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EXPLOSIVE WELDING

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Explosive welding, which is a solid-phase welding process, was probably discovered by chance by Philipchuk,[1]* who states that he first observed the effect when explosively forming an aluminium U-channel on a steel die. It was found that the U-channel could not be removed from the die because a circular-shaped area had become welded to the die. From more recent work it would appear that an excessive explosive charge must have been used in this forming exercise to have achieved the impact velocity required for welding. Allen, Mapes, and Wilson[2] carried out experiments concerned with the impact of right cylindrical bullets fired at thin targets and they noted a rippling of the surface of the bullet. Abrahamson,[3] who was concerned with the rippling or wave action, continued the work of Allen *et al.* and observed, when firing a steel bullet against an oblique copper target, that adhesion occurred between the steel and the copper; he shows a photomicrograph of the wavy interface typical of explosive welding. This, of course, leads to the conclusion that explosive welding is associated with the oblique impact between the two surfaces to be welded. Crossland and Bahrani[4] also noted that it was well known during the First World War that a bullet or shrapnel could stick to metal surfaces which they impacted, though it was not appreciated that this could be the basis of a welding process.

It is necessary to briefly define welding to get a correct perspective of explosive welding in relation to other welding processes. Simply, welding is a process for joining two or more solid components by local coalescence or union across an interface. The essential conditions for any form of welding are that the two surfaces before welding should be absolutely clean and uncontaminated and that these surfaces should be brought into contact. It is impossible to produce such surfaces by normal mechanical or chemical cleaning processes but under extremely high vacuum conditions Bowden and Tabor[5] and Keller[6] have produced nearly perfectly clean surfaces. If such surfaces are brought into contact, adhesion will occur between the asperities. This adhesion is greatly improved if, in addition to the normal force, a tangential force is applied that is not sufficient to cause sliding.

If two perfectly clean and atomically flat surfaces of the same metal are brought together, interatomic repulsive and attractive forces will come into play and equilibrium will be reached at a particular interatomic distance when the potential energy of the system is a minimum. The strength of the bond will be influenced by factors such as crystallographic misorientation across the interface, and diffusion and recrystallisation, which are very much dependent on temperature. The situation in relation to adhesion of dissimilar metals, which may have not only different atomic spacing but also a different structure, is obviously much more complex but nevertheless adhesion can still occur as a consequence of the interatomic forces.

Various clearly recognisable and distinguishable welding processes have been developed, but all of them are basically processes for removing the contaminant surface layers to allow adhesion to occur between clean metal surfaces. Four distinct welding processes can be recognised. First, there is fusion welding, in which the surfaces of the two metals are melted by the application of heat and the contaminant surface films are brought to the surface of the melt pool or go into solution. Many sources of the heat required for fusion welding have been developed and also methods of reducing the oxidation in the region of the weld. Secondly, there is flow welding, in which a third low-melting-point metal is used together with a suitable flux to wet the surfaces of the solid base metals of the two components to be joined, as for example in brazing, silver soldering, &c. Thirdly, pressure welding, either hot or cold, has been widely practised. In this process the two surfaces to be joined are compressed or hammered together with such force as to cause plastic flow at the interface, with an associated increase in the area of contact. This surface distortion breaks up the contaminant surface film and creates virgin surfaces where adhesion can take place. The effectiveness of the process is greatly improved if surface sliding also occurs during the plastic flow. Finally, we have explosive welding, in which the surface of one of the members is effectively peeled off to form a high-velocity metal jet which scours the surface of the other component. The two clean metal surfaces produced are then pressed together by the explosive pressure.

There are obvious limitations with some of these welding processes. For example, lead with a boiling point of 1620° C (1893 K) could hardly be fusion welded to steel, with a melting point of 1500° C (1773 K). Indeed, it is impossible to weld metals with vastly different melting points by fusion welding. There are, of course, formidable metallurgical problems in fusion welding of some metals and these problems are even more complex when welding together dissimilar metals. Correspondingly, it is unlikely that lead could be pressure welded to steel, as the lead would plastically deform much more readily than the steel and consequently no virgin surface could be produced on the latter. It is apparent that materials of basically different plastic properties cannot be pressure welded together. With explosive welding, melting is not a necessary condition, nor do the plastic properties of the two metals being welded impose any limitations on the process. It is, for example, possible to explosively weld a soft, low-melting-point metal such as lead to a hard, high-melting-point metal.

The main limitation with explosive welding is that, so far, it has proved possible to weld together only very simple

* Recently our attention has been drawn to an earlier report of welding having occurred under impacting conditions generated by explosives (L. R. Carl, *Metal Progress*, 1944, **46**, (7), 102).

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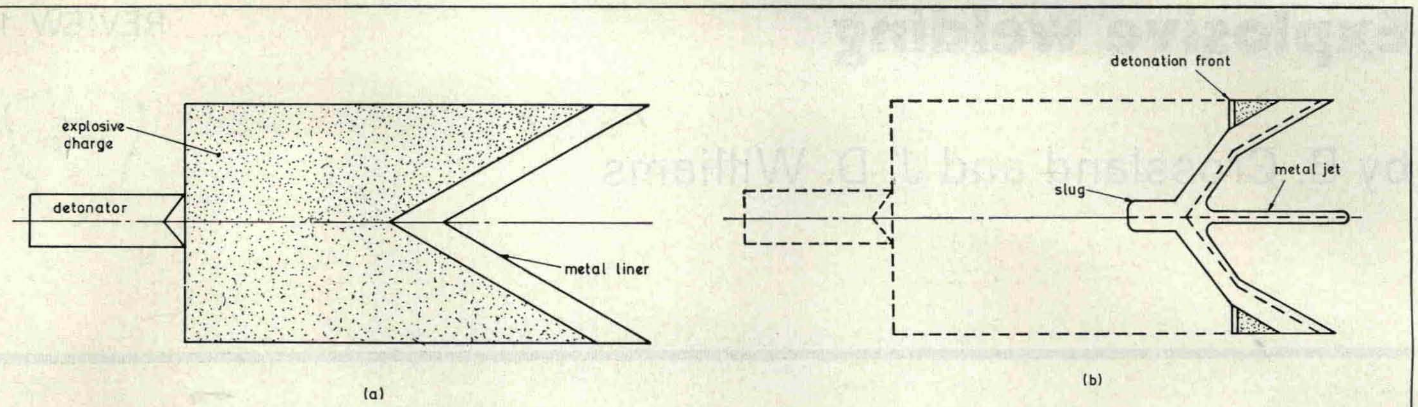


1 Hollow charge with metal liner. (a) Before explosion; (b) collapse of liner and the formation of a metal jet.

geometrical shapes such as flat surfaces, as in cladding, or cylindrical surfaces, as in welding tubes into a tube plate. Other applications have been, or are being investigated, e.g. lap welding, welding of tee junctions, spot welding, production of wire-reinforced composites, &c.

I. Mechanism of explosive welding

Many suggestions have been made regarding the mechanism of explosive welding. Philipchuk[1,7,8] and Zernow *et al.*[9] considered that it was essentially a fusion weld; Davenport,[10] Davenport and Duvall,[11] and Schmidtmann *et al.*[12] regarded it as a cold pressure-welding process; Boes[13] suggested that it was a form of friction welding, while Otto[14] concluded that it involved a shearing action. However, most of the workers in the field, such as Zabelka,[15] Pearson,[16] Hayes and Pearson,[17] Holtzman and Rudeshausen,[18] Cowan and Holtzman,[19] Wright and Bayce,[20] Holtzman and Cowan,[21] Bergmann, Cowan, and Holtzman,[22] Carlson,[23] Bahrani and Crossland,[24] and Bahrani, Black, and Crossland,[25] to mention but a few, have attributed the mechanism of explosive welding to the jetting action that occurs under oblique high-velocity impact.

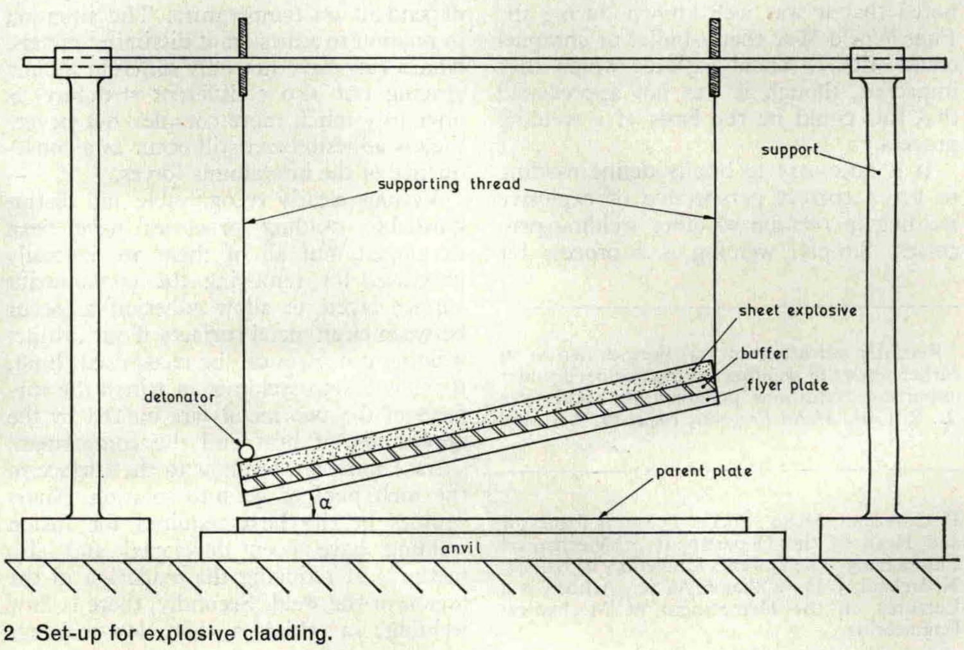
The formation of a metallic jet at the junction between two impacting plates is similar to the jet produced by the collapse of the conical or wedge-shaped liner in a hollow charge, as depicted in Fig. 1, which has been used as a weapon for defeating armour plate. The collapse mechanism and the theory of jet formation in such a case has been given by Birkhoff, MacDougall, Pugh, and Taylor.[26] When the charge is detonated the detonation wave moves down the explosive charge and when it reaches the apex of the liner it subjects the outer surface of the cone to very high pressure which causes its walls to collapse. The pressure produced in the metal in the region where the walls of the liner collide is extremely high, probably of the order of several hundred kilobars, which is much higher than the shear strength of the metal. Consequently, the material in the region of impact behaves as an inviscid fluid and the laws of fluid mechanics can be applied to the situation. It can be shown that the liner material divides into a high velocity 'metallic jet' and a slower-moving slug, as shown in Fig. 1. The high-velocity jet has remarkable powers of penetration. Though this jet behaves in a fluid-like manner it is probable that its temperature is below the melting point, but if it is trapped then the kinetic energy is converted to thermal energy and some melting will occur.

One of the arrangements for welding very commonly adopted is illustrated in Fig. 2. The top or flyer plate is supported with the minimum of constraint at a small angle of incidence, α, relative to the stationary or 'parent plate', which is supported on a relatively massive anvil plate. The top surface of the flyer plate is covered with a protective buffer such as rubber or polystyrene and above that is laid the sheet or layer of high explosive, which is detonated from the lower edge. The detonation of the explosive imparts a velocity V_P to the flyer plate, the magnitude of which depends on the ratio of mass of explosive/unit area to the mass of the flyer plate/unit area. As shown in Fig. 3, the flyer plate collides with the parent plate at an increased angle of incidence, β, and it will be seen that

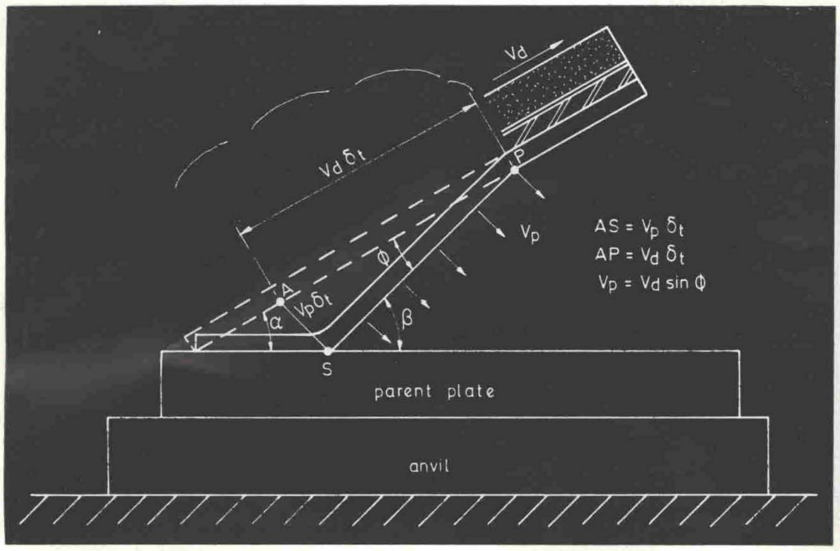
$$V_P = V_D \sin \varphi = V_D \sin (\beta - \alpha) \quad \ldots [1]$$

As the flyer plate collides with the parent plate it suffers a rapid retardation and an extremely high pressure is generated in both the flyer and parent plates in the region of impact S. As the pressure is very high compared with the shear strength of the materials involved, they behave for a very short interval of time in a similar manner to inviscid fluids and their behaviour can be treated by the laws of hydrodynamics.

