The Fracture Toughness of Beryllium

H. Conrad, J. Hurd, and D. Woodard
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ABSTRACT: Data on the fracture toughness of beryllium obtained by the authors and that available in the literature are reviewed. The effects of test method, chemistry and microstructure, temperature and strain rate, and fracture modes are discussed. The available data suggest that the fracture toughness of both hot pressed and sheet beryllium is proportional to the product of the true fracture stress and true fracture strain. A rationale for this correlation is developed on the basis of the Griffith-Crawford fracture equation. The effects of temperature and strain rate on the fracture toughness of beryllium sheet follow an Arrhenius-type relation which is in accord with that for prism slip.

KEY WORDS: hot pressed block, metal sheets, tests, temperature, fracture, microstructure, strain rate, tensile properties, electron microscopy, etch pits, surface energy

Beryllium offers considerable potential as a structural material for aerospace applications because of its low density and high modulus coupled with good strength. This potential and the increased use of beryllium in recent years has created an interest in the fracture behavior of this metal and especially in its fracture toughness.

This paper reviews the data available on the fracture toughness of beryllium, including some unpublished results by the present authors. Consideration is given to the magnitude of the fracture toughness of beryllium and the effects of chemistry and microstructure on it. Moreover, interpretations of the fracture toughness in terms of parameters derived from uniaxial tension tests, scanning electron microscope (SEM) observations, and the mechanisms of plastic flow and fracture are discussed.

The studies on the fracture toughness of beryllium carried out by the authors are presented first. These data are then included in the general discussion of the fracture toughness of beryllium which follows.

Fracture Toughness Studies

Materials and Test Methods

The fracture toughness tests conducted by the authors were on sheet specimens prepared from hot pressed block by standard industrial hot rolling techniques; the chemical compositions and grain sizes are given in Table 1. Also included in this table are the compositions and grain sizes of sheet materials tested by other investigators, the results of which are given in Table 2.

The present test specimens were generally 1 in. wide by 4 to 6 in. long with a nominal thickness of 0.125 in., and were of the form shown in Fig. 1. The specimens were prepared by milling or grinding all surfaces, which was followed in most cases by a chemical milling to a depth of 0.002 in. per surface. The as-machined notch root radii were generally about 0.002 in., although in some cases root radii of 0.0065 in. were used. The notch depth varied from 3/4 to 7/8 in. Pin holes were provided for tensile pulling.

Some specimens were tested with the notch left as-machined, while in others the notch was extended by precracking in fatigue. When the notch was extended by precracking, this was performed by cantilever bending of the specimen using a "hard" machine such as the Krouse eccentric throw-type machine. Fatigue loads were varied up to 75 percent of the expected K_{1c} values, and were cycled from tension to compression with the

FIG. 1—Single edge notch specimen used in the present study of the fracture toughness of beryllium sheet.

1 University of Kentucky, Lexington, Kentucky.
2 Brush Wellman Inc., Cleveland, Ohio.
compressive stress being twice the tensile stress. Fatigue crack growth was observed with the aid of a red dye, and the final crack length was established with a Zeiss metallograph after removal of the specimen from the fatigue machine.

The test specimens were pulled to fracture using an Instron with a crosshead speed of 0.05 in./min. The maximum fracture loads were used to compute $K$ values; they are termed $K_{\text{max}}$ realizing that they may not be exactly $K_I$. The fracture toughness test was usually instrumented by attaching a 1 in. Instron strain gage extensometer across the notch, and the tensile load versus crack opening displacement was recorded. In some cases the test was further instrumented by an acoustic pickup. This was used to detect first cracking in the case of hot pressed beryllium; it was not employed in the testing of sheet specimens.

To aid in understanding the fracture toughness of beryllium, the fracture surfaces of some of the present sheet specimens and of hot pressed specimens tested by NASA (courtesy of W. F. Brown, Jr. and M. H. Jones) were examined using scanning electron microscopy (SEM) employing standard techniques.

