Investigation of Single Crystal Silicon (SCSi) Fracture Toughness

The CERN PH-DT group is developing cooling systems that consist in micro-channel embedded in thin silicon plates for dissipating the heat of particles detectors used in high energy physics (HEP) experiments. These devices must be as thin as possible to fulfill experiment requirements, i.e., reducing material thickness crossed by particles. At the same time, increasing the internal pressure higher the heat dissipation but also apply more important mechanical constraints to the system. These two competitive aspects have led to some early prototypes to catastrophic failure. A numerical fracture prediction tool, that rely on fracture mechanics, is being developed for design optimization purpose. This tool obviously requires material properties, such as fracture toughness, which are not well known.

Specimens and Test Procedure

- Selected specimens are single edge v-notched beam (SEVNB).
- Specimens are fabricated in the ISO 5/6 cleanrooms of the EPFL-CMi.
- These specimens are tested in different bending configuration:
  - pure mode I loading is obtained with symmetric 3 and 4 points bending tests,
  - mixed-mode I/II loading is obtained with an asymmetric 4 point bending configuration.
- A bending fixture is designed and machined specifically for these tests on micro-scaled specimens.

Mode I Tests and Results

Pure mode I fracture toughness $K_{IC}$ is calculated from the relation given in the ISO standard for fine ceramic testing (ISO 23146).

$$K_{IC} = \frac{F_{IC}}{\sqrt{Bd}} \left( S_a - S_i \right) \cdot \frac{3\sqrt{\pi}}{2(1-\nu)}W \cdot Y^* \quad Y^* = f_y \left( \frac{a}{W} \right)$$

Where $Y^*$ is a geometry correction factor depending on the notch depth $a$ and the specimen width $W$. A non systematic SEM observations of the fractured specimens revealed that the crack grow may macroscopically along the (110) plane of the crystal, which is not supposed to be the weakest plane, but which is the specimen’s symmetry plane with respect to the notch. However it is yet not proven that the crack is initiated along this plane.

The value of fracture toughness found with this method is:

$$K_{IC} = 1.02 \pm 0.04 \text{ [MPa m}^{1/2} \text{]}$$

The repeatability of these tests was very good. Furthermore, the value presented here is in good agreement with the few values presented in the literature.

Dimensions of the specimens such as the depth $B$, the notch depth $a$ and the bending spans $S_i$ and $S_a$ were varied in order to observe the consistency of the model. Even using variable specimen geometry, and using both 3 and 4 point bending configuration, the standard deviation on all fracture toughness results is less than 5%.

More SEM observations of the fracture planes are required for a better understanding of the crack behavior. As it is shown in magnified view of the notch tip (where the crack is initiated), the crack may oscillate from plane to plane, possibly (111) planes which are supposed to be the weakest (highest density).

Mixed-Mode I/II Tests and Results

The mixed-mode I/II loading is obtained using an asymmetric 4 point bending configuration. Centering the v-notch in the bending support ($\phi=0$) results in a pure mode II loading (only shear stress). Varying the value of $\phi$ allows to play with the mixed mode ratio $\phi$ presented above.

The following relations, taken from literature, are used to compute the fracture toughness components of both mode I and II. These equations assume correction shape factors $F_1$ and $F_2$ that are potentially not valid for anisotropic material such as SCSi.

$$K_{II} = s \cdot F_1 \cdot \frac{S_a - S_i}{S_a + S_i} \cdot 6\sqrt{\pi} \cdot \frac{F_1(\alpha/W)}{BW^2}$$

The two graphs shown bellow are representation of the mixed-mode I/II fracture envelope obtained through these fracture tests.

SEM Observations

For more trustable results, new geometry correction factors $F_1$ and $F_2$ should be derived considering the anisotropy of the material. Extended SEM observations would also allows a better understanding of the fracture behavior.

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