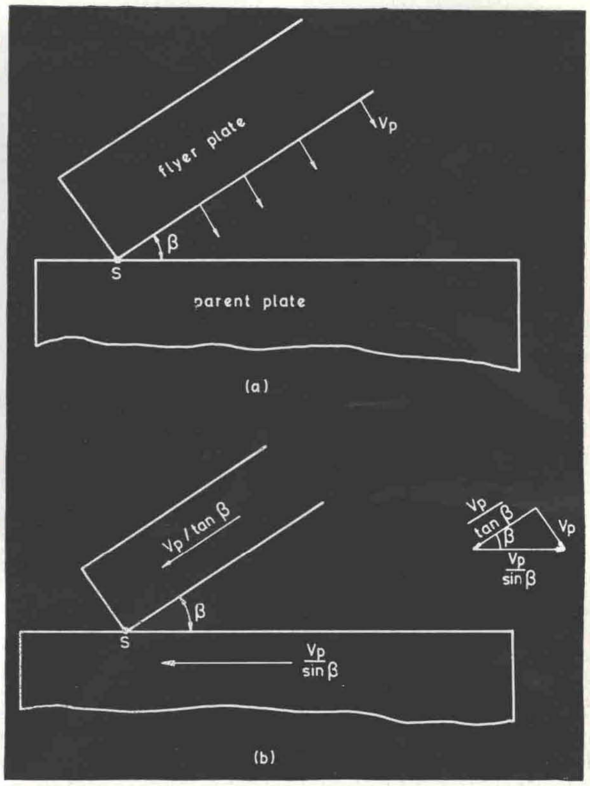
It is convenient to bring the point S in



2 Set-up for explosive cladding.



3 Mode of collapse of flyer plate



4 Change of co-ordinates for impacting plates. (a) Initial state; (b) change of co-ordinates.

Fig. 3 to rest and to do this it is necessary to apply a backward velocity of $V_P/\sin\beta$ to the parent plate, as shown in Fig. 4. If this backward velocity is applied to the system, then the velocity of the flyer plate is $V_P/\tan\beta$ towards S. Thus, the system becomes equivalent to a liquid jet of velocity $V_P/\tan\beta$ impinging a stream travelling at a velocity $V_P/\sin\beta$ at an angle of incidence of β. The liquid jet impinging the stream at S is deflected into a horizontal direction, still travelling at the same velocity, but this implies that the conservation of momentum in the horizontal plane has not been satisfied. Consequently, it must be concluded that the jet divides into salient and re-entrant jets, as shown in Fig. 5.

Applying the conservation of momentum gives

$$m\frac{V_P}{\tan\beta}\cos\beta = m_s\frac{V_P}{\tan\beta} - m_r\frac{V_P}{\tan\beta}$$

or

$$m\cos\beta = m_s - m_r \qquad \ldots [2]$$

Conservation of mass dictates that

$$m = m_s + m_r \qquad \ldots [3]$$

From equations [2] and [3]

$$m_r = \frac{m}{2}(1 - \cos\beta) \qquad \ldots [4]$$

$$m_s = \frac{m}{2}(1 + \cos\beta) \qquad \ldots [5]$$

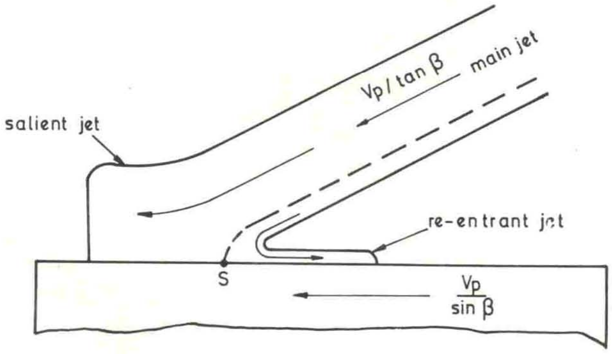
and the absolute velocity of the re-entrant jet will be

$$\frac{V_P}{\tan\beta} + \frac{V_P}{\sin\beta} = \frac{V_P}{\sin\beta}(1 + \cos\beta) \qquad \ldots [6]$$

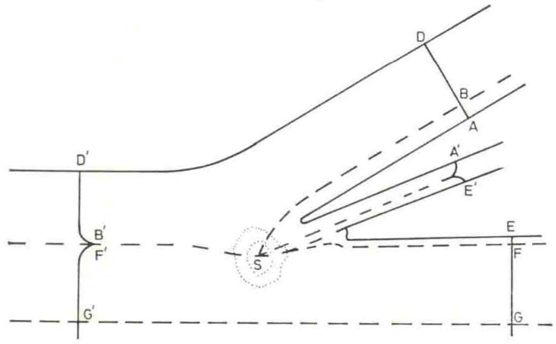
The analysis is of course strictly applicable only when the velocities of the flyer and parent plates relative to S are less than the velocity of sound in the materials of the two plates, as it ignores compressibility effects.

Walsh, Shreffler, and Willig[27] considered the case where the velocity of the main jet, $V_P/\tan\beta$, is supersonic by using compressible flow theory. If the main jet velocity substantially exceeds the sonic velocity, then attached shock waves in the flyer and parent plates will travel with the point of impact S and no re-entrant jet is produced. For a main jet velocity that is not substantially greater than the sonic velocity, there is a critical angle above which the shock wave becomes detached from point S and moves upstream so that the pressure is felt in front of the point of impact, and in these circumstances a jet can be formed.

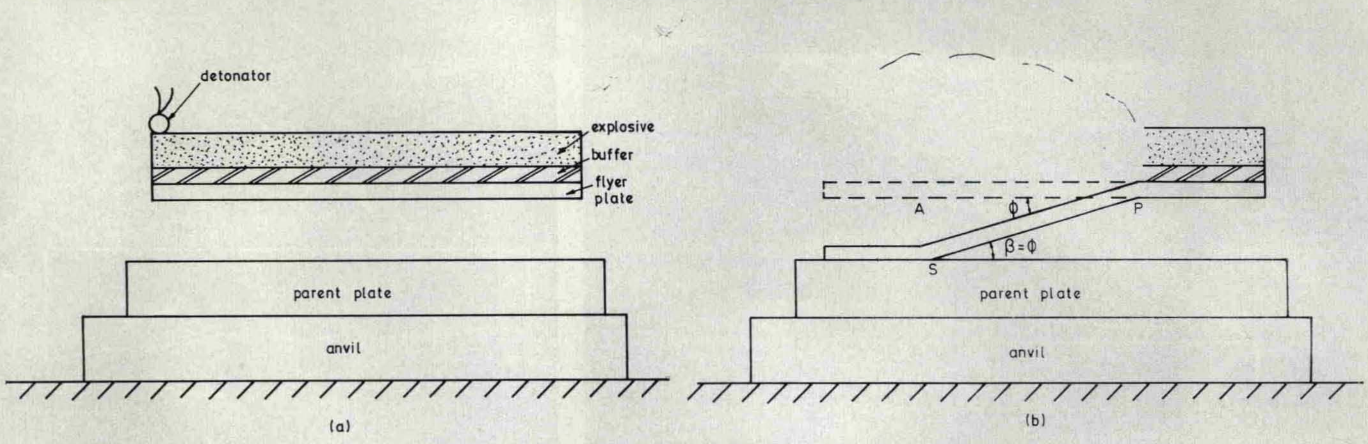
The existence of a jet in explosive welding has been hotly argued, but its existence has been confirmed by Holtzman and Cowan,[21] who employed flash X-ray to



5 Formation of salient and re-entrant jet.



6 Flow configuration in the region of collision.



7 Arrangement for explosively welding parallel plates. (a) Before detonation; (b) a short time after the initiation of detonation.

obtain pictures of a jet. Bergmann *et al.*,[22] using a framing camera, have also substantiated the existence of a jet. The existence of a jet can also be deduced from experiments in which one or both of the collision surfaces are plated with a tracer layer of another metal, as reported by Holtzman and Cowan,[21] Bahrani *et al.*,[25] and Lucas *et al.*[28] In some cases jets which are more in the form of a spray than a concentrated jet have been observed.

Essentially, in explosive welding a jet is necessary which is formed from the underneath surface of the flyer plate and which picks up by surface traction the top surface of the parent plate. It is also generally believed that a plastic zone in front of the contact point is required to aid in the removal of the surface contaminant film. Perhaps the plastic straining helps to break up the oxide film and this may be aided by the formation of a hump in front of the jet. Figure 6 shows the flow configuration in the region of collision. It will be seen, considering sections ABD and EFG, that layers AB and EF are removed and points B and F will be brought together as shown by D′B′F′G′.

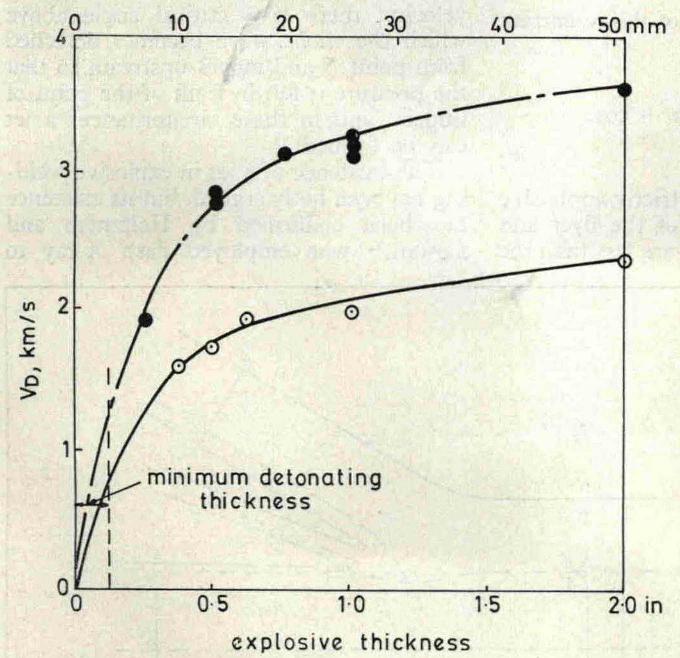
The above conditions can be met with a parallel plate set-up with an initial clearance between the flyer and parent plate, if an explosive is used that has a detonation velocity less or only slightly greater than the sonic velocity. This is shown in Fig. 7, which illustrates the parallel-plate set-up in which the detonation velocity is assumed to be equal to the sonic velocity. It will be seen that the velocity of the contact point is equal to the detonation velocity, and

$$\beta = \sin^{-1} V_P/V_D \qquad \ldots [7]$$

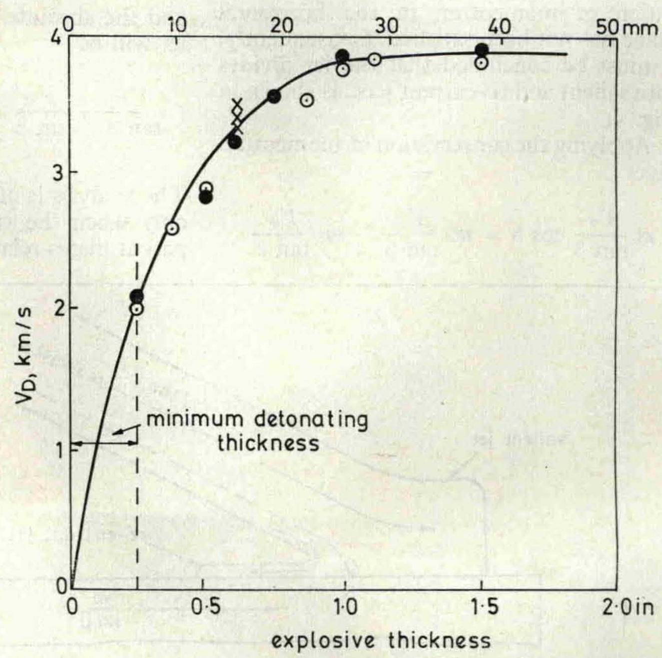
As a result the velocity of the flyer plate relative to S, $V_P/\tan\beta$, is $< V_D$ so jetting can occur and welding is possible.

From the foregoing it will be realised that the important parameters in the process are the detonation velocity of the explosive and the velocity imparted to the flyer plate. Values of detonation velocity are given by the explosives manufacturers; also values are quoted by Wright and Bayce[20] and these are given in Table I.

However, it is well known that the detonation velocity is dependent on the diameter of charge or thickness of layer, and this is of considerable significance in explosive welding where, with some explosives, the thickness of layer used is within the region where it will have a considerable effect on the detonation velocity. For instance, Fordham[29] gives the data reproduced in Table II.



8 Effect of thickness of layer of explosive on detonation velocity for *Trimonite No. 1*: ○ granules, parallel plate, $\rho = 0{\cdot}712$ g/cm^3; ● powder, pin insertion, $\rho = 1{\cdot}1$ g/cm^3.



9 Effect of thickness of layer of *Trimonite No. 3* on the detonation velocity. $\rho = 0{\cdot}98$ g/cm^3.
○ Dautriche × parallel plate ● pin insertion

More recently, Shribman and Crossland[30] have published data on the detonation velocity of the following explosives, which are readily available in Great Britain:

1. *Metabel* sheet explosive, produced by Imperial Chemical Industries, Ltd., and normally provided in sheets 10 × 5 × ⅛ in (254 × 126 × 3 mm). It has a density of 1·47 g/cm³, a detonation velocity of 7000 m/s, and an energy release of 900–1050 cal/g (3760–4500 J/g).

2. *Trimonite No.* 1, a powder explosive produced by Imperial Chemical Industries, Ltd., with a density of 1·10 g/cm³ (and in the granulated form 0·7 g/cm³) and an energy release of 1260 cal/g (5260 J/g). A detonation velocity is not given as it is very sensitive to thickness of layer.

3. *Trimonite No.* 3, as for No. 1 but with a density of 0·98 g/cm³ and an energy release of 1034–1260 cal/g (4330–5260J/g).

4. *Nitroguanadine* (picrite) is a powder explosive that is extremely difficult to handle because of its light feathery nature. At a density of 0·16 g/cm³, and a layer thickness of 1–2 in (25–50 mm), it has a detonation velocity of ~ 2300 m/s and an energy release of 950 cal/g (3960 J/g).

