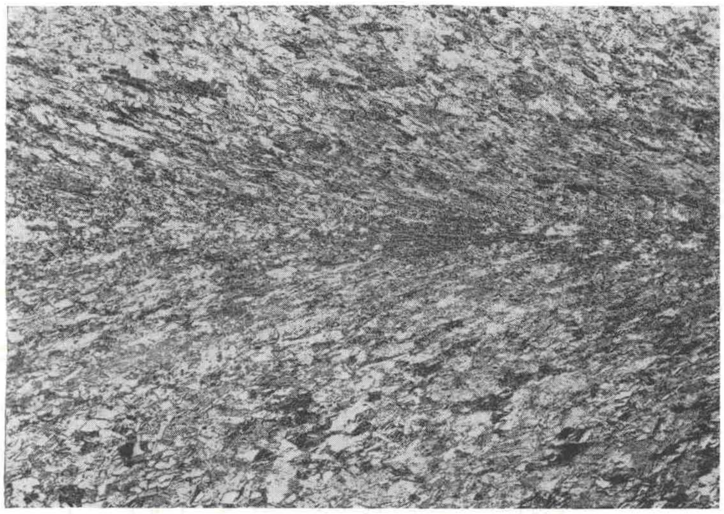
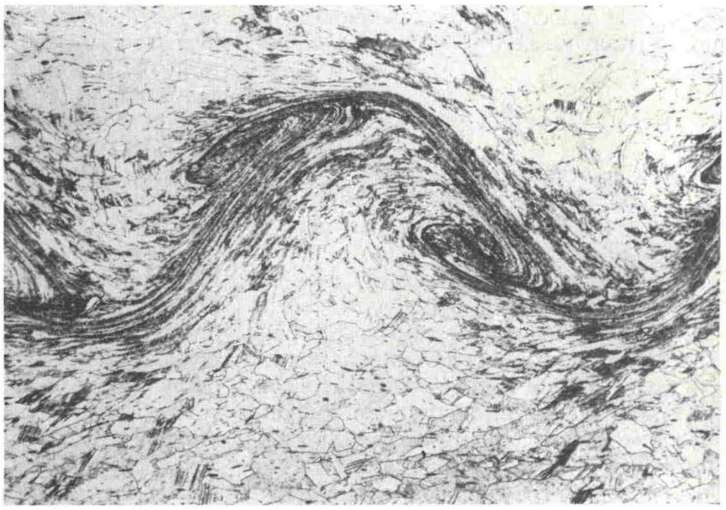
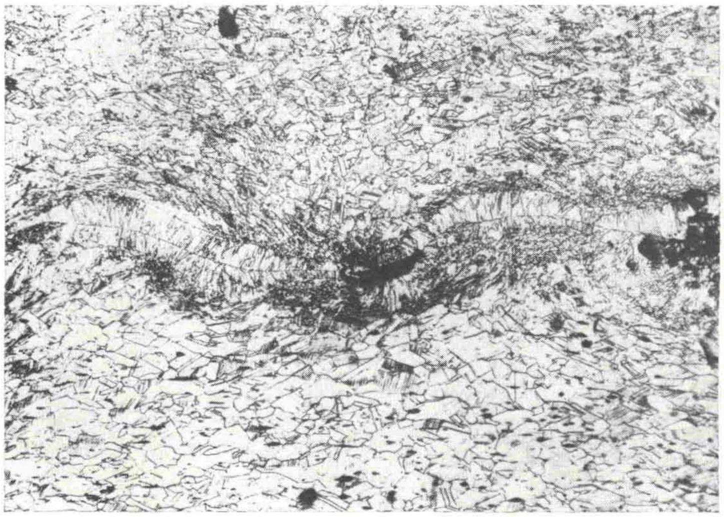


13 Straight interface in copper produced by large angle of incidence. × 90.



14 Wavy interface in copper produced by small angle of incidence. × 85.

15 Wavy interface with fusion pockets produced by small angle of incidence and excessive charge. × 100.



16 Continuous fusion weld in copper produced by high kinetic energy. × 85.

may occur on impact and on examination signs of a weld in the flyer-plate material at a point away from the interface can be observed. Apart from the possibility of spall fractures, the properties of the parent plate appear to be less critical. Thus, steel flyer plates have been successfully welded to antimony and bismuth parent plates, these being supported by mild-steel framework to prevent spalling.[32]