**Results**

*Load-Deflection Behavior*—The crack-opening displacement (COD) load curves for the sheet specimens appeared virtually linear up to the point of fracture, thus meeting the criteria for linear elastic stress analysis. Assuming that the beryllium sheet is in a state of plane strain, the maximum load $K_{\text{max}}$ values can then be labeled $K_I$. However, since there exists a thickness effect in the fracture toughness of hot pressed beryllium [$K_{\text{th}}$], one may question whether $K_{\text{max}}$ for sheet is in fact $K_I$.

*Effects of Notch Preparation*—A limited study was carried out on the effect of the method of preparing the notch or crack on the fracture toughness of beryllium sheet. The results are presented in Fig. 2. It is here seen that lower values of $K_{\text{max}}$ were obtained for specimens with as-machined notches than for fatigue precracked specimens. This suggested that the machining may have produced some damage which lowered the fracture toughness. To check this, some specimens with as-machined notches were chemically etched while others were heat treated for 30 min at 1400°F with the aim of removing the machining damage. The $K_{\text{max}}$ values after these treatments are included in Fig. 2. It is seen that $K_{\text{max}}$ increased following such treatments.

![Effect of notch root radius on the fracture toughness of beryllium sheet](image-url)

**FIG. 2—Effect of notch root radius on the fracture toughness of beryllium sheet.**
supporting the idea that the machining had produced some damage.

Fracture Toughness Values—The values of $K_{max}$, obtained in the present tests for fatigue precracked beryllium sheet are presented in Table 2. These range from 16.5 to 30.0 ksi-in.\(^{1/2}\) and are in accord with those obtained by others [2, 3, 5] for powder sheet. They are 2 to 3 times larger than that reported for ingot sheet [2].

SEM Studies—The macro appearance of the fracture surface of a fatigue precracked specimen of hot pressed beryllium obtained from NASA [12] is shown in Fig. 3a. The top bright region is the machined notch, the dark granular region the fatigue precrack, and the lighter granular region the fracture surface generated in the fracture toughness test. Not evident at this low magnification is an intermediate region joining the fatigue crack and the final fast fracture region.

SEM photomicrographs of the various regions of the fracture surface are given in Figs. 3b, c, and d. In the fatigue crack region (Fig. 3b), fracture occurred by cleavage of the grains along planes which in general made a significant angle with each other and with the general fracture surface, giving a granular appearance to the fracture surface. In the bright or fast fracture region (Fig. 3d) the cleavage planes are nearly parallel to the general fracture surface. Also, there occurred some tearing in the vicinity of the grain boundaries. The structure in the intermediate region (Fig. 3c) was a transition between that for the slow fatigue crack and the fast fracture of the fracture toughness test.

To identify the planes which were active in the various regions of the fracture surface, the etch pit technique developed by Hepler et al. [8] was employed. Examples of the etch pit geometry in the fatigue fracture and in the fast fracture regions obtained in this manner are given in Figs. 4a and 4b respectively. The shape of the etch pits in the fatigue crack region (Fig. 4a) indicates that the predominant cleavage plane is the basal plane. However, some cleavage on the $\{11\overline{2}0\}$ planes also
FIG. 3—Nature of fracture surface of fracture toughness specimen revealed by scanning electron microscopy. (a) Fracture surface of entire hot pressed block specimen, which had been fatigue precracked and then fractured in bending; (b) Fatigue precrack region; (c) Intermediate region between fatigue precrack and final fast fracture; (d) Final fast fracture region.

occurred, the relative amount increasing the higher the maximum tensile stress employed during the fatigue. In the fast fracture region (Fig. 4b), no one cleavage plane dominated. Evidence was found for the following families of cleavage planes: (0001), [1120], [1010] and [1122] and an unidentified plane. Also, there was considerable tearing along the grain boundaries. In the intermediate region between the slow fatigue crack and the final fast fracture, cleavage on the [1120] planes was most frequent, with some cleavage on the (0001) and [1010] planes also occurring. Again, tearing at the grain boundaries was observed in this region. The SEM observations on hot pressed specimens are summarized in Fig. 5.

