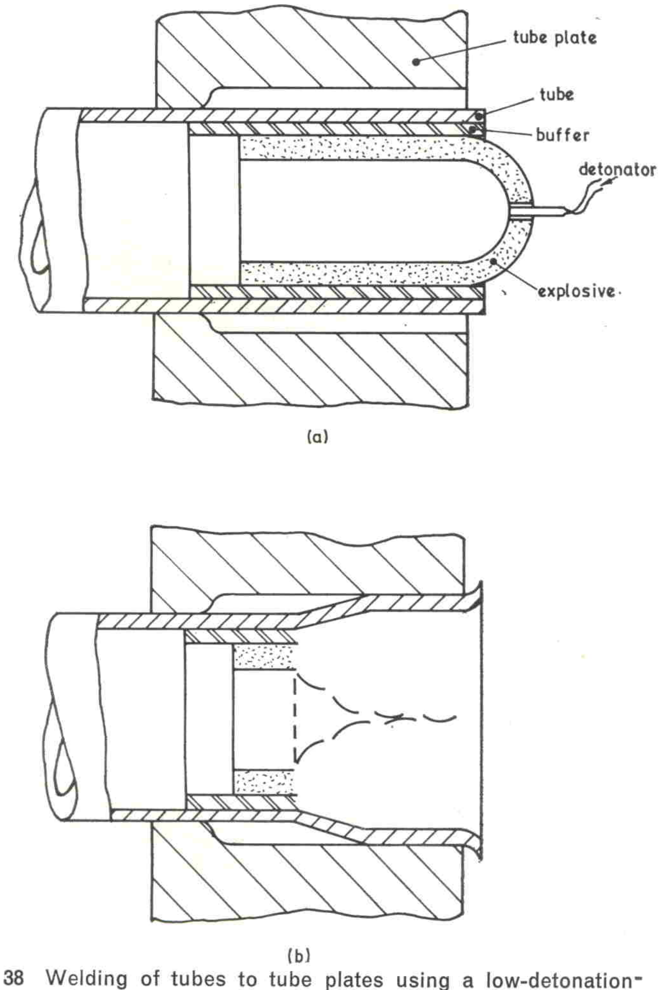
Various processes that take advantage of the explosive-welding process have been suggested by different research workers. Perhaps one of the most common problems examined is the joining of two metal plates or sheets by means of some form of lap or butt weld. Addison[60] produced lap-welded specimens by angled and parallel techniques, shown schematically in Fig. 41. A high-detonation-velocity explosive (*Primacord*) was used. Kogya and Kaisha[61] employed a shaped charge. Various forms of shaped charge are shown in Fig. 42. Polhemus[62] used the scarfed weld joint illustrated in Fig. 43. Shribman *et al.*[39] discussed various lap welds produced with a high-detonating-velocity explosive cord (*Cordtex*). They developed the arrangement shown in Fig. 44, which produced a bond on each side of the centre-line of the *Cordtex* cord (Fig. 45). With one strand of *Cordtex* plates of $\frac{1}{32}$ in (0·8 mm) thickness could be welded, but with three strands, see Fig. 44(b), $\frac{1}{16}$ in (1·6 mm) thick sheets could be welded but the upper surface of the top plate was cut by the explosive charge. Various cross-sectional shapes of explosive charge were tried, the most successful being that illustrated in Fig. 44(c). Failure of such connections tested in tension occurs well away from the welded zone.

Holtzman and Cowan[21] suggested several arrangements for butt welding sheets, including that shown in Fig. 46, though as will be seen this is strictly a type of lap weld. Polhemus adopted this form of butt weld and claims to have made a continuous weld up to 35 ft (11 m) in length in a single operation. He also shows a stainless-steel cylinder 18 in (460 mm) long × 10 in (254 mm) dia., which was welded up out of 0·050 in (1·27 mm) stainless-steel sheet using this butt-welding technique for both circumferential and longitudinal welds.

