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]

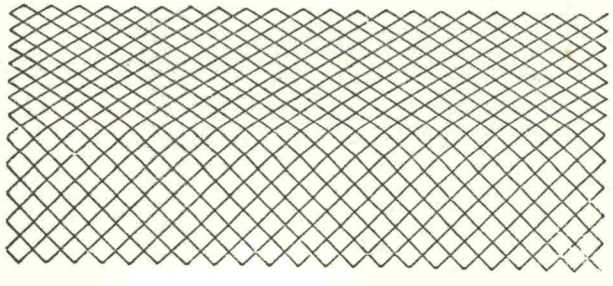
Slip occurs during shock deformation, though in general the slip lines produced are finer and more closely spaced than those observed after slow deformation.[79] Smith[80] has proposed a model to represent the passage of a compressive shock front in a metal (Fig. 60). Such a model is completely reversible 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.