In addition to a difference in the cleavage planes active in the various regions of fracture, a variation in the etch pit density also occurred. The density of dislocations was relatively high

1 It is difficult to distinguish between the [1010] and [1120] planes on the basis of the etch pits. Only a few unambiguous [1010] planes were observed in the fast fracture region.
in the fatigued regions, while there were relatively fewer pits in the final fast fracture region. In the fatigue crack region, there were concentrations of etch pits on those grains which showed (1120) cleavage. In the final fracture region, a large fraction of the etch pits occurred near the grain boundaries, where there

FIG. 4—Nature of etch pits on fracture surface of hot pressed block revealed by scanning electron microscopy. (a) Fatigue precrack region; hexagonal form of etch pits is indicative of basal planes; (b) Fast fracture region; etch pits correspond mostly to (0001) prism planes.

FIG. 6—Transition region revealed by scanning electron microscopy of the fracture surface of a hot pressed block specimen which failed during fatiguing due to an accidental overload.
Review of Fracture Toughness

General

Most of the data currently available in the literature on the fracture toughness of beryllium are summarized in Fig. 7. The values listed here are based on the maximum load and hence are designated as $K_{\text{max}}$, rather than $K_I$. They were taken from seven different sources, using four methods of initiating the crack: as-machined, etch machined, wedge opened, and notch fatigued. The arrows on the data points differentiate between these various methods.

A consideration of the data in Fig. 7 reveals that about 80 percent of the $K_{\text{max}}$ values lie between 10 and 25 ksi in. For the same thickness of $\frac{1}{16}$ in., the values for hot pressed block are similar to those for sheet. An orientation effect for hot pressed block is apparent in that the values for the longitudinal direction (parallel to the pressing direction) tend to be slightly lower than those for the transverse direction [9, 11]. No differentiation has been made by the various investigators for the two possible notch orientations in the transverse direction.

Although there is a tendency for the fracture toughness to decrease with increasing thickness, the scatter in the data of Fig. 7 is too wide to permit a positive statement regarding a thickness effect. However, the results of Harris and Dunean [6] on hot pressed block and recent results by Brown and coworkers at NASA [18] on hot pressed block and forged disks indicate that a thickness effect does in fact exist, with the fracture toughness appearing to approach a minimum value at about $\frac{1}{16}$ in. thickness.

Results on hot pressed block by Jones et al [12] indicate that as-machined notches yield higher fracture toughness values than do fatigue cracks. They also suggest that wedge-opening cracks yield higher values than fatigue cracks. However, whether there actually exists a difference between wedge-opening cracks and fatigue cracks is not completely clear at this time. A technique for producing fatigue cracks in beryllium has now been worked out, and this type of crack appears to give reproducible results [12].

In the case of sheet, the results presented in the previous section indicate that as-machined notches may give lower

FIG. 7—Fracture toughness vs. thickness for various forms of beryllium. $L =$ longitudinal, $T =$ transverse. All data were obtained from room temperature testing. Heat treatment data were not included. Test rates are unspecified.

FIG. 8—Effect of method of cracking on the fracture stress of beryllium as a function of the ratio of crack length, $L_c$, to specimen width, $W$. Data from Refs 3, 13, and 14.

occurred a change in the angle of the cleavage plane with respect to the general fracture surfaces.

Etch pit studies on fractured sheet specimens revealed the following: (a) the cleavage planes in the fatigue cracked region were principally [1120]; (b) the cleavage planes in the final fracture region were primarily [1120], [1010], and [1122] with only a very few (0001). Again, tearing along the grain boundary was observed in the final fracture region.

The fracture surface of a hot pressed specimen which failed during fatigue due to an increase in test load is shown in Fig. 6. To be noted is that the fracture proceeds immediately from the fatigue mode to the final fast fracture mode without an intermediate transition region. Similarly, no intermediate region occurred in sheet specimens with as-machined notches.
### TABLE 3—Hot-pressed beryllium chemistry and grain size values.

