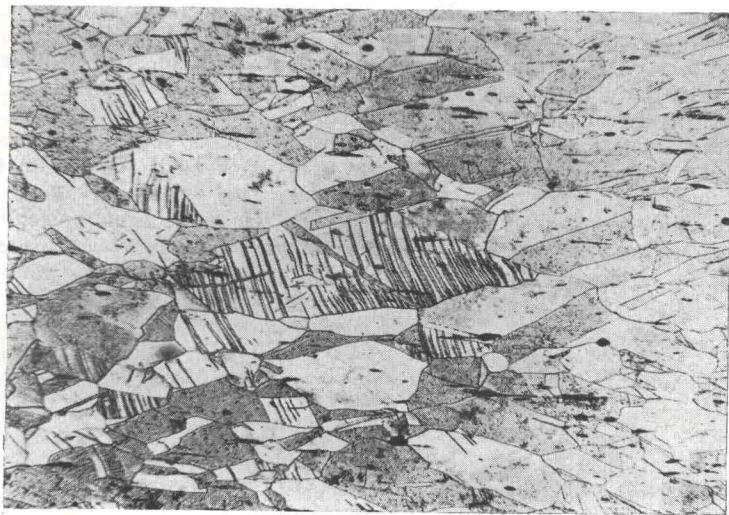
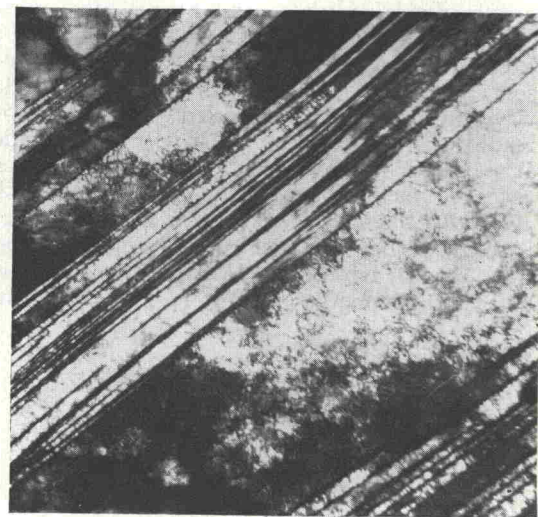




57 Mechanical twins in explosively welded copper. $\times 200$.



58 Microtwinning in welded copper. Transmission micrograph. $\times 60\,000$.

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. Smith⁸⁰ noted the similarity to carbonless martensite, and the structure has been shown⁹⁵ 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 Smith⁸⁰ 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.

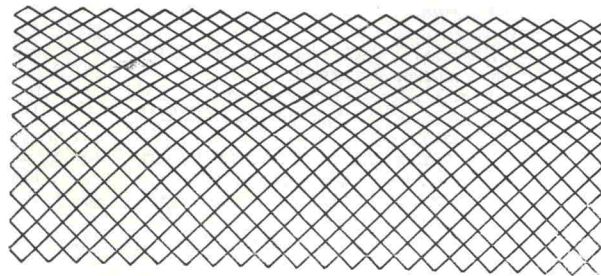
The effects of shock waves on various properties of metals have been summarised by Rowden⁸⁸ and by Holtzman and Cowan.²¹ Effects similar to those associated with increased strength by conven-



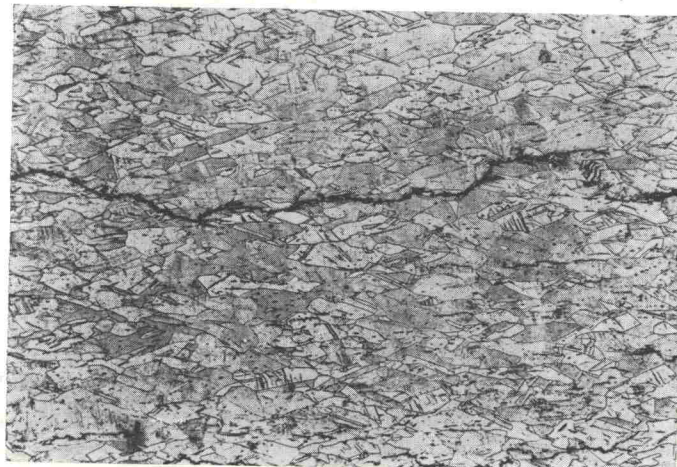
59 Shocked zone in iron. $\times 80$.

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

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



61 Spalling in explosively welded copper. $\times 85$.



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}

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