a sufficient number of observations to begin to speculate on general mechanisms [71G3] and in 1974 and 1975 the present view of heterogeneous yielding came into focus with the papers of Ananin et al. [74A2], Graham [74G2], and Grady [75G3]. Grady [75G3] first explicitly treated localized temperature distributions and later [77G2] extended these analyses to effects on phase transitions. These time-dependent temperature models also explain discrepancies between strengths determined in shock-compression and decompression measurements. Recent attempts at direct stress anisotropy measurements apparently indicate a loss of strength in glass [78K1].

The only direct evidence for the presence of localized melting upon yielding has been presented in a thorough investigation by Ananin et al. [74A2]. They recovered samples of X-cut quartz shock loaded above the Hugoniot elastic limit and below the phase transition at 14.5 GPa and observed that the recovered sample was composed of blocks of α-quartz surrounded by layers of quartz glass. Although similar observations have been made in naturally- and artificially-shocked quartz, prior work was complicated by stresses above the phase transitions and the explicit association with yielding had not been made. (See the review of petrographic features in quartz minerals by Stöffler [72S4], and a typical controlled shock loading by Müller and Defourneaux [68M4].) Recent shock measurements on lithium niobate in which hot or melted regions have a significantly different bulk modulus show major anomalies in the pressure derivative of bulk modulus which can partially be explained by heterogeneous yielding [79S2].

Grady [77G2] showed that the normal temperature distribution due to a local dissipation of shear strain energy could be conveniently expressed as

$$\theta = \theta_s + \left[Q/\sqrt{4\pi\chi t}\right] \exp\left(-h^2/4\chi\right) \tag{3.14}$$

where θ is the temperature, θ_s is the temperature resulting from isentropic homogeneous compression, $Q = \varepsilon/\rho C$ where ε is the thermal energy per unit area deposited at the position $h = 0$, ρ is the mass density, C the specific heat, and χ is the thermal diffusivity.

Solutions for typical temperature distributions at various times indicate the dominant role of thermal diffusivity in reducing local temperatures. If diffusivity is high, the temperatures may be reduced to background levels before melting or softening can occur. If diffusivity is low, high temperatures may persist for times appropriate for shock-compression experiments. Thermal time constants for low diffusivity materials are approximately 1 μs for distances of a few microns which are typical spacings between slipped regions in quartz.

The thermal energy deposited will depend directly on the elastic shear energy which may be roughly approximated by the area on the stress volume curve between the elastic compression and isotropic compression curve at constant stress. The density of slip bands must then be known to estimate the thermal energy per unit area. This latter quantity is unknown but can be estimated to affect 1 to 10 per cent of the sample volume based on observations of recovered samples by Ananin et al. [74A2]. The spacing between slipped regions is expected to vary from material to material and with magnitude of the loading and is likely to vary throughout a given sample.