It should not be implied, even if all these conditions are met, that a satisfactory weld will be achieved. Carpenter *et al.*[34] have proposed an explosive-welding criterion which they claim results in explosive welding for a wide variety of metals. The equation is

$$L = K \frac{\tau e t}{d} \beta^2 \qquad \ldots [9]$$

where L = the mass of explosive per unit area of plate
e = the density of the flyer-plate material
β = the actual collision angle
t = the thickness of the flyer plate
d = the gap between the flyer and parent plate before detonation
τ = the yield strength of the flyer-plate material
K = a constant

For a non-nitroglycerine granular dynamite, provided by the Trojan Powder Company, these authors claimed a good agreement with this equation. But Shribman[35] reported that the equation did not fit his data and pointed out that the clearance d is over-emphasised, as it is only necessary to have an adequate clearance for the terminal velocity to be achieved; he found for plate thicknesses up to 0·5 in (13 mm) that the terminal velocity was achieved within 0·2 in (5 mm). Shribman concluded from his results that the optimum conditions for bonding do not necessarily lie within the limit curves prescribed by Carpenter *et al.*

Chadwick[36] states that the impact pressure must be ten times the static yield stress, which in the absence of data on the yield of metals under the impact conditions met with in explosive-welding conditions may be a satisfactory assumption. However, some materials are more strain-rate-sensitive than others, and it is probable that the magnitude of the impact pressure requires to be higher for such materials than for materials that are not so sensitive. Shribman[35] considers that a critical value of the interface pressure calculated from an equation given by Wright and Bayce[20] is required for welding. The equation is

$$p = \rho\, U_P U_S \qquad \ldots [10]$$

where p = the interface pressure
ρ = the density of the material
U_P = the particle velocity
U_S = the shock velocity in the material

The shock velocity can be calculated from an equation given by Cowan and Holtzman[19]

$$U_S = C_0 + \lambda U_P \qquad \ldots [11]$$

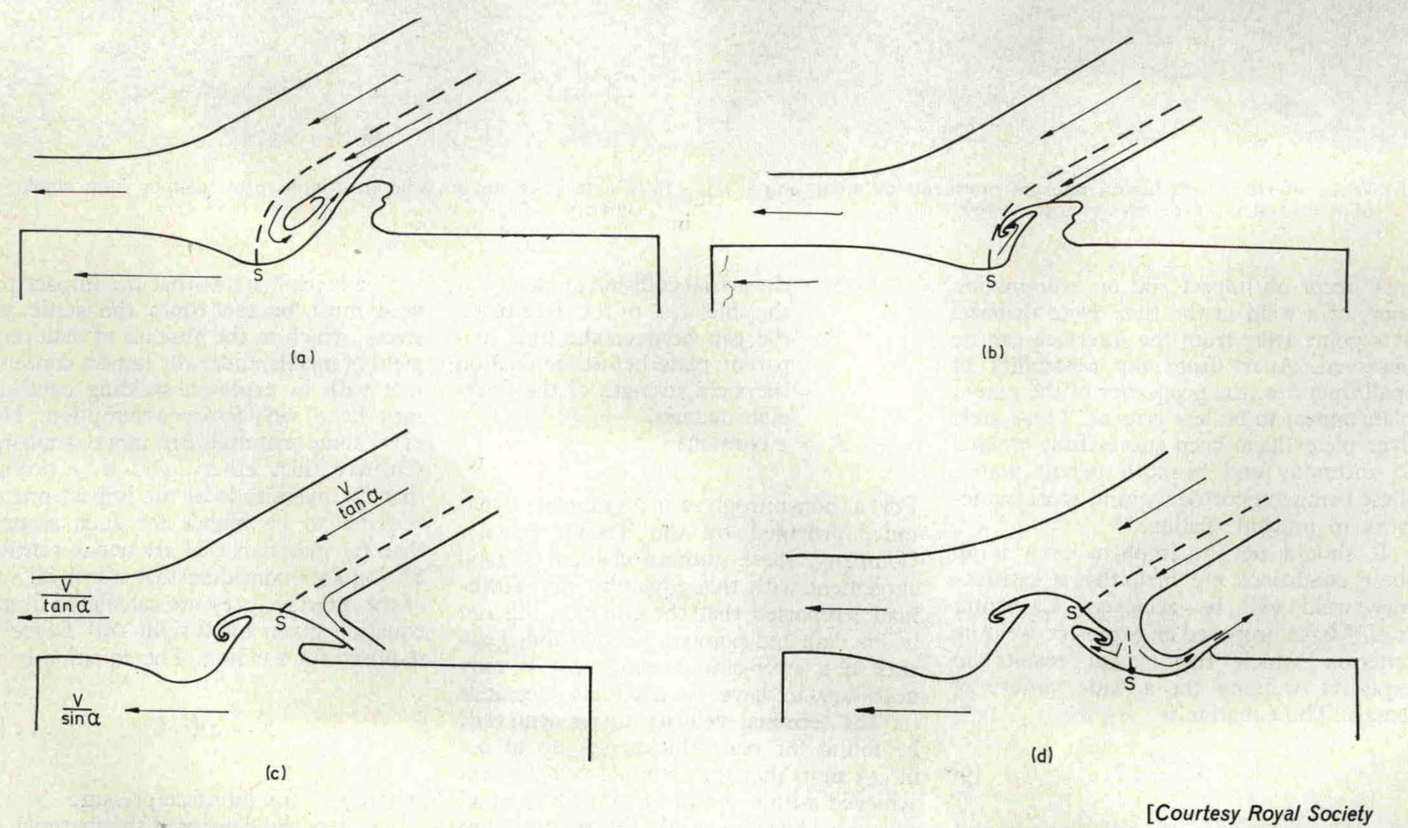
where C_0 = the bulk velocity of sound
λ = a constant which can be calculated from Walsh *et al.*[27]