<table>
<thead>
<tr>
<th>Lot Number</th>
<th>BA86L</th>
<th>RR233</th>
<th>5117</th>
<th>7001</th>
<th>7049*</th>
<th>475M</th>
<th>2172</th>
<th>2340</th>
<th>S-200E</th>
<th>N-50A I</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

#### Element, ppm

| Element | BeO, % | Fe | C | Al | Cr | Mg | Mn | Ni | Ti | Ag | Ca | Co | Cu | Mo | Pb | Si | Zn | Grain Size, μ |
|---------|--------|----|---|----|----|----|----|----|----|----|----|----|----|----|----|----|-------------|
|          | 0.41   | 1020 | 540 | 350 | 40 | 128 | 110 | 220 | 580 | 36 | 58 | 30 | 10 | 6 | 50 | N.A. | 8.5 | 14.0 |
|          | 0.92   | 725 | 860 | 210 | 20 | 100 | 200 | 420 | 430 | 420 | 335 | 40 | 100 | 6 | 50 | N.A. | 14.0 | 22.0 |
|          | 0.91   | 916 | 1070 | 320 | 100 | 100 | 200 | 280 | 300 | 300 | 1170 | 460 | 55 | 6 | 50 | N.A. | 13.0 | 19.0 |
|          | 5.02   | 1300 | 700 | 600 | 400 | 300 | 300 | 300 | 300 | 300 | 860 | 470 | 55 | 6 | 50 | 8.5 | 14.0 | 22.0 |
|          | 0.91   | 800 | 530 | 300 | 100 | 100 | 300 | 300 | 300 | 300 | 860 | 470 | 55 | 6 | 50 | 8.5 | 14.0 | 22.0 |
|          | 0.60   | 970 | 1000 | 300 | 75 | 75 | 300 | 300 | 300 | 300 | 860 | 470 | 55 | 6 | 50 | 8.5 | 14.0 | 22.0 |
|          | 1.63   | 1180 | 1070 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 860 | 470 | 55 | 6 | 50 | 8.5 | 14.0 | 22.0 |
|          | 1.67   | 1100 | 1400 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 860 | 470 | 55 | 6 | 50 | 8.5 | 14.0 | 22.0 |
|          | 1.72   | 1290 | 1400 | 700 | 700 | 700 | 700 | 700 | 700 | 700 | 860 | 470 | 55 | 6 | 50 | 8.5 | 14.0 | 22.0 |
|          | 0.69   | 800 | 450 | 200 | 100 | 100 | 100 | 100 | 100 | 100 | 860 | 470 | 55 | 6 | 50 | 8.5 | 14.0 | 22.0 |

#### Grain Size, μ

- N.A.: Not available
- Ref. A: Material A
- Ref. B: Material B
- Ref. C: Material C

<table>
<thead>
<tr>
<th>Lot Number</th>
<th>Ref. A</th>
<th>Ref. B</th>
<th>Ref. C</th>
</tr>
</thead>
<tbody>
<tr>
<td>BA86L</td>
<td>2</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>RR233</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5117</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7001</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>7049*</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>475M</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2172</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2340</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>S-200E</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>N-50A I</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*Chemical analysis is for the powder
*Chemistry values are typical
*N.A. = not available

Fracture toughness values than fatigue-fractured specimens. A comparison of several methods of cracking (pressure precracking, fatigue precracking, and failure in fatigue) on the fracture stress of sheet specimens is given in Fig. 8 [2, 13, 14]. Though the results can all be considered to lie within one scatter band, the fracture stresses for failure during fatigue tend to lie below those for pressure precracking and fatigue precracking. In this regard it should be mentioned that no intermediate zone was observed in the SEM studies of the fracture surfaces of hot-pressed specimens which had fractured during fatigue, as was also the case for as-machined notches in sheet specimens.

For hot-pressed block the K values which are available in the literature in terms of the maximum load appear to be within the scatter intercept or 5 percent specification of the ASTM Test for Plane-Strain Fracture Toughness of Metallic Materials (E-399-72). However, work by Jones et al. [12] suggests that the maximum load K value may be greater than would correspond to a 5 percent scatter band. Also, the COD-load curves may not be linear, even at very low K values. Thus, these aspects of the fracture toughness testing of hot pressed beryllium steel need to be resolved. On the other hand, the data available on forged disks [12] and sheet [7] indicate that the COD-load curves are essentially linear to the point of fracture.