The detonation velocity was measured by three methods: Dautriche, parallel plate with pin contactors, and insertion of pins in the explosive at a known distance apart.

For *Nitroguanadine* the detonation velocity for thicknesses from 1 to 2 in was found to be 2400 $^{+4.50}_{-4}$% m/s and for *Metabel* sheet explosive the detonation velocity for thicknesses of 0·125–0·5 in (3·175–12·7 mm) was 7000 ± 5%, 6990 ± 3·8%, and 7100 ± 2·8% m/s, respectively, for the three methods used. For *Trimonite No.* 1 and *No.* 3, the detonation velocity varied considerably with thickness, and the data are given in Fig. 8 and 9.

Experimental information on flyer-plate velocity is very sparse. However, Shribman and Crossland[30] give data for the explosives mentioned above. For *Metabel* sheet explosive they cite the values of the ratio V_P/V_D for various values of R, the ratio of mass of explosive to mass of flyer plate, where the explosive is uniformly distributed over the plate. They compared these data wth various equations that have been proposed and found that the best agreement was obtained with the equation proposed by Gurney[31]

$$\frac{V_P}{V_D} = \frac{0{\cdot}612R}{2 + R} \qquad \ldots [8]$$

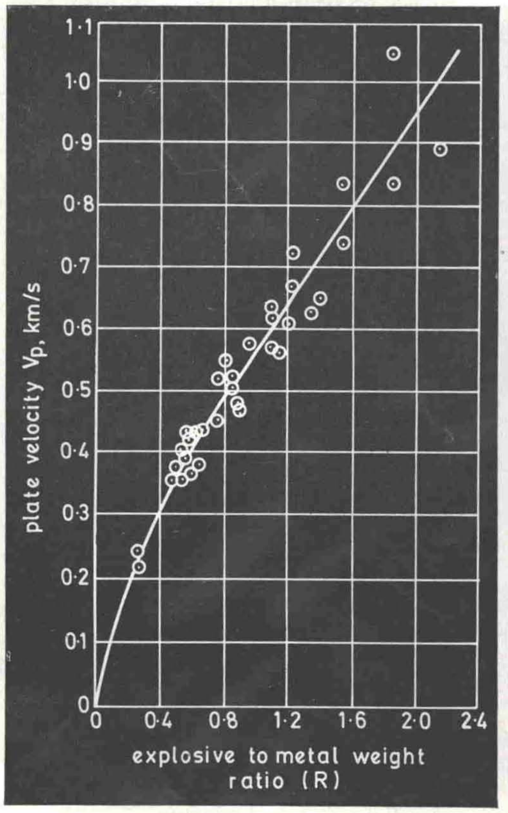
Table III gives the experimental values and those predicted by this equation.

Table I. Properties of explosives[20]

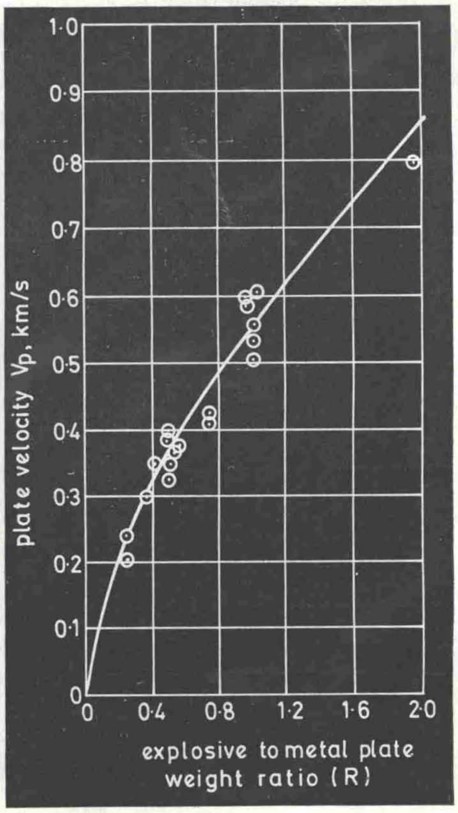
Explosive	Calorific value, cal/g	J/g	Detonation velocity, m/s	Density, g/cm³
TNT	1080	4500	6700	1·56
RDX	1280	5350	8180	1·65
PETN	1390	5400	8300	1·70
PETN	1390	5400	3500	0·5
Tetryl	1100	4600	7850	1·71
Composition B	1240	5190	7840	1·68
EL–506D	870	3640	7100	1·40

Table II. Effect of diameter on detonation velocity[29]

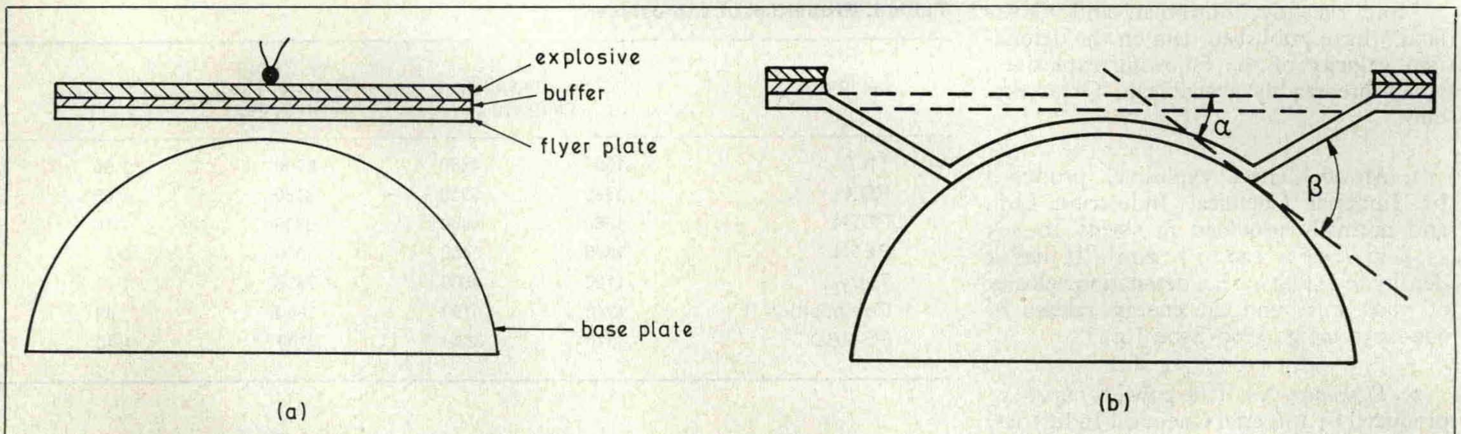
Diameter, in	Diameter, mm	Velocity of Detonation, m/s: TNT powder	Nitroglycerine powder
0·75	19	3190	1830
1·25	32	3680	2250
2·00	51	4060	2610
2·5	64	4030	—
3·0	76	4100	3150
4·0	102	4560	3290
5·0	127	—	3440
6·0	152	4815	—
8·5	216	—	3920



10 Variation of V_P with R for *Trimonite No. 1* explosive. ρ = 1·1 g/cm³.



11 Variation of V_P with R for *Trimonite No. 3* explosive. ρ = 0·98 g/cm³.



12 Variable angle of incidence experiment. (a) Set-up for the variable angle of impact; (b) a short time after the initiation of detonation.

For *Trimonite No.* 1 and *No.* 3, the value of V_D varies with thickness of explosive charge and in these cases it was found that the scatter of data was a minimum when V_P was plotted against R, as in Fig. 5, 10, and 11. These values were obtained on small plates and there is some indication for very large plates with a uniform layer of explosive that the value of V_P increases significantly with the distance from the point of initiation of the detonation. Williams *et al.*[32] found it necessary to use a non-uniform thickness of charge to ensure a constant impact velocity, but no experimental data or theoretical analysis of this aspect appear to have been published.

It is also apparent from the analysis that the sonic velocities of the materials being welded are very important. The values given in the International Critical Tables[33] are shown in Table IV.

For satisfactory welds there appear to be three essential requirements. First, it is necessary that a re-entrant jet should be formed and for this to occur the main jet velocity, $V_P/\tan\beta$, must be less than or only slightly greater than the sonic velocity in the flyer plate, so that either there are no shock waves or only detached shock waves. Secondly, a hump is needed in front of the collision point, either to disrupt the oxide film or to assist in the scouring action of the re-entrant jet. This requires that $V_P/\sin\beta$ should be less than the sonic velocity in the parent plate. Thirdly, the impact pressure must be sufficiently great to produce a fluid-like behaviour necessary for the formation of a re-entrant jet, and it is also essential that the re-entrant jet velocity should be sufficiently high to give the desired scouring action. Fourthly, the flyer plate is subject to a bending action and according to Carpenter *et al.*[34] it must be able to withstand a 5% strain. There is also the possibility that a reflected tension wave in either the flyer plate or the parent plate can cause a 'spalling' failure, though this has only rarely been noted. Such a failure is more likely to occur with a high-detonation-velocity explosive, which gives a higher pressure pulse and hence a greater reflected tension pulse, and with materials that contain planes of weakness parallel to the surface. If spalling of the flyer plate occurs in flight, welding of the two pieces of the flyer plate

Table III. Variation of ratio of flyer plate to detonation velocity/ratio of mass of explosive to mass of flyer plate (R) for *Metabel*

R	V_P/V_D Experiment	V_P/V_D Equation [8]
0·2	0·062	0·056
0·4	0·104	0·102
0·6	0·143	0·141
0·8	0·180	0·175
1·0	—	0·204
1·2	—	0·23

Table IV. Sonic velocity of metals[33]

Metal	Velocity, m/s
Aluminium	5105
Copper	3560
Gold	2645
Platinum	2500
Silver	2080
Steel	5000
Tin	2490
Zinc	3680

Table V. Metal combinations bonded by explosive cladding [21]

METALS	ZINC	PALLADIUM ALLOY	TD NICKEL	TUNGSTEN	NICHROME	MAGNESIUM	MOLYBDENUM	COLUMBIUM AND Cb ALLOYS	PLATINUM	SILVER AND SILVER ALLOYS	GOLD ALLOYS	TANTALUM	HAYNES STELLITE ALLOY 6B ©	HASTELLOY ALLOY X ©	HASTELLOY ALLOYS B,C,F ©	ZIRCONIUM AND ZIRCALLOYS	TITANIUM AND Ti ALLOYS 6Al-4V	NICKEL AND NICKEL ALLOYS ⓑ	BRONZE	CUPRO-NICKEL	BRASS	COPPER	ALUMINIUM AND Al ALLOYS	MARAGING STEEL	HADFIELD STEEL	STAINLESS STEEL, 200 SERIES	STAINLESS STEEL, 300 SERIES	STAINLESS STEEL, FERRITIC	ALLOY STEEL, AISI 4340	ALLOY STEEL, AISI 4130	LOW ALLOY STEEL, ASTM A-387	LOW ALLOY STEEL, ASTM A-302	LOW ALLOY STEEL, ASTM A-204	MEDIUM C STEEL, ASTM A-212	MEDIUM C STEEL, ASTM A-201	MEDIUM C STEEL, ASTM A-285	LOW C STEEL, AISI 1004 to 1020
LOW C STEEL, AISI 1004 to 1020	X					X	X			X		X						X		X	X	X	X			X	X	X									X
MEDIUM C STEEL, ASTM A-285						X	X			X		X	X	X	X	X	X	X	X	X	X	X	X			X	X	X								X	
MEDIUM C STEEL, ASTM A-201						X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X			X	X								X		
MEDIUM C STEEL, ASTM A-212						X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X			X	X							X			
LOW ALLOY STEEL, ASTM A-204														X	X	X	X	X		X	X	X	X			X	X						X				
LOW ALLOY STEEL, ASTM A-302														X	X		X	X		X	X	X	X			X	X					X					
LOW ALLOY STEEL, ASTM A-387														X	X		X	X					X			X	X	X			X						
ALLOY STEEL, AISI 4130																											X			X							
ALLOY STEEL, AISI 4340																											X		X								
STAINLESS STEEL, FERRITIC																	X											X									
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STAINLESS STEEL, 200 SERIES																					X		X			X											
HADFIELD STEEL																							X														
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BRONZE																			X																		
NICKEL AND NICKEL ALLOYS ⓑ									X		X			X			X	X																			
TITANIUM AND Ti ALLOYS 6Al-4V				X				X									X																				
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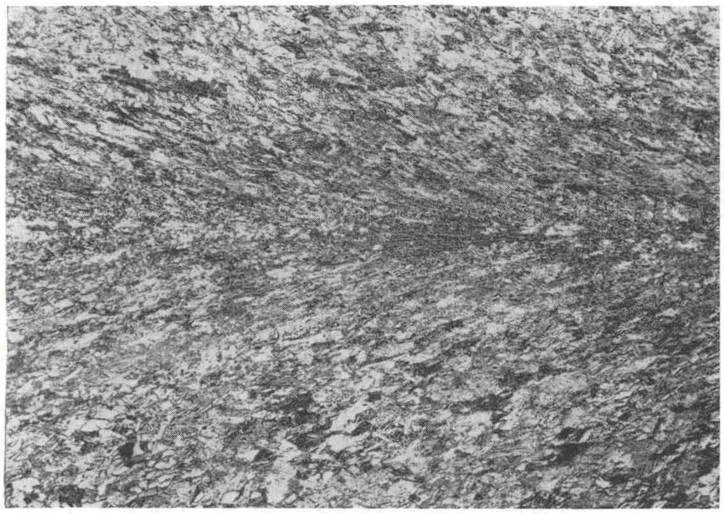
COLUMBIUM AND Cb ALLOYS		X					X	X																													
MOLYBDENUM					X		X																														
MAGNESIUM						X																															
NICHROME					X																																
TUNGSTEN				X																																	
TD NICKEL			X																																		
PALLADIUM ALLOY																																					
ZINC	X																																				

NOTES :–

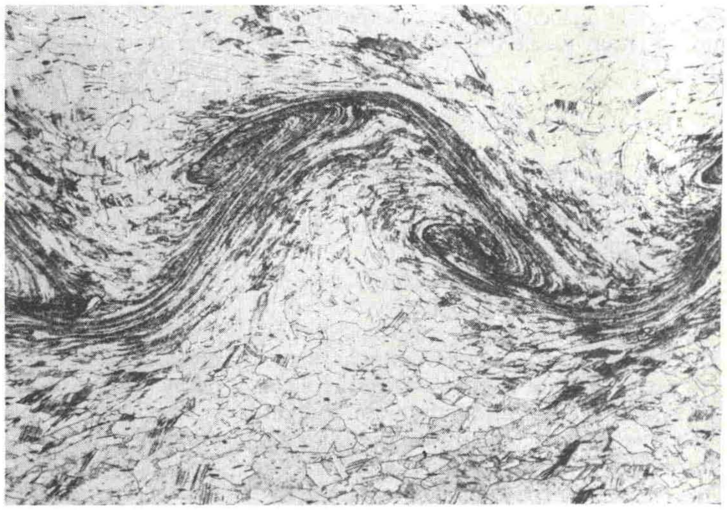
ⓐ A blank space means bonding of that combination has not been attempted. It does not mean those metals cannot be explosion bonded.