In order to delineate the conditions under which heterogeneous yielding will occur, the results of various investigations of yielding and reduction of shear strength are summarized in fig. 3.5, which shows combinations of elastic shear strain energy (not thermal energy) and thermal diffusivity for which reduction of strength upon yielding is or is not observed. As expected from eq. (3.14), the figure shows that strong solids with low thermal diffusivity show reductions in strength in almost every case. Although there are insufficient data to delineate the boundary between
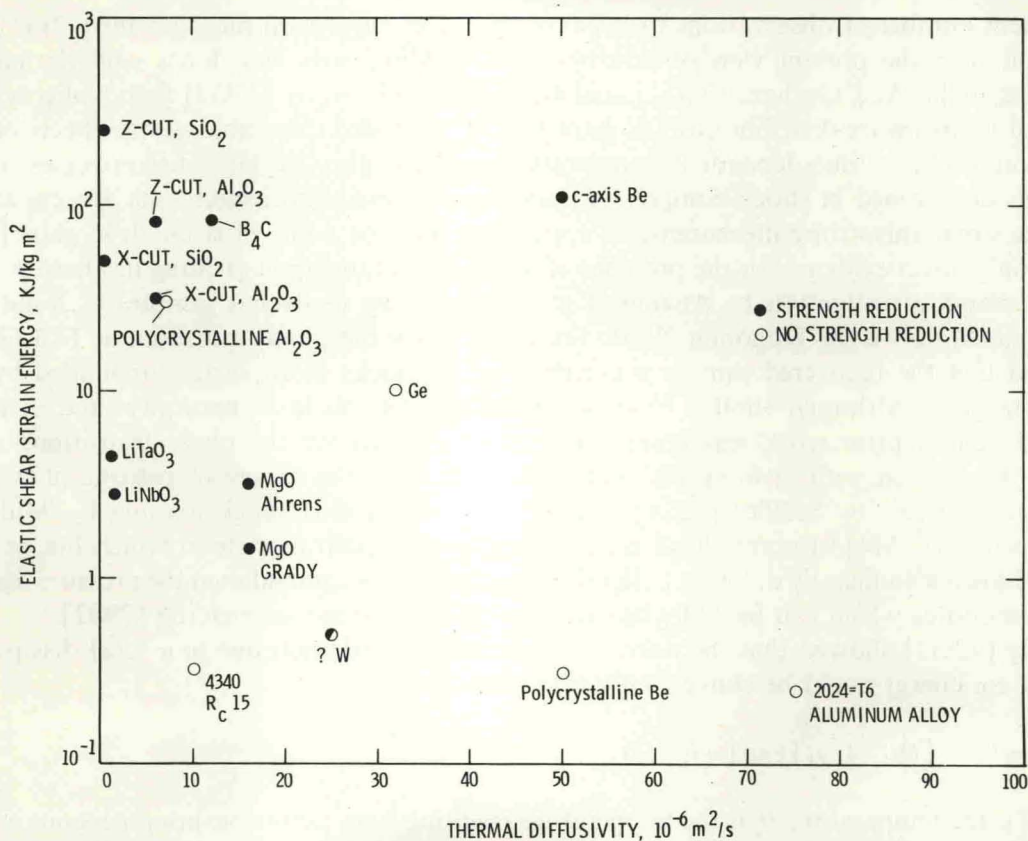
Fig. 3.5. The conditions of elastic shear strain energy and thermal diffusivity for which there is strong evidence for either strength reduction or strength retention are shown for a wide range of materials. Experiments in which complications such as porosity cloud the strength question are not shown. Metals are generally acknowledged to retain a relatively constant shear strength. Data are from sources in table 3.5 except c-axis Be [75P1], Ge [66G1], 4340 steel alloy [65B5] and aluminum alloy [61F2]. The point for tungsten is indicated ambivalently since recent work by Asay and Dandekar [78A4] has shown that strength reduction is relatively gradual. Except for the metal alloys, tungsten and polycrystalline Al_2O_3, the data are for monocrystalline materials.

materials which show strength reduction and those which retain their strength, the figure shows some indication that germanium, beryllium and MgO are close to critical boundaries.

The collected data shown in fig. 3.5 provide qualitative support for explanation of strength reductions in terms of local hot regions resulting from dissipation of elastic shear strain energy. The notable exception is polycrystalline Al_2O_3. Since the yield process is localized on the scale of a few microns, the exception may possibly be the result of impurities at grain boundaries where local thermal diffusivity may be much higher than for the bulk material. Alternately, the poly-crystalline behavior might possibly result from much finer spacing between slip regions. Decompression measurements from states above the Hugoniot elastic limit of polycrystalline MgO [77M2] indicate significant strength. This behavior is consistent with the local heating model since decompression occurs at times for which significant reductions in temperature may be expected.

The consequences of such heterogeneous response to shock loading are profound. Usual assumptions of homogeneous, equilibrium thermodynamic behavior are clearly violated. Local