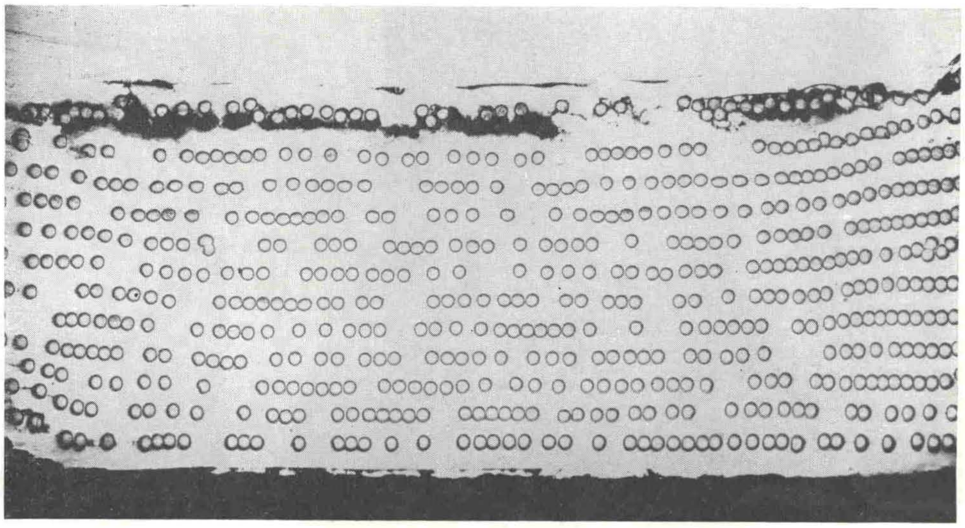
suitable third metal as a thin sheet between the weld plates. Boes[13] and Rosenstiel *et al.*[76] also referred to the use of a third-metal layer electroplated to one weld component as a means of avoiding the formation of brittle intermetallics between aluminium and stainless steel.

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.

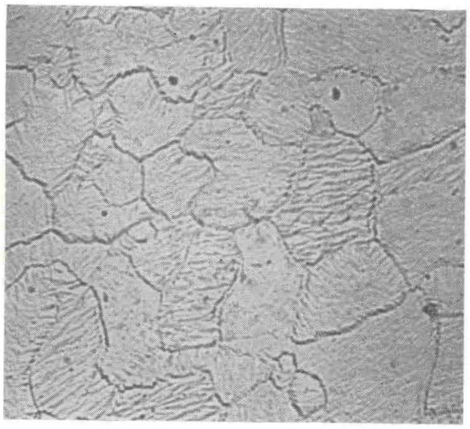
Thermal conductivities of solid metals are typically 0·5 cal/sec cm degC (209 W/m.K) and consequently small pockets of molten metal will experience extremely high quenching rates by conduction of heat into the adjacent colder regions. Cowan and Holtzman[19] have shown that in a time of $10^{-5}$s, the 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



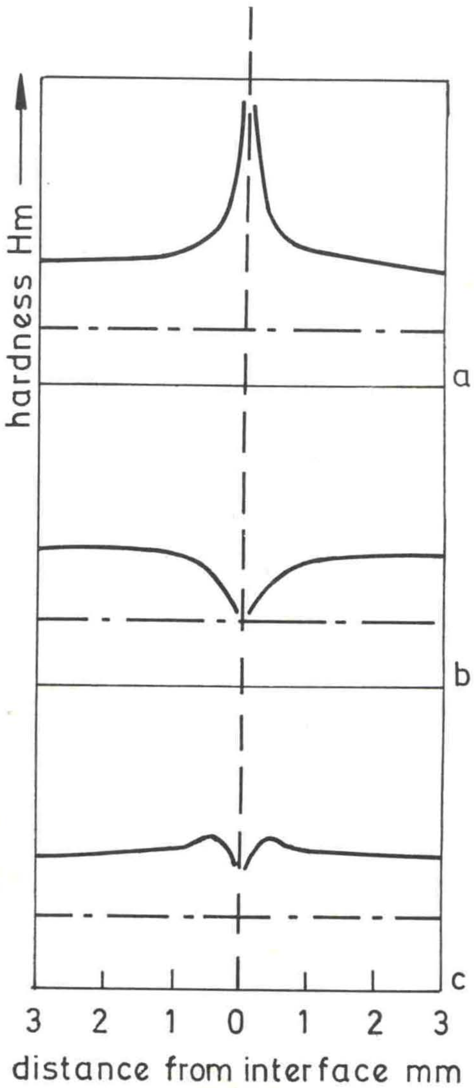
[Courtesy 'Nature'.