For mild steel-to-mild steel he claimed that with pressures of $0{\cdot}411 \times 10^6$ lbf/in^2 (28·4 kbar) or below there was no bonding, but at $0{\cdot}65 \times 10^6$ lbf/in^2 (45 kbar) up to $\nless 1{\cdot}93 \times 10^6$ lbf/in^2 (133 kbar) there was consistent bonding. For titanium-to-titanium, the respective figures were $0{\cdot}44 \times 10^6$ lbf/in^2 (30 kbar) and $0{\cdot}64 \times 10^6$ lbf/in^2 (44 kbar), and for copper-to-copper satisfactory bonds were achieved at $0{\cdot}77 \times 10^6$ lbf/in^2 (53 kbar) and above.

As yet the conditions for a satisfactory weld have not been fully described. In the meantime preliminary tests are required to determine the correct conditions; however, if the size of the test-piece is too small the results may not be representative. For instance, the dimensions in the plane of the flyer plate should be much greater than the thickness of the plate and the thickness of the charge, otherwise edge effects are of significance. One test-piece of great value is that suggested by Bahrani and Crossland[24] and shown in Fig. 12. It consists of a semi-cylindrical parent plate with the flyer plate suspended so as to be tangential to it, the detonation being initiated at the centre. As the flyer plate wraps itself around the parent plate the initial and final angles of obliquity vary, so that from one test-piece a range of angles is covered. The only criticism is that the clearance does not remain constant, but this is probably relatively unimportant as long as the minimum clearance is not too small to prevent the terminal velocity being achieved, or the largest clearance is not so great as to allow the terminal velocity to decay significantly.

In all these discussions the combinations of metals that can be welded have not been discussed. It is probably correct to say that no one has mentioned combinations that cannot be welded. Table V is a reproduction from Ref. 21 and lists the combinations that have given good bonds. Also, the form of the bond produced has not been discussed, but from Fig. 13–16 it will be apparent that many types of interface are possible. At large angles of obliquity the jet completely escapes and a straight interface with an indication of a shearing action on each side of the interface is obtained. At small angles interfacial waves are formed with the vortex areas in front of and behind the waves. These vortex areas contain a mixture of each surface and it appears that the jet has been partially or completely trapped. Lucas and Williams[37] have shown that the kinetic energy of the re-entrant jet in a typical welding situation far exceeds that required to cause melting when it impacts the parent plate. If the charge is too great and the angle is too small, then the wavy interface is seen to consist of molten pockets in the vortex area and solidification cavities are sometimes observed in the centre of these pockets. If the kinetic energy is sufficiently high, these areas of melting will join up to form a continuous cast interlayer in which the vortex areas can still be distinguished. At even smaller angles the interlayer appears to be of a much more nearly uniform thickness. The cast interlayer may be weakening, especially if brittle intermetallic compounds are formed.

The formation of waves at the interface has been studied by Abrahamson,[3] Cowan and Holtzman,[19] Otto,[14] Bahrani *et al.*,[25] and Hunt.[38] Otto has proposed two alternative explanations of welding. The first, which is applicable to two plates welded in contact, is a type of friction weld resulting from relative sliding between the plates. The second explanation relates to welding between obliquely colliding plates. By chance one plate moves ahead of the other and a tongue of metal from it penetrates the slower plate. This raises a tongue in the second plate, ahead of the collision point, and this penetrates the first plate.



[Courtesy Royal Society

17 Mechanism of wave generation. (a) Hump interfering with jet; (b) formation of tail; (c) formation of forward trunk; (d) formation of front vortex. (*After Bahrani et al.*[25])