Much of the scatter in the data of Fig. 7 can be attributed to


<table>
<thead>
<tr>
<th>Material Number</th>
<th>Ref</th>
<th>Thickness, in.</th>
<th>Orientation</th>
<th>Yield Strength, ksi</th>
<th>Ultimate Strength, ksi</th>
<th>Elongation, %</th>
<th>$U_r$, lb-in./in.</th>
<th>$K_{max}$ load, ksi-in.^1</th>
</tr>
</thead>
<tbody>
<tr>
<td>7001 (1-400)</td>
<td>1, 5</td>
<td>0.32</td>
<td>L</td>
<td>43.9</td>
<td>67.3</td>
<td>0.6</td>
<td>0.41 x 10^3</td>
<td>8.0 (L) 3 pt bend</td>
</tr>
<tr>
<td>8-200E R.T.</td>
<td>11</td>
<td>1.00</td>
<td>L</td>
<td>33.0</td>
<td>42.0</td>
<td>1.5</td>
<td>0.64</td>
<td>9.4 (L) WOL</td>
</tr>
<tr>
<td>−100°F</td>
<td>1.00</td>
<td>L, T</td>
<td></td>
<td>34.9</td>
<td>47.9</td>
<td>2.2</td>
<td>1.10</td>
<td>11.2 (T)</td>
</tr>
<tr>
<td>−320°F</td>
<td>1.00</td>
<td>L, T</td>
<td></td>
<td>35.0</td>
<td>51.8</td>
<td>1.9</td>
<td>0.63</td>
<td>8.5 (L)</td>
</tr>
<tr>
<td>N-501I (Brake)</td>
<td>6</td>
<td>0.30</td>
<td>L</td>
<td>29.2</td>
<td>45.2</td>
<td>1.5</td>
<td>0.67</td>
<td>7.8 (L)</td>
</tr>
<tr>
<td>N-501I (GA)</td>
<td>8</td>
<td>0.10</td>
<td>T</td>
<td>30.4</td>
<td>49.3</td>
<td>3.0</td>
<td>1.50</td>
<td>6.3 (T)</td>
</tr>
<tr>
<td>N-501I I</td>
<td>6</td>
<td>0.35</td>
<td>T</td>
<td>28.4</td>
<td>49.7</td>
<td>3.4</td>
<td>1.70</td>
<td>14.9 (T) SEN (cleaved)</td>
</tr>
<tr>
<td>668L (HP-20)</td>
<td>8</td>
<td>0.13</td>
<td>T</td>
<td>30.5</td>
<td>44.7</td>
<td>2.0</td>
<td>1.36</td>
<td>14.6 (L) DCB</td>
</tr>
<tr>
<td>RR 233 (HP-20)</td>
<td>2</td>
<td>0.47</td>
<td>L</td>
<td>31.6</td>
<td>45.9</td>
<td>3.4</td>
<td>1.54</td>
<td>23.6 (T) 3 pt bend</td>
</tr>
<tr>
<td>5117 (S-200)</td>
<td>2</td>
<td>0.20</td>
<td>L</td>
<td>36.9</td>
<td>47.4</td>
<td>1.4</td>
<td>0.68 x 10^3</td>
<td>11.2 (L) 3 pt bend reduced to 10.0 for 0.5 inch thickness correction</td>
</tr>
<tr>
<td>7040 (S-200)</td>
<td>5</td>
<td>0.25</td>
<td>L</td>
<td>32.8</td>
<td>44.1</td>
<td>1.4</td>
<td>0.63</td>
<td>10.9 (L) 3 pt bend reduced to 10.0 for 0.5 inch thickness correction</td>
</tr>
<tr>
<td>478M (HP-20)</td>
<td>5</td>
<td>0.25</td>
<td>L</td>
<td>28.8</td>
<td>36.5</td>
<td>1.8</td>
<td>0.67</td>
<td>12.7 (L) 3 pt bend reduced to 11.0 for 0.5 inch thickness correction</td>
</tr>
<tr>
<td>S-200I (GA)</td>
<td>6</td>
<td>0.35</td>
<td>L</td>
<td>40.1</td>
<td>42.4</td>
<td>1.0</td>
<td>0.43</td>
<td>13.2 (L) SEN (cleaved)</td>
</tr>
<tr>
<td>S-200I (GA)</td>
<td>6</td>
<td>0.50</td>
<td>L</td>
<td>40.1</td>
<td>42.4</td>
<td>1.0</td>
<td>0.43</td>
<td>11.7 (L) SEN (cleaved)</td>
</tr>
<tr>
<td>S-200II (LRL)</td>
<td>6, 10</td>
<td>0.50</td>
<td>T</td>
<td>41.0</td>
<td>57.0</td>
<td>3.3</td>
<td>1.89</td>
<td>23.9 (T) (develed)</td>
</tr>
<tr>
<td>S-200D</td>
<td>7</td>
<td>0.50</td>
<td>T</td>
<td>43.0</td>
<td>53.0</td>
<td>3.0</td>
<td>1.50</td>
<td>14.5 (T) 3 pt bend</td>
</tr>
<tr>
<td>S-200</td>
<td>9</td>
<td>1.00</td>
<td>L</td>
<td>33.5</td>
<td>43.5</td>
<td>1.2</td>
<td>0.53</td>
<td>23.4 (T) WOL (as-machined, reduced to 12.0 for precracking correction)</td>
</tr>
</tbody>
</table>