ⓑ Includes Inconel,* Monel,* and Incoloy, registered trademarks of International Nickel Company.

ⓒ Registered trademark of Union Carbide Corporation.

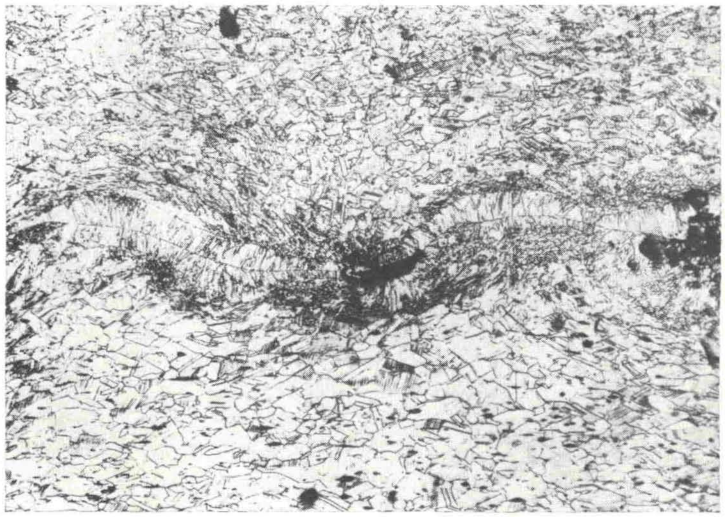


13 Straight interface in copper produced by large angle of incidence. × 90.



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]

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

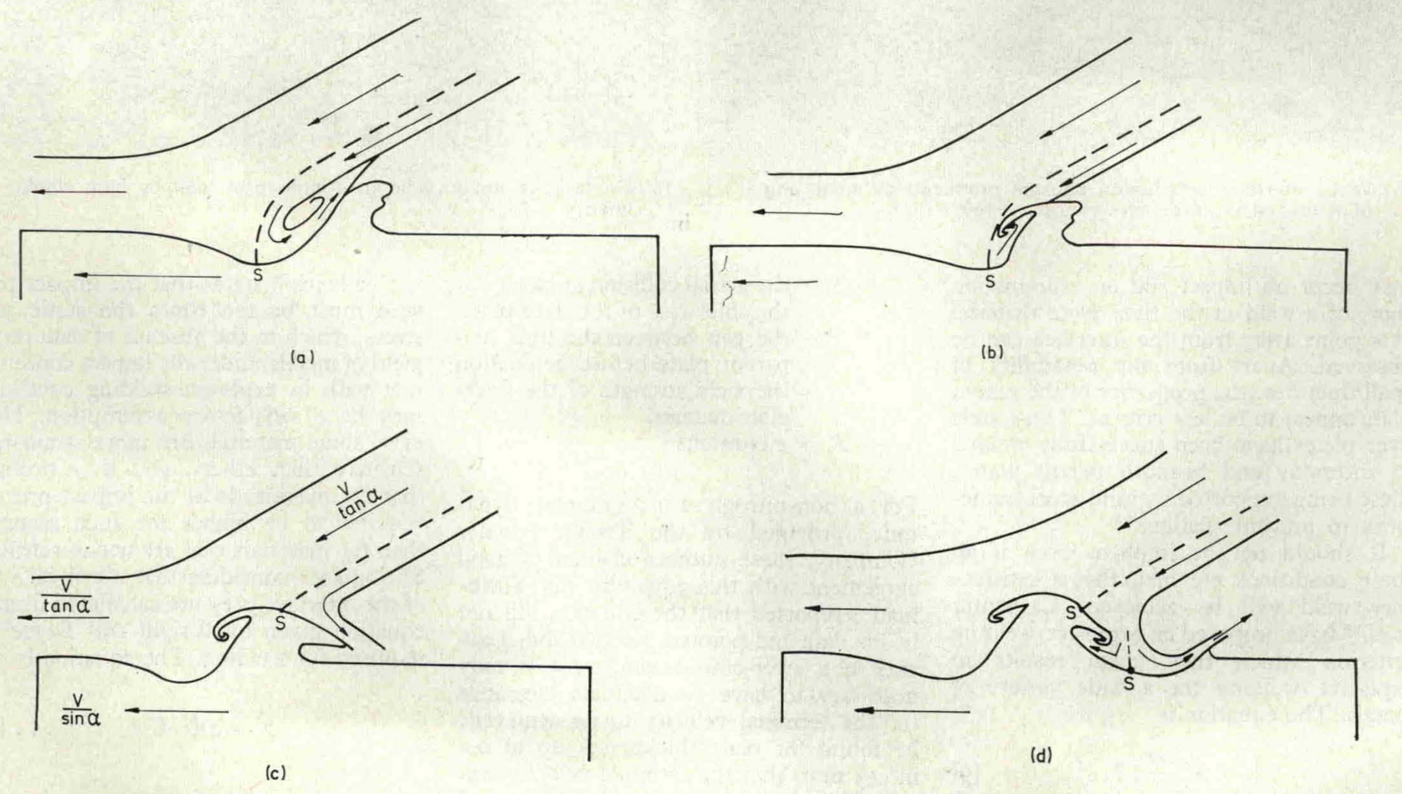
where C_0 = the bulk velocity of sound
λ = a constant which can be calculated from Walsh *et al.*[27]

For mild steel-to-mild steel he claimed that with pressures of $0{\cdot}411 \times 10^6$ lbf/in² (28·4 kbar) or below there was no bonding, but at $0{\cdot}65 \times 10^6$ lbf/in² (45 kbar) up to $\nless 1{\cdot}93 \times 10^6$ lbf/in² (133 kbar) there was consistent bonding. For titanium-to-titanium, the respective figures were $0{\cdot}44 \times 10^6$ lbf/in² (30 kbar) and $0{\cdot}64 \times 10^6$ lbf/in² (44 kbar), and for copper-to-copper satisfactory bonds were achieved at $0{\cdot}77 \times 10^6$ lbf/in² (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.

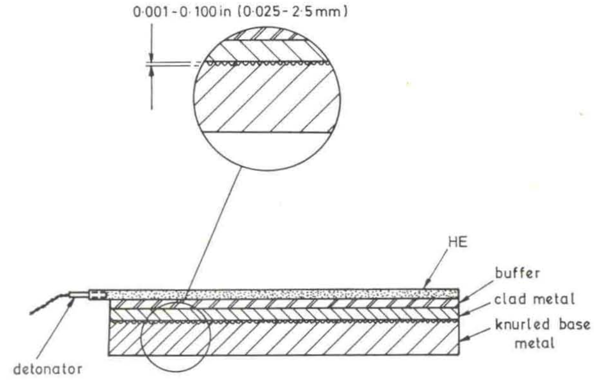
In all these discussions the combinations of metals that can be welded have not been discussed. It is probably correct to say that no one has mentioned combinations that cannot be welded. Table V is a reproduction from Ref. 21 and lists the combinations that have given good bonds. Also, the form of the 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.



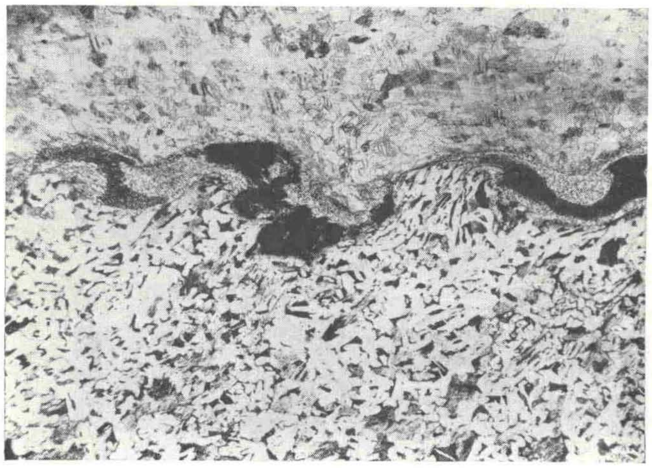
[Courtesy Royal Society

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])

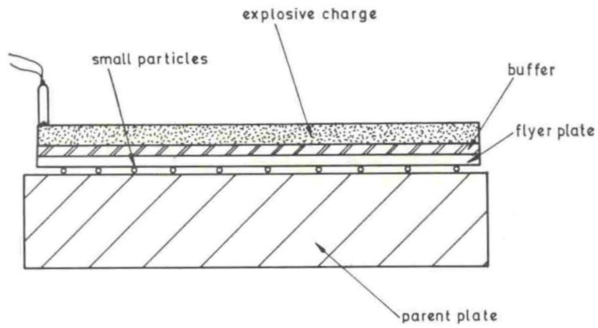


[*Courtesy Amer. Soc. Tool Manuf. Eng.*

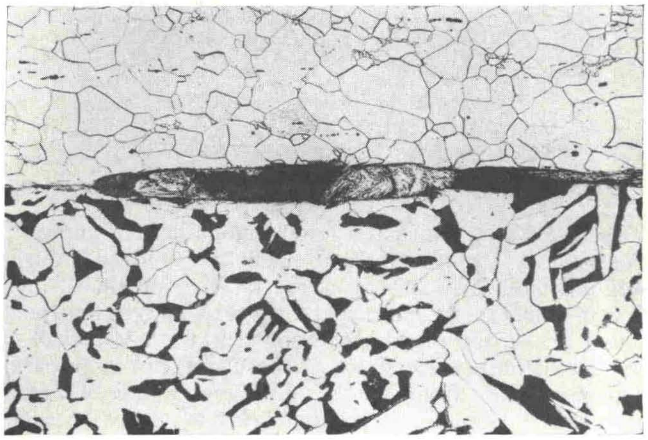
18 Flat-plate cladding. (*Philipchuk.*[1])



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

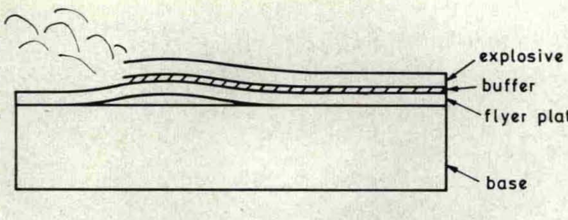
The inclined-angle set-up shown in Fig. 2 is strictly needed only if a high-detonating-velocity explosive is being used, to bring the collision-point velocity down to an acceptable value. However, the use of such an explosive gives rise to problems of spalling and surface damage. There is, in addition, 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.

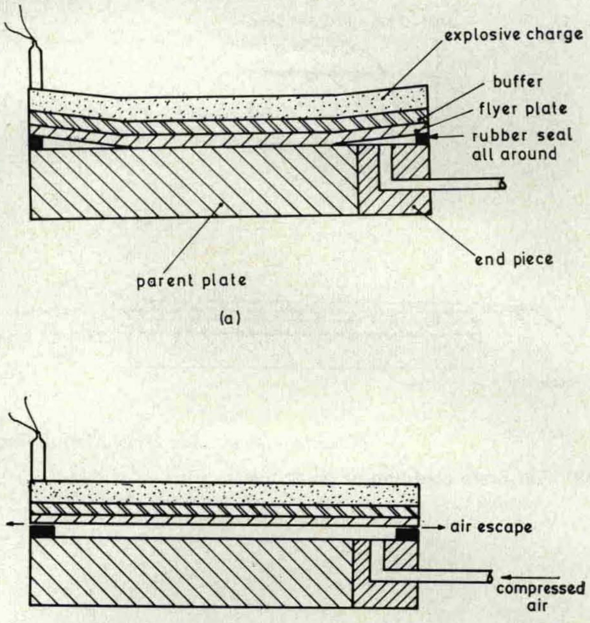
Philipchuk[1] suggested supporting the flyer plate on a knurled or grooved parent plate, as shown in Fig. 18, but Shribman *et al.*[39] showed that this produced a weld with voids and excessive melting (see Fig. 19). As a consequence, this would seem to be an unacceptable method for high-quality welds.

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.

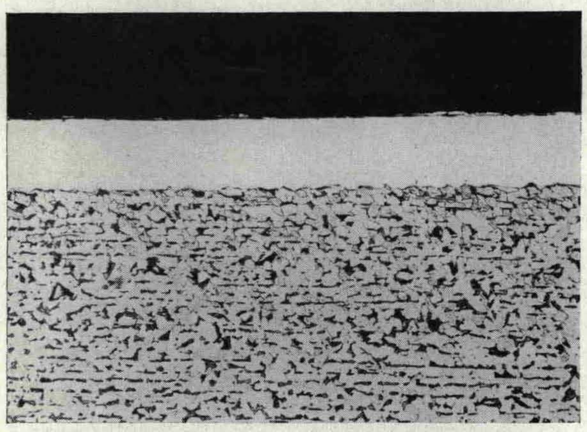
Otto[14] suggested that welding could be achieved with plates in contact using a high-detonation-velocity explosive, but attempts by Crossland and Bahrani[4] to repeat this work with *Metabel* sheet explosive proved abortive. However, using



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.

