Table 3.7
Recent investigations of residual metallurgical effects of shock loading

Material, Reference	Peak pressure, p GPa	Stress pulse duration, Δt μs	Remarks
Copper			
Hooker et al. [71H5]	100	0.7	Elongated dislocation cells, 0–5° misorientation, no twins
Higgins [71H3]	43.3	1.0	Cube-oriented samples develop well-defined subgrains, recrystallize on annealing
Chojnowski and Cahn [73C6]	15.5, 41.0	2.0	Annealing studies correlated to hardness and microstructure
Dietrich and Greenhut [73D3]	5.0–10.0	—	Annealing studies correlated to microstructure
Kingman [73K2]	3.0–14.0	—	Introduces X-ray topography as a probe of shock-induced microstructure
Chang et al. [75C1]	0.2–8.5	—	Shock-induced decreases of 1–7% in Young's modulus
Teslenko [77T1]	10.0–31.0	—	X-ray line broadening and hardness
Murr [78M8]	5.5–34.5	2.0	Dislocation structure correlated to mechanical properties
Copper - 1.9% beryllium			
Nordstrom et al. [75N3]	10.0–50.0	0.66	Microstructure and thermomechanical properties
Copper - 8.6% germanium			
Mikkola and coworkers [73B1, 76M1, 78L1, 78W4]	1.6–47.5	0.004–3.5	Broad investigation, recently emphasizing hardening mechanisms
Aluminum alloy 2024			
Lee and Ma [78L2]	0.15–1.1	—	Shock-induced decreases in Young's modulus
Aluminum - 3.85% copper			
Stein [75S3]	1.4	0.85	Precipitation phenomena considered
Nickel			
Murr and coworkers [75M2, 78M8, 78M9]	8.0–46.0	0.5–6.0	Microstructure, stored energy, hardness, and strength quantitatively related to p, Δt
Meyers [77M4]	20.0	1.2–10.1	Work softening in static tension after shock loading
Teslenko [77T1]	10.0–36.0	—	X-ray line broadening and hardness
Chromel A and Inconel 600			
Murr and Huang [75M2]	25.0	0.5–6.0	Dislocation and twin densities, and hardness correlated to t_1, Δt
Inconel 718			
Meyers and Orava [76M2]	51.0	—	Effect of shock on thermomechanical behavior
Stainless steel 304			
Murr and coworkers [75M3, 78M10]	15.0–45.0	0.5–6.0	Formation of twin faults, bct and hcp phases correlated to t_1, Δt
Kestenbach and Meyers [76K1]	10.0	2.8	Microstructural changes correlated to grain size
Hadfield steels			
Dorph [77D4]	—	—	Shock hardening mechanisms investigated
Iron, mild steel			
Bouchard and Claisse [73B2]	—	—	Effect or ordering by Al alloying and heat treatment on twinning
Huo and Ma [75H2, 75H3]	10.0, 30.0	—	X-ray line broadening
Ganin et al. [78G1]	—	—	Hardness related to twin spacing and dislocation density
β-Titanium alloy			
Rack [76R1, 78R2]	2.0–26.0	1.8	Strength correlated to microstructure
Molybdenum			
Murr and coworkers [76M6, 78W3, 78M10]	14.0–35.0	0.5–8.0	Direct observation of vacancies, vacancy clusters. Twinning investigated
Beryllium			
Galbraith and Murr [75G1]	0.9	—	Shock-induced microstructures observed

conducted in apparatus subject to careful analysis (for an example of such an analysis, see [72S3]), but experience shows that the use of a well-designed and carefully fabricated experimental assembly incorporating suitable momentum-trapping plates permits satisfactory recovery for most purposes [64M1, 67R1, 77K4].

In early investigations, recovered samples were subjected to mechanical testing and examination by optical microscopy. These probes have subsequently been augmented by observations of X-ray line broadening, energy release and resistivity changes during annealing, magnetic effects, etc. Examination is now predominantly by transmission electron microscopy.

Except for effects of certain phase transformations, the metallurgical changes produced by shock loading involve the same general features as those produced by other means, but they appear at much lower levels of deformation. Some effects arising as a result of the high rates of shear present in shocks can be produced by quasi-static deformation only at very low temperatures.

Recovery observations of bcc metals are dominated by those of iron [65A3, 66Z2, 73L1], which develops dense distributions of dislocations and twins easily and profusely, although it has recently been shown that twinning is suppressed when the imposed shear can be accommodated by motion of a sufficient number of dislocations [72R1]. Murr and coworkers have recently investigated another bcc metal, molybdenum, in some detail [76M5, 76M6, 78W3, 78M10].

Most recent investigations of the residual effects of shock compression have dealt with fcc metals and alloys. Deformation structures produced in these materials are strongly correlated to their stacking fault energy, with dense planar arrays of stacking faults and dislocations predominating in materials in which this parameter has a low value and dislocation cell structures developing when the stacking fault energy is large. The dislocation cell structure that develops in these materials becomes increasingly dense and of finer scale with increases in the applied stress. Twins are produced by stress pulses exceeding some threshold of amplitude and duration and continue to grow for the duration of stress application. They eventually become a prominent feature in the structure of even such a high stacking-fault-energy material as nickel. Some observations suggest that twins form when the dislocation cell size is reduced to some minimum value of the order of 0.15 μm. Various observers have reported misalignments of the cells, indicating grain rotation during the course of deformation.

Copper has been subjected to detailed examination on several occasions since the early work of Smith, with several rather comprehensive studies having been reported [66D3, 67B3, 73L1]. Murr [78M8] has recently summarized observations of the relationship between dislocation arrangements and work hardening. Nickel has also been the subject of considerable investigation and quantitative relationships among dislocation parameters, mechanical properties, and history of applied stress have recently been proposed and interpreted by Murr and Kuhlmann-Wilsdorf [78M9] and Murr [78M8].

Studies of electrical resistivity (see section 4.10), and electron spin resonance [64G1] have been interpreted to mean that point defects develop in high concentrations in shock-loaded samples. Observations by transmission electron microscopy have disclosed high concentrations of dislocation loops resulting from aggregation of vacancies and interstitials, but it is only recently that direct observations have been made of both these dislocation loops and individual vacancies [76M6]. This investigation, conducted on molybdenum, shows an increase in total density from $5 \times 10^{13}/\mathrm{m}^3$ loops of 57 Å average diameter in the initial annealed material to 4×10^{18} and $7 \times 10^{18}/\mathrm{m}^3$ loops of average diameter 104 and 157 Å, respectively, in material loaded to 15 and 25 GPa for 2 μs. At the lower stress 75 per cent of the observed loops were collapsed vacancy