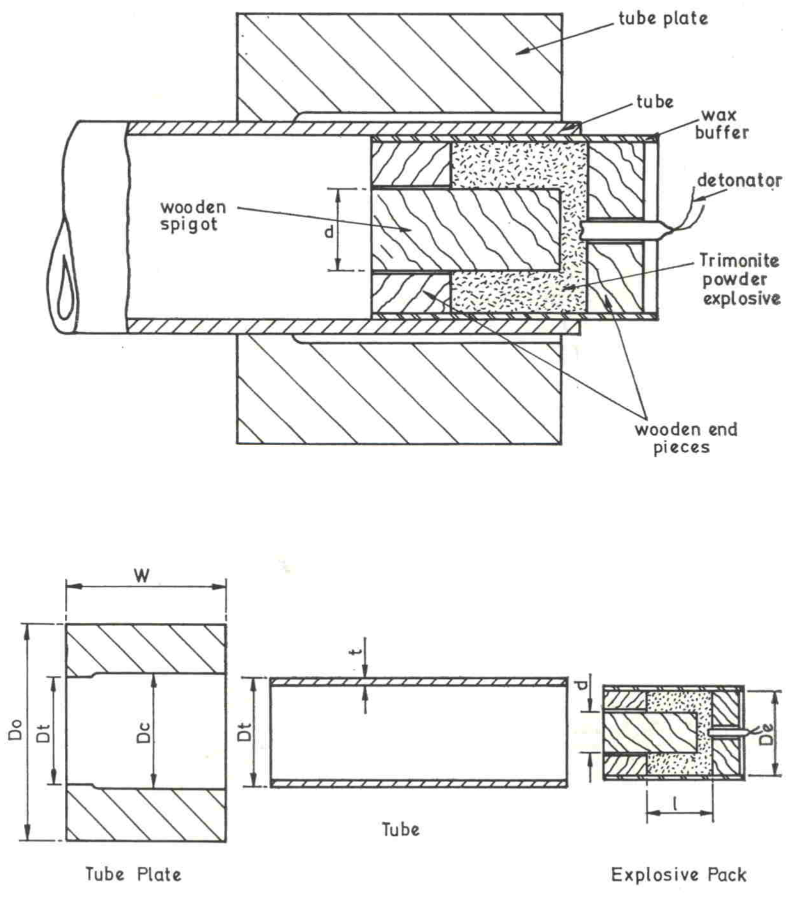
Holtzman and Cowan[21] also suggested the set-up shown in Fig. 47 for making a tee weld. Stone[43] notes the increasing use of aluminium superstructures in ships, which at the present time requires that the aluminium bulkheads be joined to the steel deck with a lapped, bolted, or riveted connection. The crevices created by this joint give rise to corrosion which can lead to major repairs after less than one year at sea. He shows an aluminium/steel explosively clad transition joint in which an aluminium strip is welded explosively to a steel strip and it is then possible to weld the steel to the steel ship's plate and the aluminium to the aluminium plates of the superstructure. This self-same technique has also been applied to the aluminium/steel transition joint for an aluminium anode for use in primary aluminium plants. Figure 48 depicts the steps in the procedure.

Davenport[11] demonstrated the extreme versatility of the explosive-welding process in assembling a honeycomb grid. This was produced by explosively welding together a bundle of copper-plated aluminium wires inside a copper tube and then slicing out a disc of the desired thickness and chemically dissolving away the aluminium. These honeycombs have found applications for the grids of vacuum tubes, radiation collimators, &c.

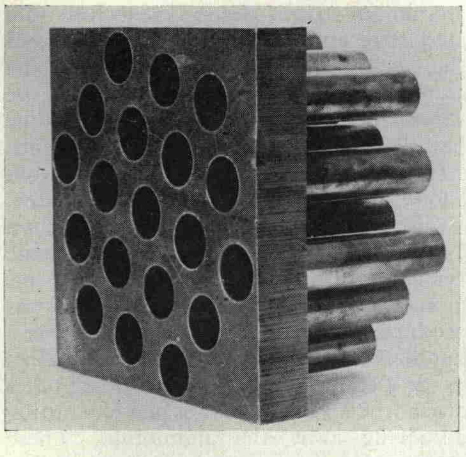
Jarvis and Slate[63] have briefly reported on the explosive fabrication of composite materials. They used a parallel-plate technique and a high-detonation-velocity sheet (7–5 km/s) explosive; as might be expected, they were unable to obtain a weld. However when a layer of tungsten wires was inserted between the plates in a direction parallel to the direction of the detonation wave, a successful bond was achieved. A



38 Welding of tubes to tube plates using a low-detonation-velocity explosive. (a) Before detonation; (b) after detonation.



39 Experimental set-up for welding tubes to tube plates.



40 A group of hard-drawn, thin-walled copper tubes welded in a brass tube plate.

tension test indicated that the bond between the tungsten wire and the copper plates was fairly good. By positioning multiple layers of alternate wires and foils a composite (Fig. 49) was produced which had a final volume fraction of wire of 17%. The wire diameter was 0·006 in (0·15 mm) and the copper-foil thickness 0·012 in (0·30 mm). The multilayer composite gave a tensile strength which could have been predicted from the strength of the two starting materials. The explosive production of fibre-reinforced materials gives promise of some very interesting developments.

V. Metallurgy of explosive welding

1. General observations

At the end of Section I it was noted that there are three main types of interface in explosive welds. For large angles of obliquity, i.e. $\sim 15^\circ$, the re-entrant jet that is formed from the two surface layers completely escapes, and this leads to a solid-phase bond as illustrated in Fig. 13. This shows the localised plastic flow which occurs and it will be noted that it is not consistent with the suggestion of relative sliding proposed by Otto.[14]