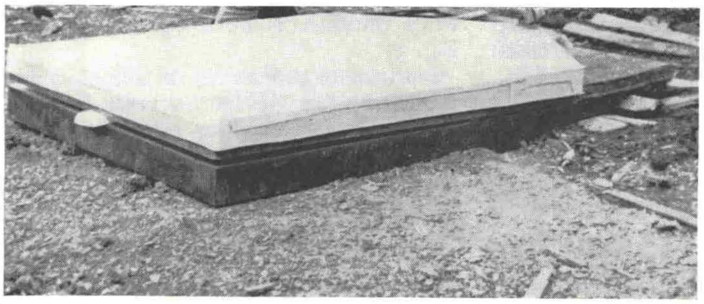
Yet another arrangement has been proposed by Williams *et al.*[32] using polystyrene particles to separate the flyer and parent plate. They note that a slight initial angle of obliquity, with an explosive with a detonation velocity less than the sonic velocity, gives a better wave form and reduces the 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.

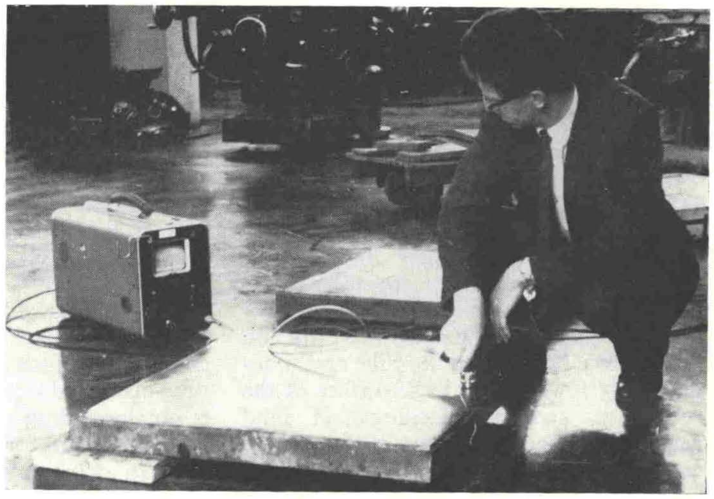
To summarise, if a very thin flyer plate, such as the 0·005 in- (6·127 mm) thick brass flyer plate shown in Fig. 24, which was studied by Shribman,[35] is to be welded, then a contact method should be used even though a small area of no bonding will be found near the detonator. For plates of up to $\frac{1}{16}$ 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,



25 Arrangement for explosive cladding [3 ft-(1 m) square steel base with ½ in-(12·7 mm) thick aluminium bronze.]



26 Testing the finished product.

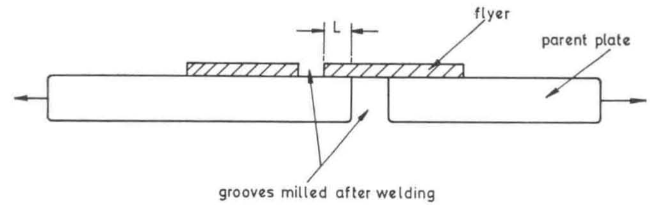
the specimen will bend through 180° without failure of the bond. De Maris gives data for fatigue tests on cantilever specimens of *Inconel* welded to ASTM A-302-B FbQ steel; the fatigue results lay between the *S/N* curves for the two materials before cladding, and the fractures did not initiate at the interface. With other combinations he noted a slight weakening of the flattened and stress-relieved clad material compared with the steel of the parent plate, but he attributed this to a reduction in hardness of the steel. Gelman *et al.* clad constructional steel with other steels and in general found a reduction of fatigue strength, which was, however, improved by a subsequent heat-treatment. Banerjee carried out repeated tension fatigue tests on stainless steel clad to steel; the results are shown in Fig. 31, 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 steel. Banerjee 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 side shear tests were carried out. A very slight reduction in shear strength of the specimen subjected to 10 cycles of 15 to 700° C (288 to 975 K) was noted, but this could have been attributed to recrystallisation.

A problem with explosively or conventionally clad plate is the non-destructive testing of the plate to establish weld integrity. Very few techniques are available and perhaps the only one readily available is ultrasonics, though Dewy[50] shows an isothermal plot of poorly bonded nickel plating on steel established by a thermographic method which might be applicable to clad plate. Addison *et al.*[44] 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 as a transmitter and receiver. Banerjee[49] 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 conditions.

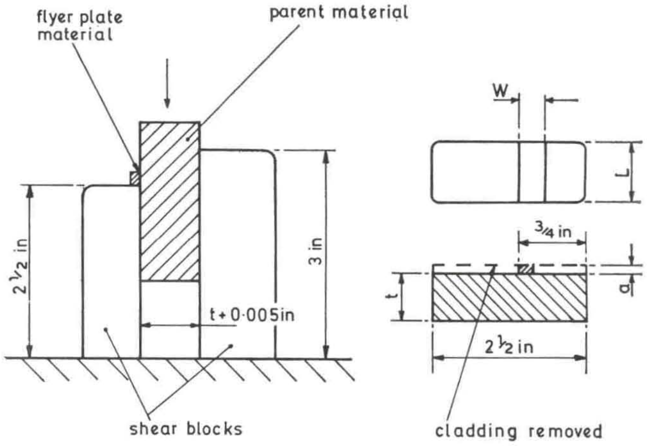
III. Tube welding

The cladding of the inner surfaces of tubes and cylinders was mentioned at about the same time by Philipchuk,[1] Wright and Bayce,[20] Carlson,[23] Holtzman and Cowan,[21] and later by Dalrymple and Johnson.[51] Philipchuk used an outer tube knurled at the bore and supporting an inner tube with a smooth outer surface, as shown in Fig. 32. The other workers adopted the arrangement shown in Fig. 33.

The application of explosive welding of tubes to tube plates has only recently been mentioned by Crossland *et al.*,[52] Chadwick

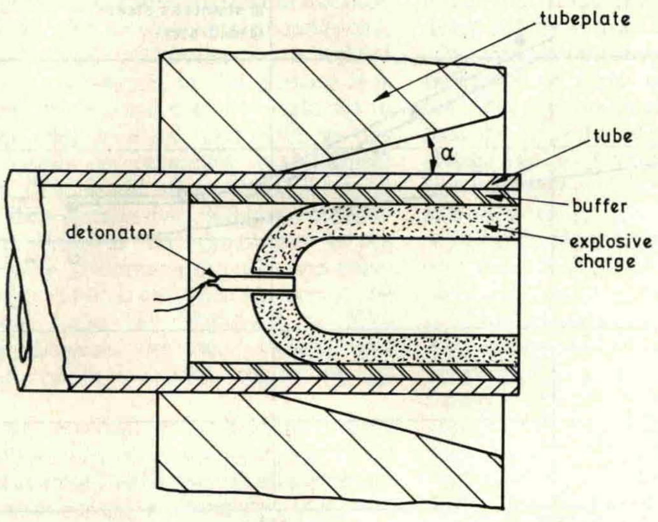


27 Specimen for tensile shear test on cladded plate.

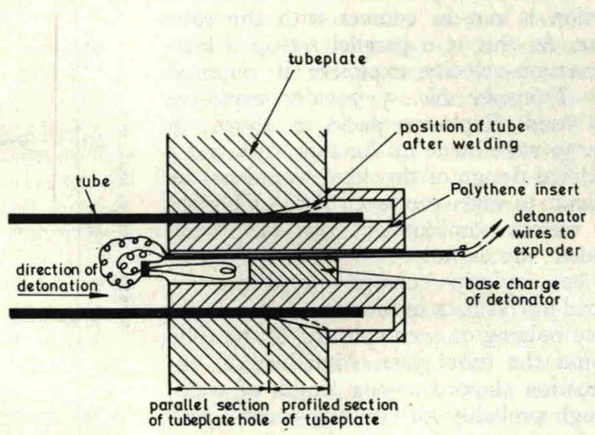


28 Shear tests on clad plate. Test-specimens: $t > 2W$; $W = 1\frac{1}{2}a$.

in	0·005	¾	2½	3
mm	0·127	19·1	63·5	76·2



34 Tapered-hole technique. (Before detonating the explosive charge).

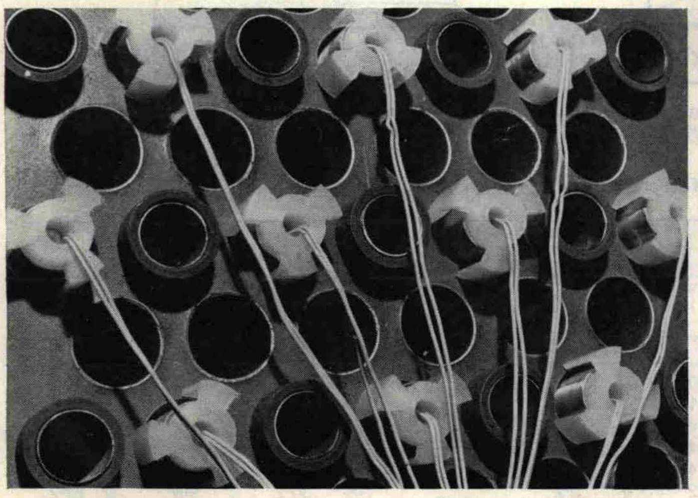


[Courtesy Welding Inst.

35 Schematic diagram of assembly for explosive welding (*YIMpact* system). (*Cairns and Hardwick.*[54])

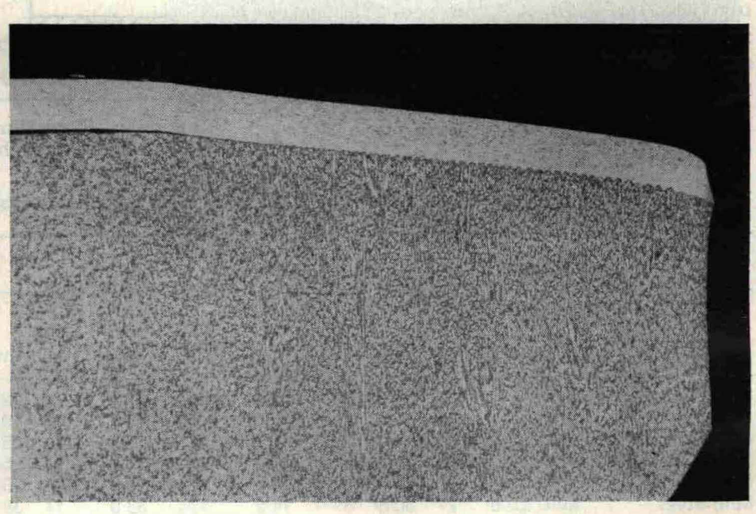
So far, data are not available for the radial velocity imparted to the tube wall immediately before impact. Chadwick[36] considers that the equations for estimating the velocity of the flyer plate in cladding are equally applicable to tube welding, though as in that case the charge is more confined this may not be true. If the minimum charge weight for a reliable weld is determined, then the minimum ligament thickness can be established for which the distortion in adjacent unwelded tube holes is acceptable.

Chadwick *et al.*,[53] Cairns and Hardwick,[54] and Robinson *et al.*[59] have discussed methods of testing the integrity of the welds between tube and tube plates obtained by the angular-geometry method. Chadwick *et al.* reported on push-out or pull-out tests on tubes in which a plug was used to try to push out a length of $1\frac{1}{4}$ in (31·8 mm) of $\frac{3}{4}$ in (19·1 mm) O.D. × 0·040 in (1 mm) wall thickness stainless-steel tube from a mild-steel tube plate. A load of 18 tonf (180 kN) was applied without failure of the bond at 20° and 600° C (295 and 875 K), and after quenching 200 times from 600° C into hot water. Peel tests have also been conducted but peeling stops abruptly in the weld zone and ultimately the strip breaks without failure of the bond. In shear tests failure occurs away from the weld interface. Chadwick *et al.* also mention fatigue tests in which the tube/tube-plate joint was subjected to repeated bending and satisfactory results were achieved. Cairns and Hardwick also carried out thermal-cycling tests in which three aluminium-brass tubes were welded into small tube plates at each end. The tube plates were connected by steel tie-bars and the whole assembly was then subjected to 10 cycles at a given temperature, followed by a hydraulic-pressure test applied to the outside of the tubes. The explosively welded tubes showed no signs of leakage even up to a cycling temperature of 450° C (725 K), whereas roller-expanded joints showed a significant decrease in the leakage pressure above 200° C (475 K) and they were completely ineffectual above 250° C (525 K). Robinson *et al.* describe manual and automatic ultrasonic tests of tube-to-tube plate welds that give results which are confirmed by metallography, peel, and leak tests. However, the method cannot detect unfavourable metallurgical conditions at the interface, such as a cast interlayer or brittle intermetallic phases.



[Courtesy Welding Inst.

36 Arrangement of charges and hard-steel rings in the *YIMpact* system. (*Cairns and Hardwick.*[54])



[Courtesy Welding Inst.