* $U_r$ defined as in Table 2.
* All specimens fatigue precracked unless indicated otherwise.

L = Pressing direction.
T = Transverse to pressing direction.

The fact that conditions did not exist for yielding true $K_{max}$ values. However, when one considers those data which meet, or approximately meet, ASTM specifications for a valid $K_{max}$ value, there still exists a range in the values for the fracture toughness of beryllium. In the discussion to follow some of the metallurgical factors which may lead to this variation are considered. Also, it is shown that there appears to exist a correlation between the fracture toughness of beryllium and certain parameters which can be obtained from a standard tensile test.

The data to be used in the discussion to follow are listed in
Since the data presented in Tables 2 and 4 were obtained by a number of investigators using a variety of specimen geometries, methods of precracking and test methods, the conclusions drawn therefrom can only be considered to be tentative at this time. It is thus the intent of this review to provide the background and guidelines for future work, rather than list absolute data for use in design.

Effects of Chemistry, Grain Size, and Thermal Treatments

The effects of BeO content and grain size on $K_{\max}$ for hot pressed beryllium are presented in Fig. 9. $K_{\max}$ decreases with increase in BeO content and decrease in grain size, the latter effect being contrary to any Hall-Petch type relation. This suggests that for the ranges considered here the oxide content is more important in hot pressed beryllium than the grain size. The effects of BeO content and grain size on $K_{\max}$ for beryllium sheet are shown in Fig. 10. If one includes the ingot sheet, the trend appears to be opposite to those for hot pressed block in that $K_{\max}$ increases with increase in BeO content and decrease in grain size.

From data in the literature and work by the authors, it is concluded that heat treatments may either raise or lower the fracture toughness of beryllium. This is in doubt related to the solution and precipitation reactions which occur during such heat treatments and which, as is well known, can be quite complex in commercial beryllium. Although the subject of the effects of heat treatment on the fracture toughness of beryllium

FIG. 9—Effects of BeO content and grain size D on the fracture toughness of beryllium hot pressed block at room temperature.

FIG. 10—Effects of BeO content and grain size D on the fracture toughness of beryllium sheet at room temperature.
FIG. 12—Variation of the fracture toughness of beryllium sheet with tensile properties at room temperature.

is an important one, in view of the complexity of the subject and the paucity of data, it will not be dealt with further here.

Correlation of Fracture Toughness with Tensile Properties

The relationships between fracture toughness of hot pressed beryllium and the yield strength, ultimate strength, and the percent elongation are shown in Fig. 11. There is a general tendency for the fracture toughness to increase with decrease in strength and increase in elongation. Increasing the oxide content gave smaller grain sizes and higher strengths, but lower $K_{\text{max}}$ values.

$K_{\text{max}}$ values for beryllium sheet versus the yield strength, ultimate strength, and percent elongation are shown in Fig. 12. In contrast to hot pressed block, $K_{\text{max}}$ for the sheet increases with increase in strength. In this case increasing the oxide content and decreasing the grain size yielded both a higher strength and a higher fracture toughness.

Figure 13 shows that the fracture toughness of both hot pressed block and sheet correlates reasonably well with the square root of the product of the true stress at fracture $\sigma_F$ (derived from the ultimate stress in Tables 2 and 4) times the true strain at fracture $\varepsilon_F$ (derived from total elongation) that is, with $U_T = \sigma_F \varepsilon_F$. This yields:

$$K_{\text{max}} = MU_T^{1/2} \quad (1)$$

where $M = 414$ (lb/in.)$^{1/2}$ for hot pressed block and 190 (lb/in.)$^{1/2}$ for sheet.

