decompression wave in aluminum alloy 2024 subjected to 10 and 17 GPa shocks. Curran later concluded [65C4] that the apparent high strength was an effect of the high rate of inelastic deformation rather than the compression, but Erkman and Christensen [67E1] were able to explain wave profiles obtained in similar circumstances on the basis of a rate-independent model. This issue has been investigated on a number of subsequent occasions, but remains to be resolved [74H1, 77L2].

When an observation of an elastic-plastic wave profile is carried through to the decompression phase, the observed pulse shapes deviate markedly from the ideal elastic-plastic stress pulse of fig. 3.4b. In particular, the distinction between the elastic and plastic decompression waves is so blurred as to suggest that the elastic range itself is poorly defined. Examination of a broad range of published compression waveforms reveals that they approach the ideal elastic-plastic form more closely as the peak compression increases. The approach of the decompression waveform to the ideal is correspondingly improved. When decompression from pressures of a few GPa is studied in copper and aluminum alloy 6061-T6, it is found that the elastic decompression wave overtakes the plastic compression wave prematurely because of the disperse structure of this latter wave. At pressures of about 10 GPa this plastic wave approximates a shock much more closely, and overtaking occurs at the time predicted by the elastic-plastic model [71C3, 71C4]. The decompression profile observed under these conditions still fails to exhibit a well-defined elastic-plastic form, although some structure is certainly evident.

For many years it has been assumed that a properly implemented model based either on dislocation-mechanical concepts or on their continuum-mechanical equivalents would describe both compression and decompression waveform observations. This objective has been accomplished in several instances [73R1, 74H1], but the models are quite complex and recent time-resolved wave profile measurements show considerable detail not yet explained. In recent years evidence has been accumulating to suggest that inhomogeneous mechanisms must be taken into account in explaining at least some of the observed deformation phenomena. This need is most apparent for the case of nonmetallic materials, as is discussed in section 3.4, but investigations of incremental compression or decompression of shock-compressed metals suggest that the effect may be influential for these materials as well [77L2, 78A5].

Strong solids. An important but generally unrecognized property of brittle solids is their possession of unusually large Hugoniot elastic limits. In a shock-compression experiment, strain is imposed very rapidly and gives rise to high pressure as well as a large shear stress. Under these conditions crack propagation may be inhibited or may not occur with sufficient rapidity to prevent shear stresses from exceeding the inherent strength of the material. Data summarized in [71G3] show that some solids exhibit strength ranging from 1 to almost 10 per cent of their shear modulus. More recent data on the response of several strong polycrystalline solids to shock loading are reported by Gust et al. [73G6], while Pope and Johnson [75P1] have reported high strengths for c-cut beryllium monocrystals which they attributed to tertiary slip. The strains to failure for a number of strong solids have been summarized in table 3.1. It appears that such data could profitably be used to study the inherent shear strength of solids.

3.4. Heterogeneous yielding and reduction of shear strength

Evidence that heterogeneous yielding is a dominant feature in the shock compression of certain solids is largely indirect and the process is not yet subject to quantitative analysis. Nevertheless, substantial anomalies in strengths observed upon loading just above the Hugoniot elastic limits for quartz, sapphire, magnesium oxide and lithium niobate based on conventional models of yield and plastic flow require that unique deformation modes be invoked. A yield process in which the local dissipation of the elastic shear strain energy leads to high local temperatures appears to have the correct semi-quantitative features to explain the strength anomalies. Such heterogeneous yielding has been ascribed to brittle solids but exceptions observed for brittle solids such as monocrystalline germanium and polycrystalline Al_2O_3 blur that distinction. Based on the present review of experimental observations and theory, it appears that those solids which can be expected to undergo heterogeneous yielding are perhaps best described as *strong solids with low thermal diffusivity*.

The present phenomenon of heterogeneous yielding is thought to be an adiabatic shear process similar to the shear banding phenomenon observed in metal deformation under large rapid shear loading (see, e.g., [78W1]). Heterogeneous yielding is distinguished from the more general phenomenon by the unique feature that it occurs within the first few nanoseconds or tens of nanoseconds after shock loading and is controlled by inherent strength and thermophysical material properties.

Table 3.5 summarizes the principal developments in studies of reductions in shear strength. The first observations of the effect resulted from both electrical and mechanical measurements on α-quartz by Neilson et al. [62N2], Wackerle [62W1], and Fowles [61F2, 67F1]. In 1971 there were

Table 3.5
Studies of reduction of shear strength

Material	Date	Measurement	Strength reduction?	Remarks	Reference
α quartz	1961	piezoelectric	yes	loss of strength	Neilson et al. [62N2]
α quartz	1961	luminescence	—	linear features	Neilson et al. [62N2]
α quartz	1962	$U - u$	yes	loss of strength	Wackerle [62W1]
α quartz	1962	$U - u$	yes	loss of strength	Fowles [61F3, 67F1]
MgO	1966	$U - u$	yes?	possible loss	Ahrens [66A1]
Al_2O_3 ceramics	1968	$U - u$	no	strength retained	Ahrens et al. [68A1]
B_4C ceramics	1971	$U - u$	yes	loss of strength	Gust and Royce [71G5]
BeO ceramic	1971	$U - u$	yes?	5.6% porosity	Gust and Royce [71G5]
Al_2O_3 ceramics	1971	$U - u$	no	1 to 6.6% porosity	Gust and Royce [71G5]
α Al_2O_3	1971	$U - u$	yes	some strength retained*	Graham and Brooks [71G3]
α Al_2O_3	1973	optical absorption	yes	loss of strength	Gaffney and Ahrens [73G1]
α quartz	1974	recovery	—	observed slip bands*	Ananin et al. [74A2]
α quartz	1974	piezoelectric	yes	some strength retained*	Graham [74G2]
quartzite	1975	decompression	yes	first thermal model*	Grady et al. [75G3]
α Al_2O_3	1976	decompression	yes	partial strength recovery	Bless and Ahrens [76B6]
Tungsten	1976	t_1 vs. u	yes	small effect	Dandekar [76D1]
MgO, (100)	1977	$U - u$, decompression	yes	loss of strength*	Grady [77G2]
MgO, polyxtal	1977	lateral release	no	slow strength reduction	Meier and Ahrens [77M2]
Theory	1977	theory	yes	explicit thermal model*	Grady [77G2]
Glass	1978	longitudinal and normal stress	yes	stress anisotropy	Kanel' et al. [78K1]
$LiNbO_3$	1979	$U - u$	yes	strength reduction*	Stanton and Graham [79S2]
$LiTaO_3$	1979	$U - u$	yes	strength reduction*	Stanton and Graham [79S2]
α Al_2O_3	1979	optical absorption	yes	loss of strength	Goto et al. [79G1]

(See also review of geophysical phenomena resulting from meteorite impacts Chao [67C2] and Stöffler [72S4].)

* These papers review status of knowledge and propose mechanisms.