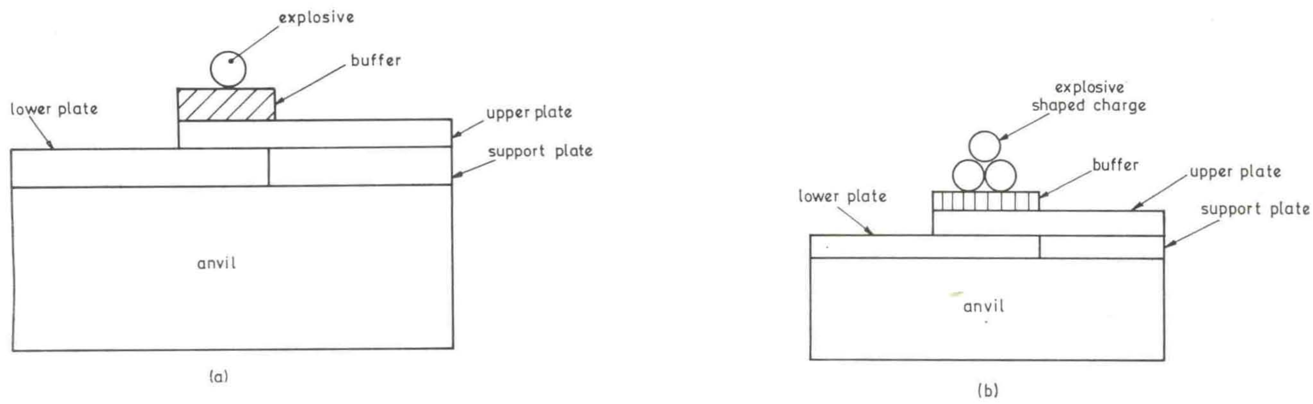
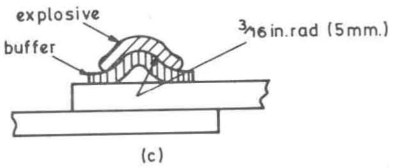




44 Shaped charge used for welding of 1/16 in-(1·6 mm) thick plates.

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.

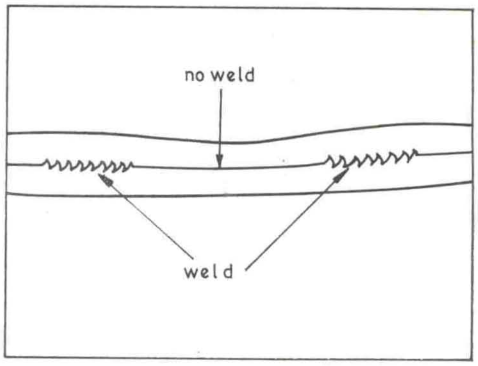
Thin foils taken from positions adjacent to the interface in copper/copper welds have shown high dislocation densities of the order of 10^{11} cm^{-2} and intense microtwinning.[28,37,65,66] Trueb[66] succeeded in producing thin foils from sections normal to the interface between brass/copper and 1070/1008 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.

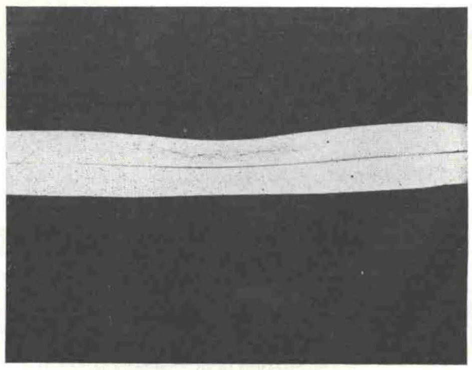
Referring to microhardness values across solid-phase bond interfaces, three basic types of behaviour have been noted; these are shown in Fig. 52. It is clear from Fig. 52(a) that, in addition to shock-hardening, there is localised interfacial work-hardening due to severe plastic flow in the weld zone.[60,65,69–72] 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

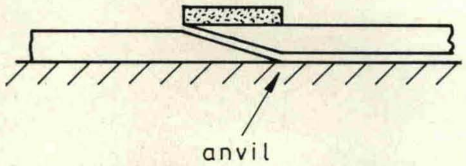


(a)

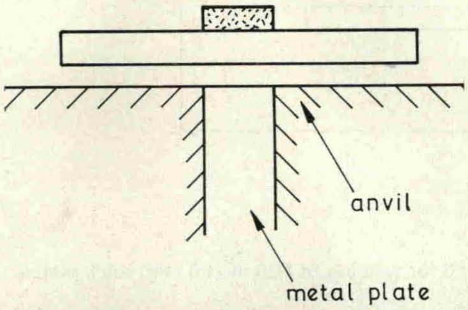


(b)

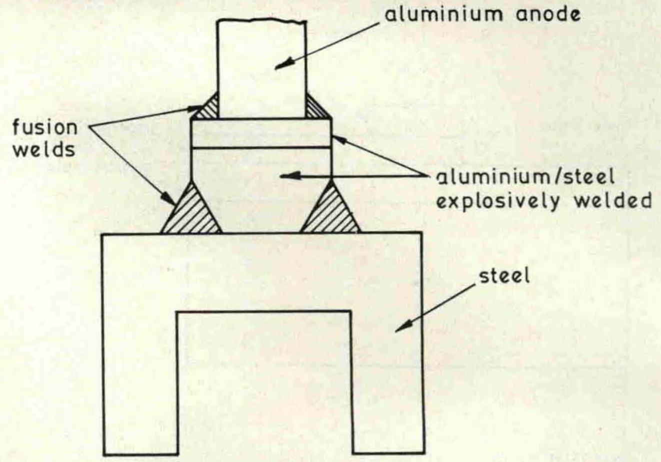
45 Seam weld in brass sheet made with *Cordtex*. (a) Form of interface under the line charge; (b) micrograph of interface in the region of the line charge. × 1¼.



[*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