

Table 4. Shear strengths of shock loaded crystals

| Crystal                        | Structure | $\tau_{\max}^{[a]}$<br>kbar | $C_{44}$<br>kbar | $\tau_{\max}/C_{44}$ | Loss of shear strength    |
|--------------------------------|-----------|-----------------------------|------------------|----------------------|---------------------------|
| SiO <sub>2</sub>               | Trigonal  |                             | 579              |                      |                           |
| Z-cut[24] <sup>[b]</sup>       |           | 62                          |                  | 0.108                | Yes                       |
| X-cut[38]                      |           | 33                          |                  | 0.057                | Yes                       |
| Al <sub>2</sub> O <sub>3</sub> | Trigonal  |                             | 1472             |                      |                           |
| 0° orientation                 |           | 83                          |                  | 0.056                | Yes                       |
| 90° orientation                |           | 72                          |                  | 0.049                | Yes                       |
| 60° orientation                |           | 68                          |                  | 0.046                | Yes                       |
| MgO[46]                        | Cubic     |                             | 1559             |                      | Yes? limited              |
| [100]                          |           | 25                          |                  | 0.016                | shock data                |
| TiO <sub>2</sub> [47]          | Cubic     |                             | 1239             |                      |                           |
| [001]                          |           | 33                          |                  | 0.027                | ?                         |
| [100]                          |           | 12                          |                  | 0.0096               | ?                         |
| Si[44]                         | Cubic     |                             | 796              |                      |                           |
| [100]                          |           | 28                          |                  | 0.035                | ?Yes, possible transition |
| [111]                          |           | 12                          |                  | 0.015                | No                        |
| Ge[111][43]                    | Cubic     | 10                          | 672              | 0.015                | No                        |
| NaCl[45]                       | Cubic     |                             | 128              |                      |                           |
| [111]                          |           | 2.3                         |                  | 0.018                | Yes? one experiment       |
| [110]                          |           | 0.28                        |                  | 0.0022               | No                        |
| [100]                          |           | 0.09                        |                  | 0.0007               | No                        |

[a]  $\tau_{\max}$  is taken to be the maximum observed value of  $\frac{1}{2}(\sigma_x - \sigma_y)$ , where  $\sigma_x$  is the maximum observed HEL value and  $\sigma_y$  is the minimum lateral stress computed from atmospheric pressure elastic constants. The rationale for taking maximum values is based on the likelihood that the lower values are caused by samples of inferior quality due to internal strains or other defects. In anisotropic crystals lateral stresses may vary due to lateral anisotropy. Because of non steady effects these maximum values may relax to lower stress values.

[b] Reference numbers following the various materials indicate the source for the HEL values used to compute  $\tau_{\max}$ .

data for SiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, Ge[43], and Si[44] with limited information available for NaCl[45], MgO[27, 46] and TiO<sub>2</sub>[27, 47]. One immediate conclusion that can be drawn from an examination of the existing data is that not all solids which are brittle at room temperature and atmospheric pressure exhibit loss of shear strength under shock loading. Furthermore, as previously stated, polycrystalline Al<sub>2</sub>O<sub>3</sub>, a brittle solid, responds as an elastic-plastic solid. On the other hand, crystalline Al<sub>2</sub>O<sub>3</sub> and SiO<sub>2</sub> exhibit a substantial loss of shear strength.

Thus the experimental evidence indicates that a general model proposing that brittle materials lose their shear strength when shocked above the HEL is not suitable to predict material response. Definitions of brittle materials as ordinarily posed are based

on crack propagation at stresses less than that necessary to cause slip and inelastic deformation. The large isotropic pressure component of shock experiments will not permit crack propagation; hence, in contrast to static experiments, materials cannot fail by crack propagation and inherent strength properties may be observed in bulk materials.

It appears possible that different shear-failure mechanisms may be encountered in a given crystal shock loaded along different crystallographic axes. If loading is accomplished in a direction which causes no shear on the slip plane, failure cannot be expected by conventional slip mechanisms. Experimental evidence for this is shown in Table 4 where large HEL values are observed in [100] Si and [111] NaCl, while much lower values are observed in other directions. There is

some evidence, admittedly inconclusive, for loss of shear strength in both cases. The [111] NaCl investigation shows one experiment with a wave velocity lower than bulk sound speed. The high pressure [100] Si data show velocities less than bulk sound speed; however, this observation is inconclusive because of the possibility of a phase transition. In any event, the possibility of preferential loss of shear strength in various crystallographic directions in a given crystal should not be overlooked. In fact, it would be highly desirable if various crystals were studied in detail for experimental evidence to examine this question.

The shock compression data[28] on high density polycrystalline  $\text{Al}_2\text{O}_3$  indicate elastic-plastic response and no loss of shear strength. Although at first glance this seems inconsistent with the results of the present investigation, there is no reason that the yield mechanisms of the polycrystal and single crystal should be the same. In fact, the HEL values for various polycrystalline  $\text{Al}_2\text{O}_3$  samples as shown in Table 5, show a marked dependence on porosity of the sample. This indicates that the

Table 5. Hugoniot elastic limits of polycrystalline  $\text{Al}_2\text{O}_3$

| Density<br>$\text{g cm}^{-3}$ | HEL<br>kbar  | Reference |
|-------------------------------|--------------|-----------|
| 3.98                          | $112 \pm 13$ | 28        |
| 3.969                         | 70–136       | 29        |
| 3.92                          | 140          | 49        |
| 3.81                          | $83 \pm 5$   | 28        |
| 3.76                          | 58–72        | 20        |
| 3.72                          | 80           | 49        |

HEL is governed by grain boundary and intergranular effects and that the shear strength of intergranular material is apparently less than that required to exceed the shear strength of the crystallite.

The elastic-plastic response of polycrystalline  $\text{Al}_2\text{O}_3$  and the elastic-isotropic response of single crystal  $\text{Al}_2\text{O}_3$  support the view that a critical shear stress must be exceeded before

a loss of shear strength occurs. Furthermore, this observation indicates that shear strength effects at high pressure are different for polycrystalline and single solids of the same chemical composition.

It seems clear that if slip cannot occur under shock-loading due to an insufficient number of mobile dislocations or due to shear stress of insufficient magnitude on the slip plane, that failure must occur by different mechanisms than ordinarily encountered. The shock data indicate that as the shear stress values approach the theoretical shear stress estimates, substantial loss of shear strength is observed in the high pressure phase. If solids are observed to sustain shear strengths under shock loading which approach or are greater than 0.03 G, a loss of shear strength should be anticipated.

It is perhaps noteworthy that all of the oxides investigated support maximum stress values in excess of 25 kbar and that both of the materials which are known to lose their shear strength are oxides. Since the oxides are known to have elastic properties dependent principally upon the oxygen ion framework [36, 48] the critical shear stress observed for oxides may be a property of the oxygen framework and single crystal oxides are good candidates for materials with large HEL's and a corresponding loss of shear strength.

## 6. SUMMARY AND CONCLUSIONS

The shock compression data for sapphire show that the compressional behavior of sapphire is analogous to quartz in that both solids exhibit large HEL values and both exhibit a substantial loss of shear strength when shocked above the HEL. Sapphire and quartz are best characterized as elastic-isotropic solids and not elastic-plastic solids. These conclusions are based upon observations of: (1) common high pressure compression curves for various HEL values, (2) high pressure shock velocities less than local bulk sound speed, and (3) the volume