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

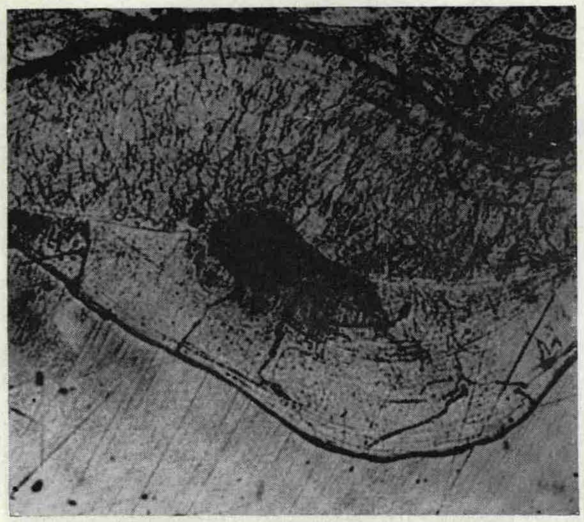


50 Carbon replica of vortex in Fig. 14. × 6 000.

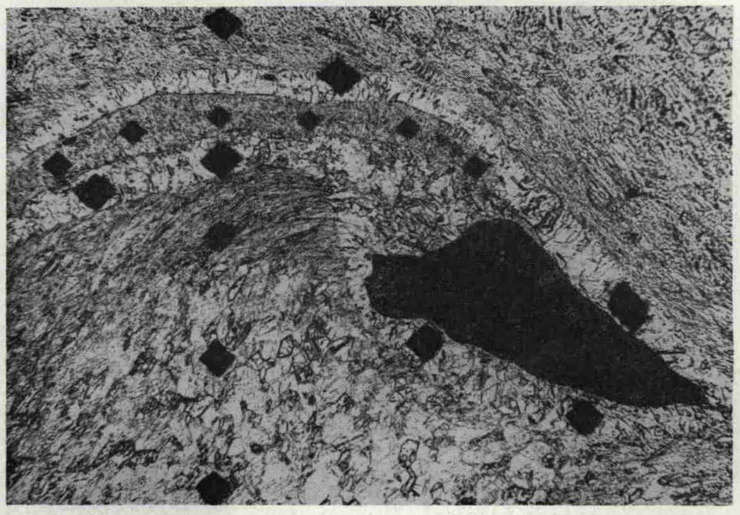
51 Carbon replica of solid-phase bond in Fig. 14. × 1200.




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.

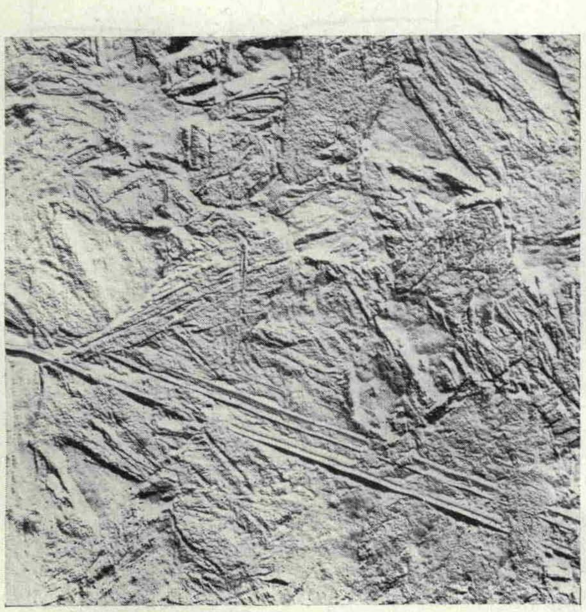
in nature (Fig. 54). Philipchuk[7] has also reported the presence of hard, white layers in welds in a low-alloy steel and in titanium. Lucas and Williams[37] noted two distinctly different types of resolidification structure in a titanium/titanium weld. As shown in Fig. 55, one appears to be martensitic 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

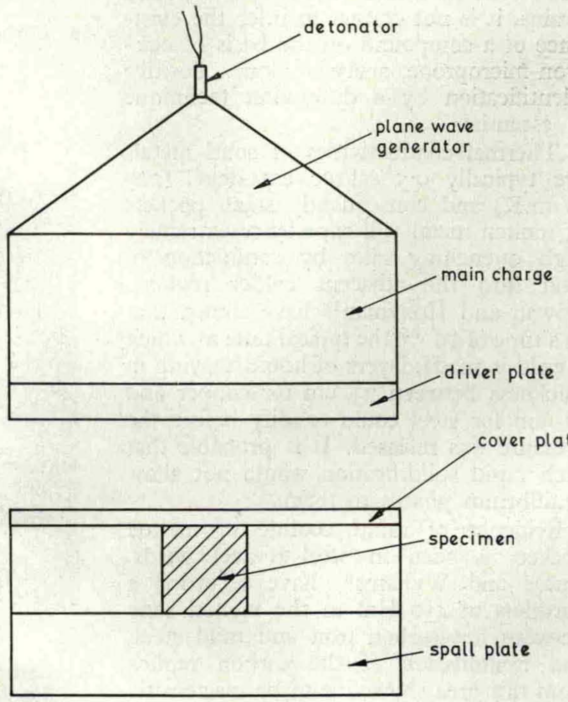
On detonating the explosive charge, the flyer plate experiences progressively along its length an oblique stress wave which reverberates within the plate. The compressive component of stress normal to the plate surface is reflected as a tension wave from the lower surface. Consequently, the plate is 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. ▷