37 Aluminium brass tube *YIMpact* welded to Naval brass tube plate. × $6\frac{1}{2}$. (*Cairns and Hardwick.*[54])

IV. Other explosive-welding processes

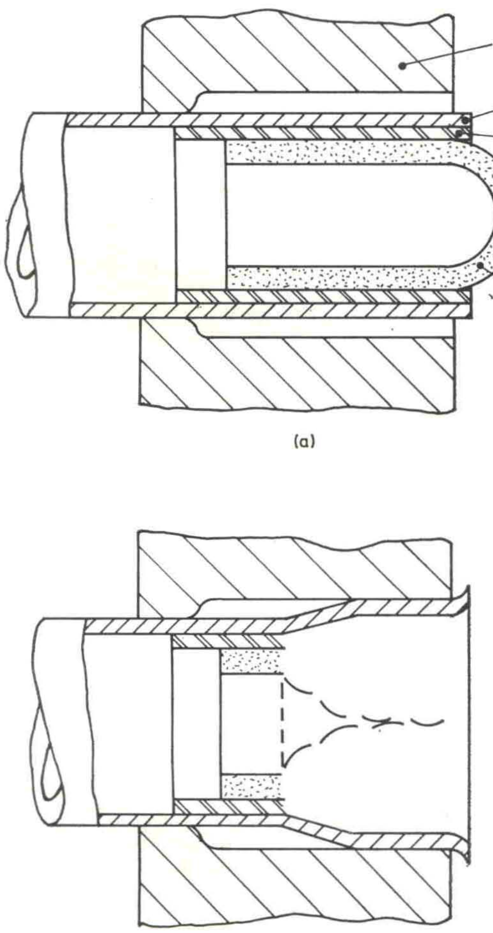
Various processes that take advantage of the explosive-welding process have been suggested by different research workers. Perhaps one of the most common problems examined is the joining of two metal plates or sheets by means of some form of lap or butt weld. Addison[60] produced lap-welded specimens 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.

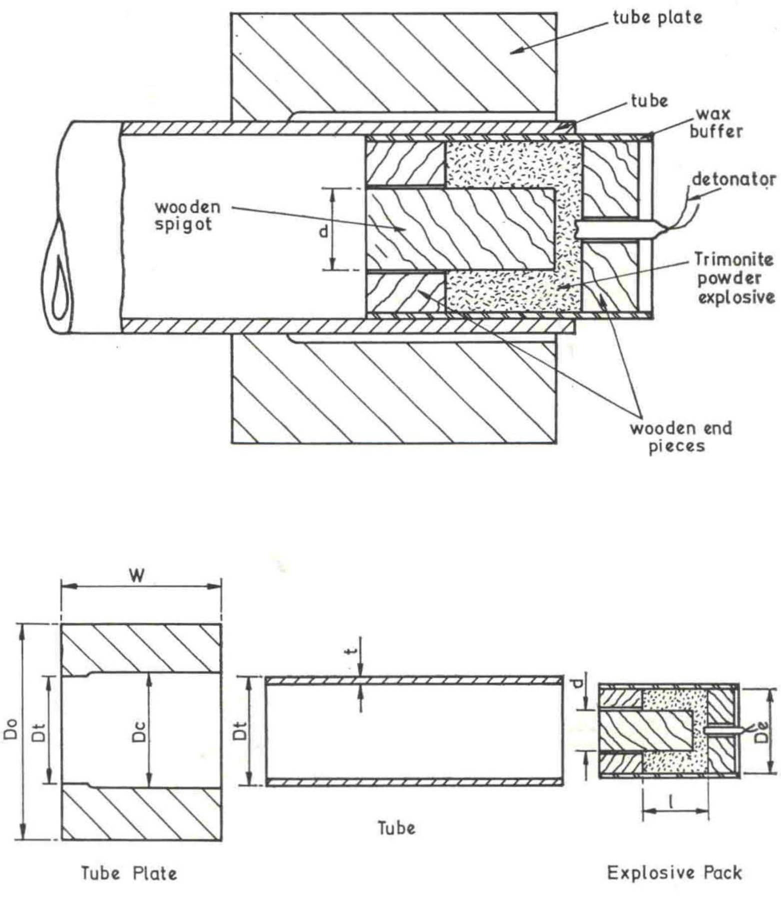
Holtzman and Cowan[21] also suggested the set-up shown in Fig. 47 for making a tee weld. Stone[43] notes the increasing use of aluminium superstructures in ships, which at the present time requires that the aluminium bulkheads be joined to the steel deck with a lapped, bolted, or riveted connection. 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.

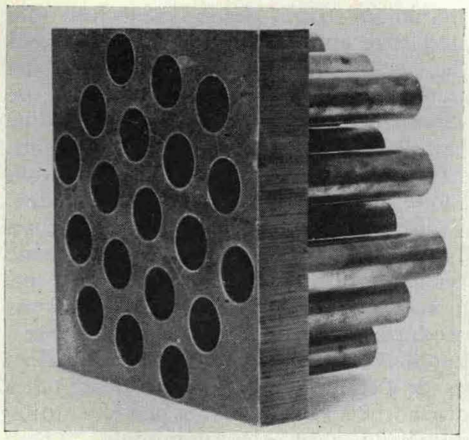
Jarvis and Slate[63] have briefly reported on the explosive fabrication of composite materials. They used a parallel-plate technique and a high-detonation-velocity sheet (7–5 km/s) explosive; as might be expected, they were unable to obtain a weld. However when a layer of tungsten wires was inserted 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. $\sim 15°$, 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]

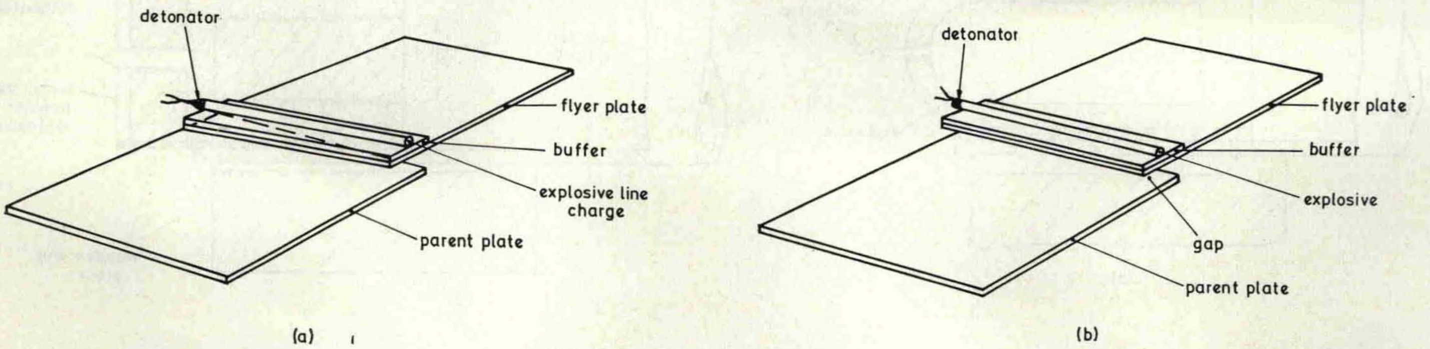
More usually, smaller collision angles, i.e. $< 5°$, are employed, especially in the parallel-plate technique, and under these conditions the jet is trapped as explained by the mechanism of Bahrani *et al.*[25] illustrated in Fig. 17. In Fig. 15 it can be seen that the interface of such a weld consists 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.

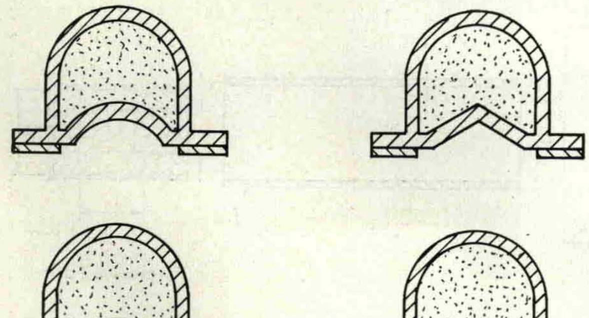
2. Solid-phase bonded interface

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-

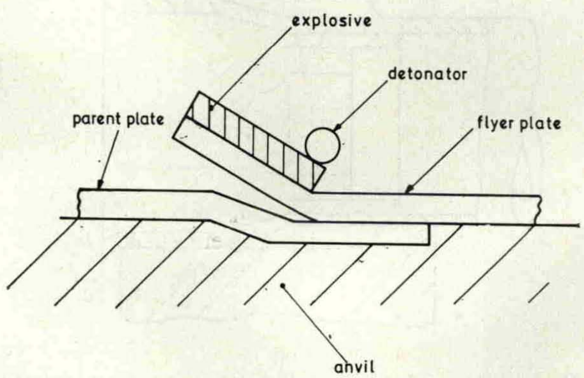


[Courtesy 'Welding']

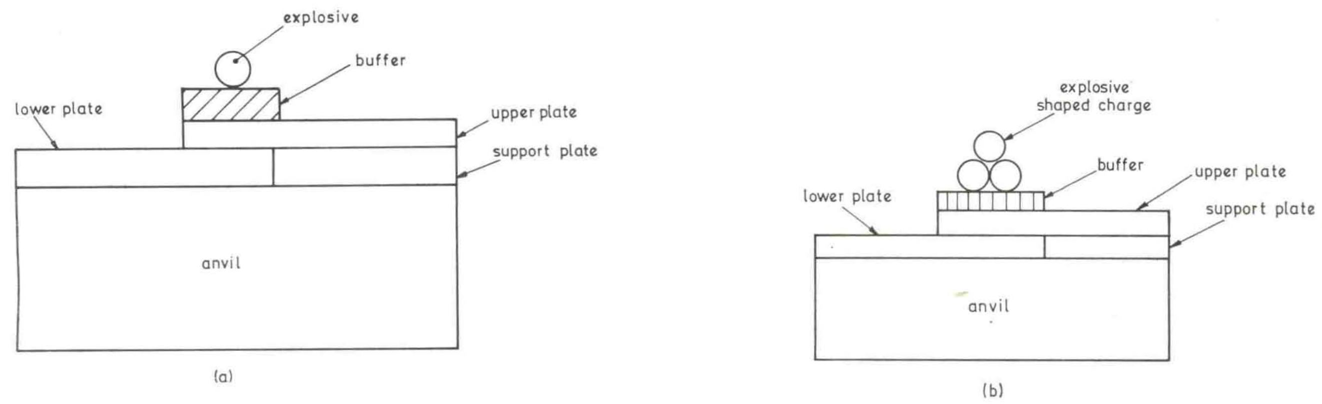
41 Welding of lap joints, (a) Inclined technique; (b) parallel technique. (*Addison, Kogya, and Kaisha.*[61])

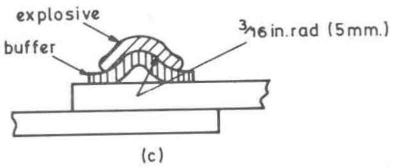


42 Line charge shapes.



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





44 Shaped charge used for welding of 1/16 in-(1·6 mm) thick plates.

lisation across the weld zone and the presence of a weld can be detected only by the different residual grain size.[37,67,68]

The extent to which localised heating during welding affects the nature of the interface in the very short time for which it exists is not well established. Holtzman and Cowan[21] and Trueb[66] have found no evidence of solid-state diffusion zones in explosive welds, although the latter author has reported that clear evidence of recrystallisation exists, particularly in small isolated hot spots along the bond zone. Buck and Hornbogen[64] observed recrystallisation and evidence of melting in a zone of $<10^{-4}$ cm thickness.

Differential polishing and etching of bimetallic welds present difficulties in metallographic examination. Trueb[66] found that the resulting step in the replica completely prevented observation of any diffusion zone that may have been present. Buck and Hornbogen[64] overcame this difficulty by careful vibration-polishing and polish-etching techniques. Also, by careful vibration polishing and shadowing of the replicas in a direction parallel to the interface, Lucas *et al.*[28] have obtained definite evidence of diffusion layers $< 10^{-4}$ cm thick in weld couples whose alloy systems normally contain intermetallic compounds. These authors also reported clear evidence of recovery and recrystallisation, revealed by transmission microscopy of thin foils taken from the interface regions of welds in aluminium, copper, and stainless steel.

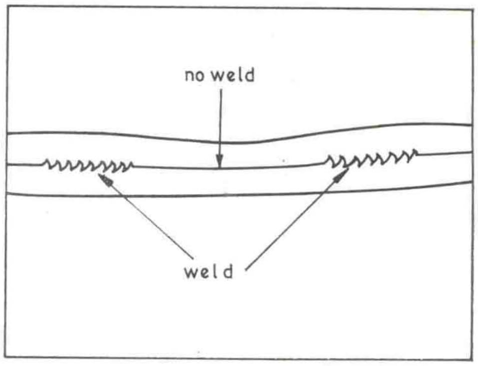
Thin foils taken from positions adjacent to the interface in copper/copper welds have shown high dislocation densities of the order of 10^{11} cm^{-2} and intense microtwinning.[28,37,65,66] Trueb[66] succeeded in producing thin foils from sections normal to the interface between brass/copper and 1070/1008 steels. No evidence of interfacial diffusion was found, although his transmission microscopy of copper/copper welds showed that the structure could vary between heavily deformed, recrystallised, and melted, from place to place along the interface.

Microhardness traverses across sections normal to explosive welds have been reported by several authors. The results of such tests vary considerably. Without exception, the general hardness of the flyer and parent plates is found to have been increased by the passage of shock waves through them. In many cases extremely high hardnesses have been reported in phases formed at the interface as a result of melting and rapid quenching. Both these features will be discussed in later sub-sections.

