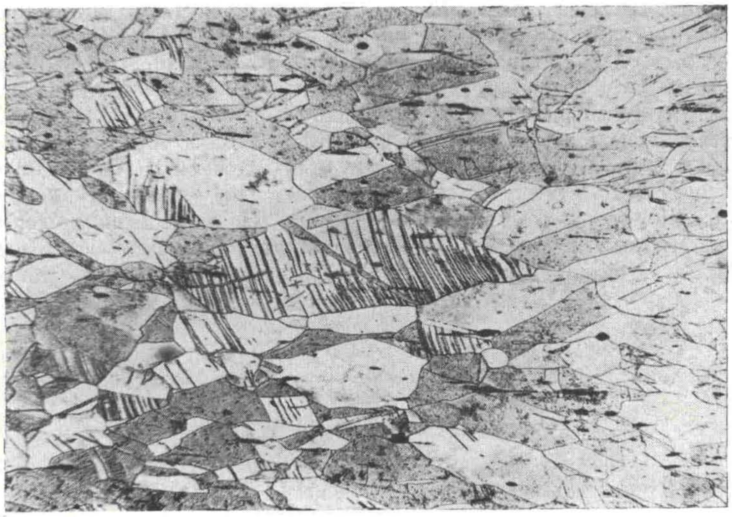
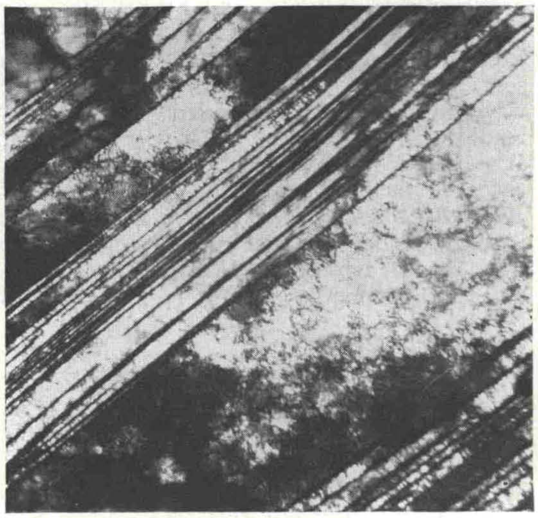


57 Mechanical twins in explosively welded copper. × 200.



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 → 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]

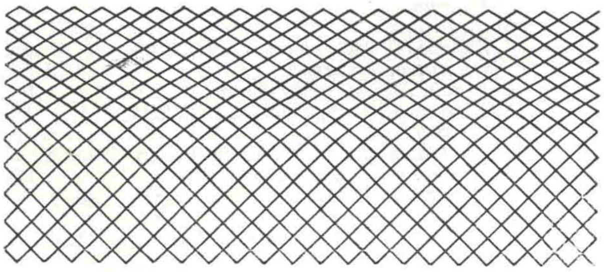
The useful hardening effect of shock waves in metals has been known for many years. Hardness increases normally attained only after large plastic deformation by conventional metal-working processes have been obtained with very little deformation by shock-hardening. Probably the best-known commercial 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.

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