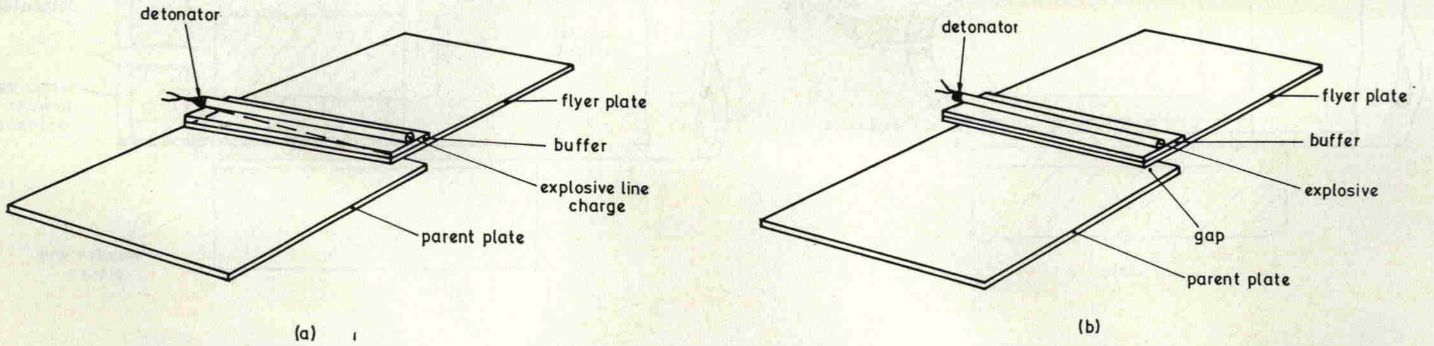
More usually, smaller collision angles, i.e. $< 5^\circ$, are employed, especially in the parallel-plate technique, and under these conditions the jet is trapped as explained by the mechanism of Bahrani *et al.*[25] illustrated in Fig. 17. In Fig. 15 it can be seen that the interface of such a weld consists of alternate regions of solid-phase bonding and fusion-bonded pockets. The grain size in the fusion pockets may be of the order of 1 μm and optical microscopy is therefore unable to resolve the detail in these regions as shown in Fig. 14. However, by means of electron microscopy of carbon replicas from the vortex regions (Fig. 50) Lucas *et al.*[28] have found clear evidence of melting in the vortex area in all the welds examined, including tungsten-to-tungsten with a melting point of 3400° C (3673 K).

Under extreme conditions it is possible to produce a weld interface consisting entirely of fusion bonding (Fig. 16), which according to the mechanism proposed by Bahrani *et al.* is due to the linking up of the molten pockets.

In addition to the features observed at the weld interface, it is clear that metallurgical changes are effected in the two component members by the intense stress waves generated both by the detonation of the explosive layer and the high-velocity collision during welding. Severe mechanical twinning and phase changes in the shock-affected zones on each side of the weld interface have been reported. Spall fractures which occur away from the interface have also been recorded.

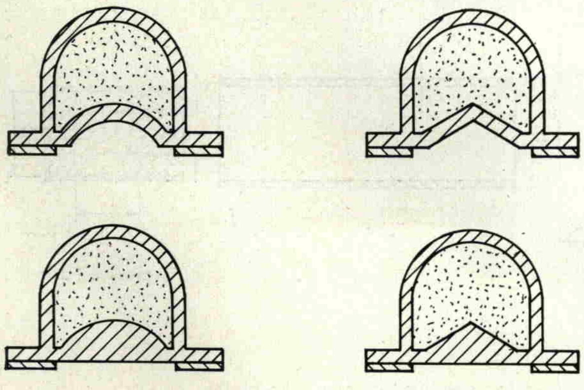
2. Solid-phase bonded interface

As can be seen from Fig. 13, the high impact pressure and jetting action have caused considerable plastic flow at the interface. Electron micrographs of carbon replicas taken from this type of bond have been published by Holtzman and Cowan,[21] Buck and Hornbogen,[64,65] Trueb,[66] and Lucas *et al.*[28] A typical example is shown in Fig. 51, from which it can be seen that the original interface is no longer distinguishable. The bond zone is a band, $\sim 10^{-3}$ cm thick, composed of several layers of highly elongated grains, $\sim 10^{-4}$ cm thick, and no evidence of original surface-oxide films remains. Annealing of this type of weld interface allows complete recrystal-

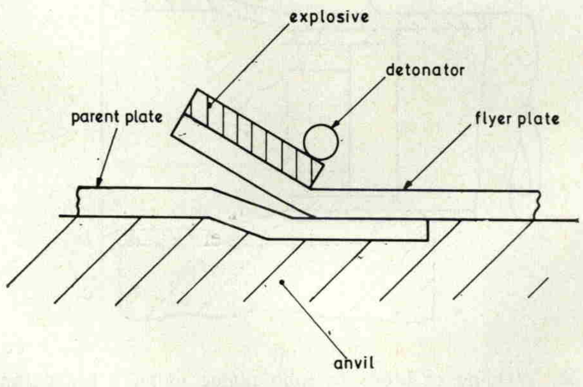


[Courtesy 'Welding'

41 Welding of lap joints, (a) Inclined technique; (b) parallel technique. (*Addison, Kogya, and Kaisha.*[61])



42 Line charge shapes.



43 Welding of lap joints. (*Polhemus.*[62])