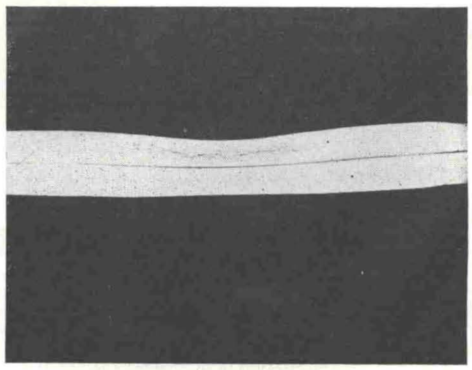
Referring to microhardness values across solid-phase bond interfaces, three basic types of behaviour have been noted; these are shown in Fig. 52. It is clear from Fig. 52(a) that, in addition to shock-hardening, there is localised interfacial work-hardening due to severe plastic flow in the weld zone.[60,65,69–72] Hardness profiles, as shown in Fig. 52(b), have also been reported[17,71] and it would appear in such cases that sufficient heat has been generated at the interface to cause total recrystallisation during and subsequent to the welding process. Figure 52(*c*)[17,24] represents the intermediate case where a smaller quantity of heat has been generated, thus allowing only partial recrystallisation.

Electron-microprobe and X-ray diffraction techniques have been employed to examine the nature of the explosive-bond interface. It is doubtful whether either technique can reveal the presence of diffusion at the interface unless this has occurred in layers several microns thick. Such layers would be expected only as a result of melting and they will be discussed in the next section. Holtzman[72] and Buck and Hornbogen[65] have reported abrupt transitions of the type 100% A → 0% A in dissimilar metal welds over distances smaller than the resolution of the electron-probe microanalyser.

According to Wright and Bayce,[20] their electron-probe analysis results afford a clear indication of solid-phase diffusion in a copper/gold weld. In support of this

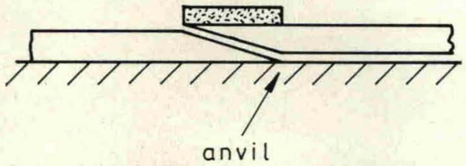


(a)

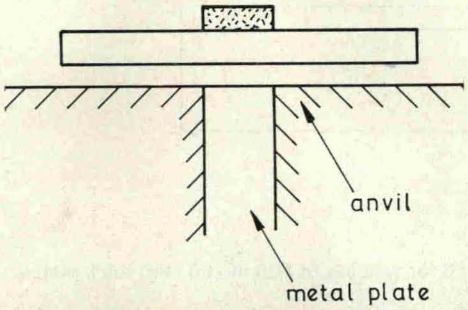


(b)

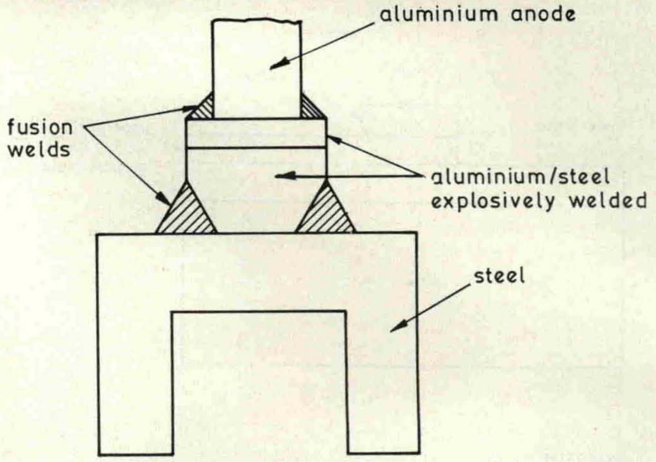
45 Seam weld in brass sheet made with *Cordtex*. (a) Form of interface under the line charge; (b) micrograph of interface in the region of the line charge. × 1¼.



[*Courtesy Weld Research Council.*
46 Butt weld. (*Holtzman and Cowan.*[21])



47 Tee weld. (*Holtzman and Cowan.*[21]) [*Courtesy Weld. Research Council.*



[*Courtesy Welding Inst.*
48 Aluminium/steel transition joint. (*Stone.*[43])

claim they refer to an X-ray diffraction investigation on the same weld reported earlier by Davenport.[11] This investigation showed that the ordered α' phase was present at the interface, and Wright and Bayce point out that this would not be expected under the conditions of high cooling rate that any molten pocket would experience. The optical micrograph of the weld interface in question is wavy and considerable melting appears to have occurred.

Pietteur[73] has reported electron-probe traverses across the interface of a steel/copper weld in adjacent positions near the crest of a wave. These indicated that at the peak of the wave there was an abrupt change from steel to copper, while on a line slightly to the rear of the wave crest evidence of an intermediate phase consisting of Cu 80%–Fe 20% was visible. The optical micrograph again clearly showed that a layer of previously melted alloy extended forward from the vortex of the previous wave and, although present in both the above traverses, its thickness had decreased to below the resolution of the probe at the peak of the wave.

It can be concluded that the solid-phase bond obtained in an explosive weld is formed by the flowing together of grossly elongated surface grains, after the removal of the original surface contaminants by jetting. The differences between the observations of various workers is a consequence of the measuring techniques adopted, the differences between the explosives used, the ratio of mass of charge to that of the flyer plate, and the dimensions of the flyer plate. The temperatures reached at the interface and the cooling rate may well differ from one experiment to the next. It has been suggested[28] that the extremely high rates of strain in the weld zone could lead to a high concentration of point defects by the non-conservative motion of jogs. This could account for the increased diffusion rates referred to by Tylecote[74] and by Wright and Bayce.[20] The recovery and recrystallisation observed in thin foils[28] indicates that considerable dislocation and atomic rearrangement has occurred during and immediately after bonding, and it is not unreasonable to assume that detectable interfacial diffusion may take place in dissimilar metal welds.

3. Melting at the interface

There are three main sources of heating at the weld interface: the heat of detonation of the explosive, internal heating in the metal subjected to shock waves and high rates of deformation, and adiabatic heating of gases compressed between the plates.[28] Of these, the most important is the heating due to plastic deformation, particularly in the vortices of wavy interfaces where severe turbulence occurs, resulting in melting.

Molten layers observed in explosive welds are typically 5×10^{-3} cm thick and their structure and properties are governed by three main factors: alloying behaviour in dissimilar metal welds, extremely high cooling rates, and entrainment of atmospheric gases and surface contaminants.

In general, melting in explosive welding is not desirable because of the inherent weakness associated with cast structures. Figure 16 shows a continuous line where columnar grains meet[21,37] and typical gas porosity is illustrated in Fig. 53.[21]

Numerous reports have included evidence of alloy formation in the molten regions of dissimilar-metal welds. In the majority of cases the different electrochemical properties of the two metals allow only one metal to be etched, while the other metal and the alloy zone remain unetched. By careful polishing and etching, however, it has been shown that the alloy pockets may contain micron-sized crystals arranged in a swirled pattern, as seen in vortices of welds between similar metals.[37,68]

Metal combinations whose alloy systems normally contain intermetallic compounds may form such compounds in the melted zones when welded together explosively. These compounds are normally very hard and often cracking can be seen in these regions of high hardness, or cracks may originate from the indentation caused by a microhardness indenter. Numerous authors have published data regarding compounds and their effects on the properties of a weld. Rowden,[48] Bahrani and Crossland,[45] Lucas and Williams,[37] Carlson,[23] and Hollingum[75] have stated that compound formation occurs in titanium-to-mild steel welds. This phase has a reported hardness[45] of 1290 Hm, and tensile shear strengths of welds containing the compound are about one fifth of those with no compound.[23] Rowden[48] has shown that stress-relieving at 400°C (675 K) increases the thickness of the layer and causes more cracks to appear, though the shear strength differs little from the as-welded condition.

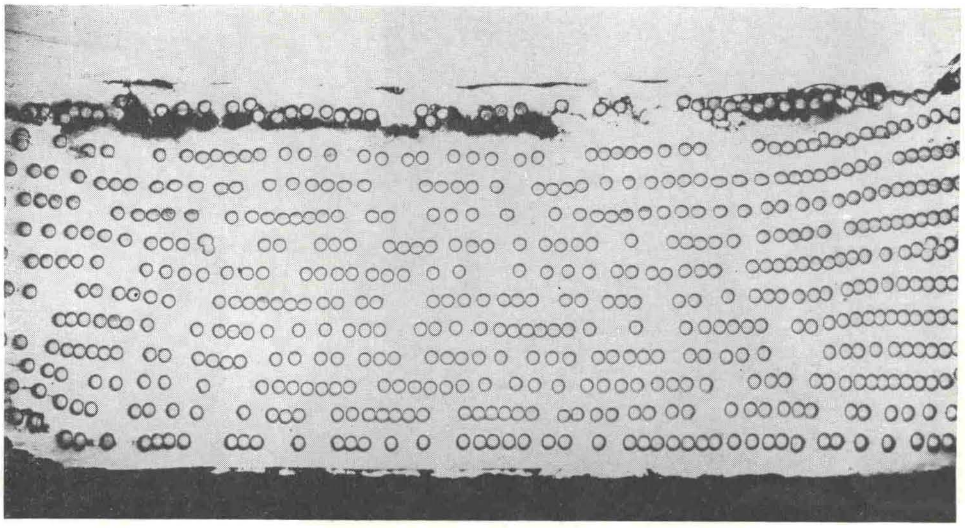
Welds between tantalum and mild steel have also been found to contain intermetallic compounds[20,60] with a measured hardness[21] of 1100 Hm. Holtzman and Cowan[21] concluded that a homogeneous compound Fe_2Ta was formed, and microhardness tests showed a uniform value across a layer. Wright and Bayce,[20] however, have observed various compositions of such layers by electron-probe analysis and therefore suggest that a transition or defect compound may have been formed. These workers also showed that the problem of brittle alloy formation in welding can be overcome either by proper control of the welding parameters to minimise melting, or by introducing a suitable third metal as a thin sheet between the weld plates. Boes[13] and Rosenstiel *et al.*[76] also referred to the use of a third-metal layer electroplated to one weld component as a means of avoiding the formation of brittle intermetallics between aluminium and stainless steel.

Deribas *et al.*[77] employed electron-probe and X-ray diffraction analysis to study alloy zones in explosive welds. They found that all metal couples examined could be placed in one of two classes according to their alloying behaviour. Class 'A' included the couples steel/copper, molybdenum/tungsten, and silver/steel, in which alloy compositions varied continuously between 0 and 100%. Class 'B' contained titanium/steel, iron/zirconium, and copper/lead for which definite stoichiometric compounds occurred. It was noted that these compositions were often not in agreement with normal phase equilibria for the couples examined, which suggested that these alloy zones are in a metastable condition.

Apart from the work of Deribas *et al.*[77] little definite evidence for the occurrence of non-equilibrium phases in welds has been reported. Buck and Hornbogen[64] noted the presence of an interfacial layer of uniform appearance and 10^{-4} cm thick in carbon replicas taken from a copper/mild steel weld. On heating to 250° C (525 K) this layer was seen to decompose into two stable phases. They concluded that the layer resulted from alloying in the molten state and that rapid cooling had caused a metastable phase to form. Several workers have found that the rear vortex of a wavy weld contains a higher fraction of the flyer plate, while the front vortex contains a higher fraction of the base plate.[37,45,48,75] Lucas and Williams[37] have pointed out that, since molten pockets have been seen to consist of sub-micron-sized grains, it is not correct to infer the existence of a compound on the basis of electron-microprobe analysis alone. Positive identification by a diffraction technique is essential.

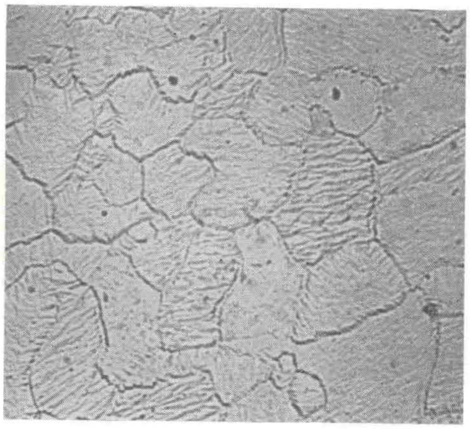
Thermal conductivities of solid metals are typically 0·5 cal/sec cm degC (209 W/m.K) and consequently small pockets of molten metal will experience extremely high quenching rates by conduction of heat into the adjacent colder regions. Cowan and Holtzman[19] have shown that in a time of 10^{-5}s, the typical time in which a weld is made, layers of liquid varying in thickness between 73 μm for copper and 31 μm for steel could solidify before the pressure was released. It is probable that such rapid solidification would not allow equilibrium phases to form.

Evidence of rapid cooling of melted pockets is seen in steel-to-steel welds. Lucas and Williams[37] have recorded a hardness of 450 Hm in the melted zone between low-carbon iron and mild steel, and examination of the carbon replica from this area showed it to be martensitic



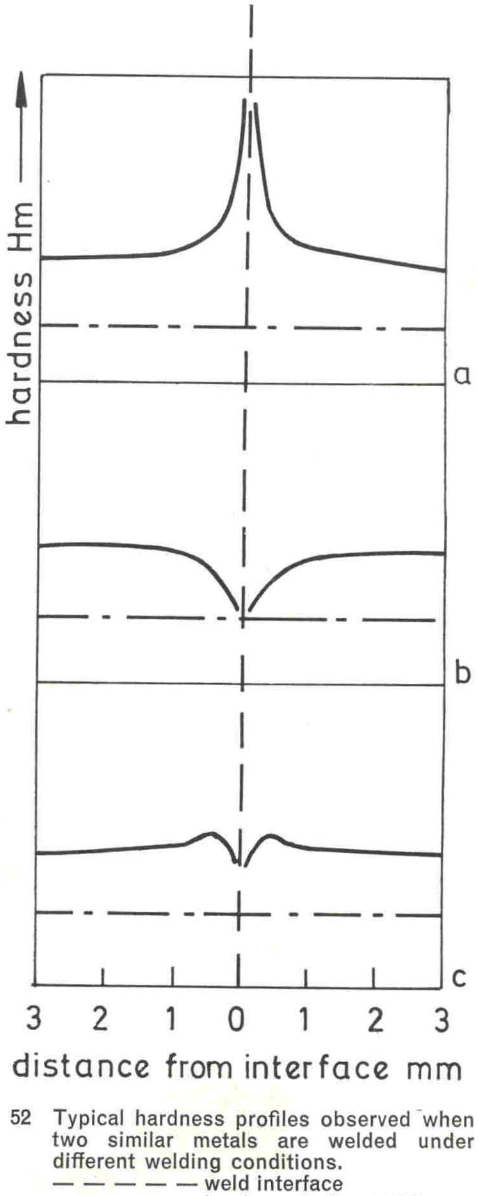
[Courtesy 'Nature'.

49 Composite of tungsten wires in copper matrix. × 8. (*Jarvis and Slate.*[63])

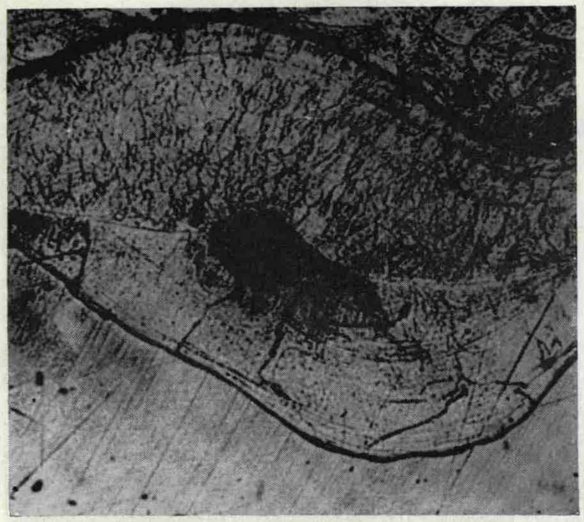


50 Carbon replica of vortex in Fig. 14. × 6 000.

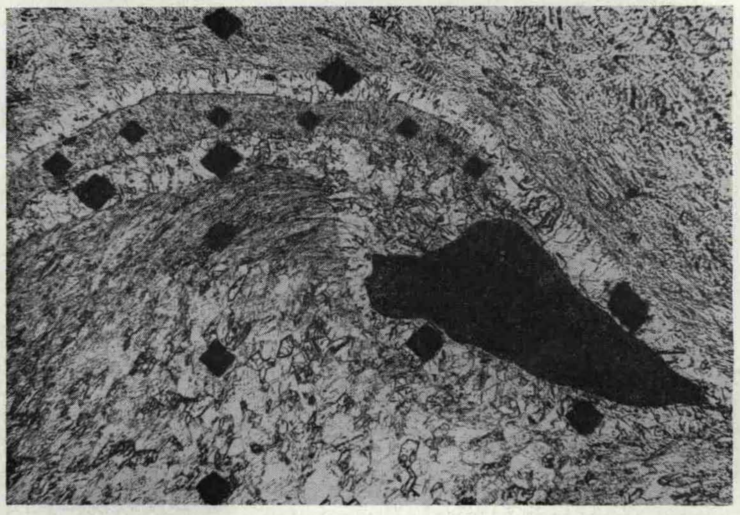
51 Carbon replica of solid-phase bond in Fig. 14. × 1200.



52 Typical hardness profiles observed when two similar metals are welded under different welding conditions.
— — — — — weld interface
— - — - — hardness before welding
———— hardness after welding



[*Courtesy Weld. Research Council.*
53 Solidification cavity in copper-to-nickel bond. × 280. (*Holtzman and Cowan.*[21])



55 Explosive weld in titanium. × 170.

in nature (Fig. 54). Philipchuk[7] has also reported the presence of hard, white layers in welds in a low-alloy steel and in titanium. Lucas and Williams[37] noted two distinctly different types of resolidification structure in a titanium/titanium weld. As shown in Fig. 55, one appears to be martensitic with a hardness of ~ 550 Hm, while the dark-etching region has a hardness of 850 Hm. These authors suggested that these pockets might have resulted from the entrainment of air or surface oxides in the molten vortices, as indicated in Fig. 17, followed by rapid cooling. Clear evidence of surface-oxide entrainment in aluminium/aluminium welds has been reported by Davenport[11] and by Murdie and Blankenburgs.[67] Zones of high hardness in welds between tantalum plates have been observed by Addison.[60]

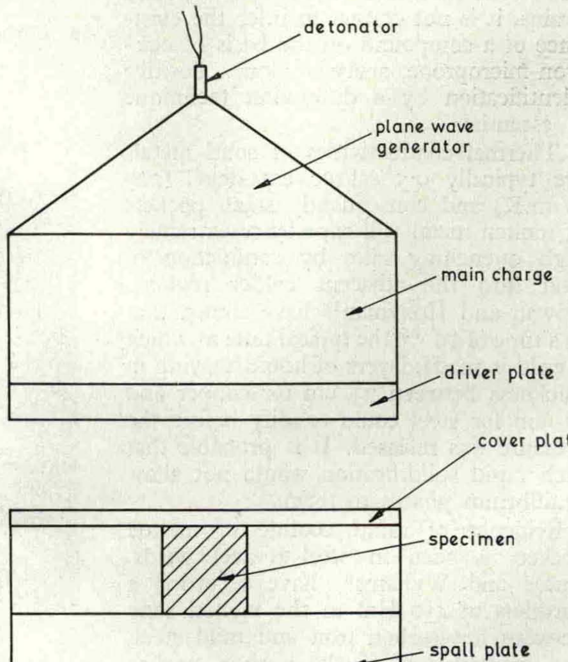
4. Effects of shock waves in welding

On detonating the explosive charge, the flyer plate experiences progressively along its length an oblique stress wave which reverberates within the plate. The compressive component of stress normal to the plate surface is reflected as a tension wave from the lower surface. Consequently, the plate is accelerated downwards in a series of steps. Duvall and Erkman[78] have shown that 90% of the terminal velocity is reached after three compressive waves have passed through the plate. When the flyer plate impacts the parent plate, further stress waves are generated in both plates.

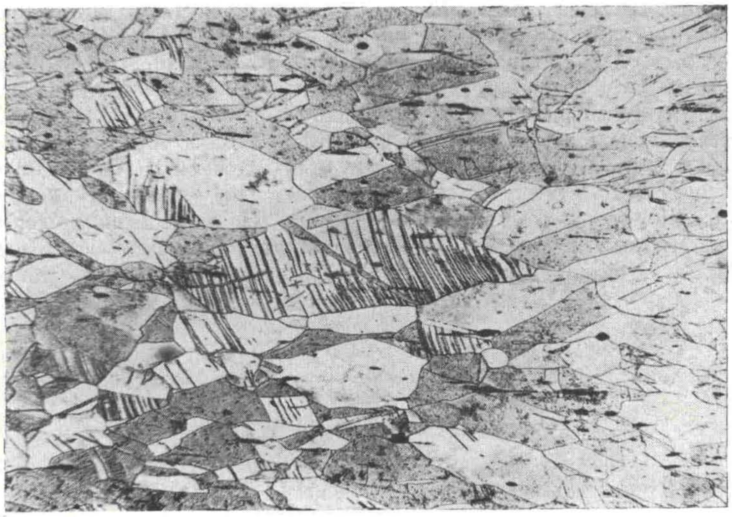
Much work has been reported on the effects of shock waves [e.g. 79-92]. Experimental arrangements used in shock-wave studies are shown in Fig. 56; they are designed to impart a plane shock wave with a peak pressure of 15–9000 kbar[93] to the specimen, depending on the explosive charge. However, in explosive welding the peak pressure in the oblique shock wave rarely exceeds 200 kbar.[28] Consequently, it might be expected that structural changes in explosively welded components would be similar to, but less severe than, those observed in shock experiments; reports of their presence have not appeared extensively in the literature. The heat generated at the interface may further modify the structure after the shock waves have decayed.

Mechanical twinning is frequently observed in explosive welds, not only in b.c.c

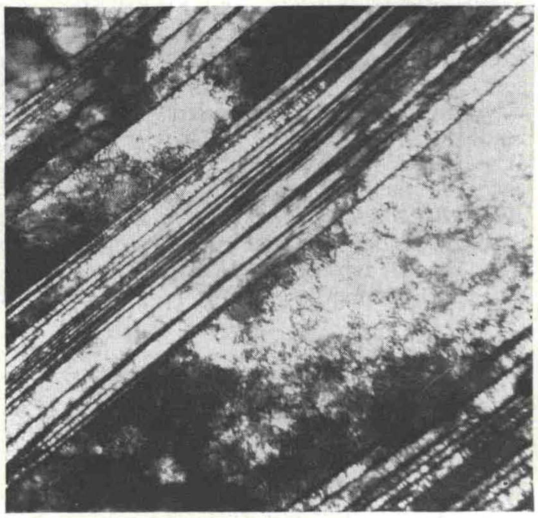
54 Carbon replica of vortex of a weld in low-carbon steel. × 850.



56 Arrangement for plane-shock-wave experiments. ▷



57 Mechanical twins in explosively welded copper. × 200.



58 Microtwinning in welded copper. Transmission micrograph. × 60 000.

metals but also in f.c.c. metals of low stacking-fault energy. Smith,[80] Trueb,[66] Lucas *et al.*,[28,37] and Brillhart *et al.*[81] have reported macrotwinning and microtwinning in copper, the lowest pressure quoted for twinning being 75 kbar.[81] Figures 57 and 58 are typical of twinning in copper. Pressures of 350 kbar are required to induce twinning in nickel,[94] and it is unlikely that such pressures would occur in normal welding practice.

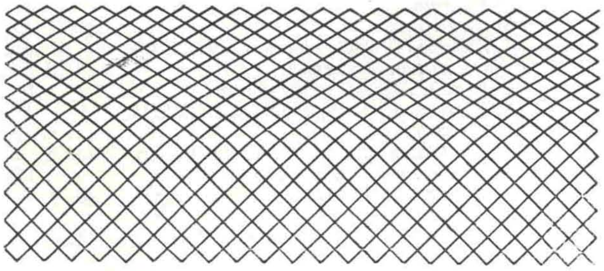
In addition to mechanical twinning, ferritic iron shows evidence of a reversible phase change giving rise to the shocked structure shown in Fig. 59. Smith[80] noted the similarity to carbonless martensite, and the structure has been shown[95] to result from the reversible transition b.c.c. α-ferrite $\rightarrow$ h.c.p. ε-martensite which occurs at pressures $>$ 130 kbar. Austenitic stainless steel undergoes permanent transformation by shock waves to form both b.c.c. and h.c.p. martensites.[28,84]

The useful hardening effect of shock waves in metals has been known for many years. Hardness increases normally attained only after large plastic deformation by conventional metal-working processes have been obtained with very little deformation by shock-hardening. Probably the best-known commercial application is the surface-hardening of Hadfield steel for use in railway points and crusher jaws, &c.[82]

Slip occurs during shock deformation, though in general the slip lines produced are finer and more closely spaced than those observed after slow deformation.[79] Smith[80] has proposed a model to represent the passage of a compressive shock front in a metal (Fig. 60). Such a model is completely reversible on passage of a tensile shock wave. However, the large line and point-defect densities found by various workers,[28,64,66] together with the hardening effects of internally reflected shock waves, clearly indicate that this reversible model is an over-simplification of the atomic arrangement in the shock front.

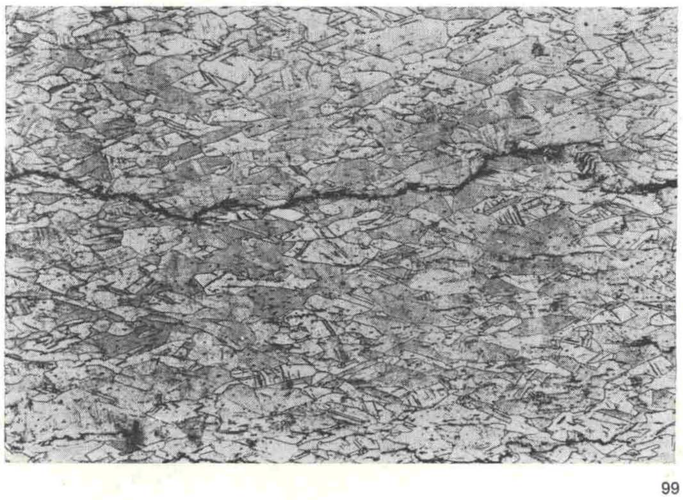
The effects of shock waves on various properties of metals have been summarised by Rowden[88] and by Holtzman and Cowan.[21] Effects similar to those associated with increased strength by conven-

59 Shocked zone in iron. × 80.



[*Courtesy Amer. Inst. Min. Met. Eng.*

60 Uniaxial distortion of the lattice. (*C. S. Smith.*[80])



61 Spalling in explosively welded copper. × 85.

tional work-hardening, i.e. lower ductility, greater notch-sensitivity, and poorer corrosion-resistance, appear to result from explosive-hardening. However, there is some evidence that the effects of shock waves in metals can be annealed out more readily than is normally the case.[37,70,88] It is useful to note that, provided that excessive melting and thus heating are avoided at the interface, explosive welding is able to weld metals in the heat-treated or work-hardened conditions without loss of mechanical strength.[23,57]

A further effect of shock waves in explosive welding is spalling, which is caused by the reflected tension wave. While this feature is not often observed in normal welding conditions, since only moderate explosive-charge mass/flyer-plate mass ratios are used, nevertheless instances have been reported[37,75] and a typical example is shown in Fig. 61. Such failures are more likely with high-detonation-velocity explosives and with materials with planes of weakness parallel to the surface of either plate.

Acknowledgements

This review would have been impossible without the assistance of many people. In particular, the authors would like to thank their collaborators Dr. A. S. Bahrani, Dr. V. Shribman, Mr. W. Lucas, Mr. S. K. Banerjee, and Mr. K. Wylie, whose data they have used extensively. They would also like to take this opportunity to acknowledge that the work from Queen's University reported here has been made possible only through generous grants from the Science Research Council.

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