Effects of Temperature and Strain Rate

Work by Harrod et al. [8] on hot pressed block and Pall [15] on sheet has shown that the fracture toughness of beryllium is dependent on both strain rate and temperature. The effects of temperature on $K_{\text{max}}$ for hot pressed and sheet beryllium are presented in Fig. 14. It is here seen that $K_{\text{max}}$ decreases with decrease in temperature for both materials, with the sheet exhibiting a ductile-to-brittle type transition in the vicinity of room temperature.

Pall [15] has shown that the effects of temperature $T$ and strain rate $\dot{\varepsilon}$ on $K_{\text{max}}$ for sheet can be correlated through an Arrhenius-type parameter $p = T \ln (A/\dot{\varepsilon})$ where $T$ is the absolute temperature; see Fig. 15.

Discussion

Correlation of Fracture Toughness with Tensile Properties

Of considerable interest is the correlation between the fracture toughness and the product of the true fracture stress and the true strain at fracture. If this correlation is valid, then $K$ for beryllium could be derived from the results of an ordinary tensile test. A rationale for this correlation can be developed by starting with the Griffith-Orowan equation

$$\sigma_F = \left( \frac{2E\gamma_F}{\pi c} \right)^{1/2} \quad (2)$$

where $\sigma_F$ is the fracture stress, $E$ the elastic modulus, and $\gamma_F$ the...
Inserting Eq 6 into Eq 3 yields
\[ K = \left( \frac{2E\sigma_p}{3(n + 1)} \right)^{1/2} = \left[ \frac{2E\sigma_p}{3(n + 1)} \right]^{1/3} \]  
(7)

Comparing Eq 7 with Eq 1 then gives
\[ M = \left( \frac{2E}{3(n + 1)} \right)^{1/3} \]  
(8)

Equation 8 offers the possibility of calculating the plastic zone height from the observed proportionality between \( K_{\text{max}} \) and \( U_{\text{f}}^{1/2} \). Typical values of the necessary parameters for hot pressed block are \( M = 414 \) (lb/in.)\(^{1/2} \), \( E = 40 \times 10^6 \) lb/in.\(^2 \), and \( n = 0.18 \). Inserting these into Eq 8 gives \( l = 0.008 \) in. For sheet specimens, typical values of \( M, E, \) and \( n \) are 190 (lb/in.)\(^{1/2} \), 40 \( \times \) 10\(^6 \) psi, and 0.18, respectively. This gives \( l = 0.002 \) in. from Eq 8.

It appears that \( K_{\text{max}} \) correlates with \( U_{\text{f}}^{1/2} \) especially for material tested under plane strain conditions, that is, with a thickness of \( \frac{1}{2} \) in. or greater. It is suggested that perhaps even better agreement may be obtained if the actual energy under the stress-strain curve were measured, rather than calculating this energy using a specific expression for the stress-strain curve. Thus, the possibility exists that the fracture toughness of beryllium can be predicted from the stress-strain behavior under uniaxial tension and perhaps also in a bond test.

**Effects of Strain Rate and Temperature on Fracture Toughness**

Pall’s [15] work indicates that the fracture toughness of beryllium sheet is given by an Arrhenius-type relation of the form
\[ \dot{\varepsilon} = A \exp \left[ -\frac{HK_0}{RT} \right] \]  
(9)

where \( \dot{\varepsilon} \) is the strain rate, \( A \) is a constant, \( H \) is the activation energy (enthropy) for the process (which is a function of the fracture toughness value), and \( R \) and \( T \) have their usual meaning. Pall’s parameter is then
\[ p = T \ln \left( \frac{A}{\dot{\varepsilon}} \right) = \frac{H(K_0)}{R} \]  
(10)

**FIG. 15**—Fracture toughness of beryllium as a function of the parameter \( p = T \ln \left( \frac{A}{\dot{\varepsilon}} \right) \). From Ref 15.
Of interest is the nature of the rate controlling mechanism associated with the activation energy $H$. Some indication of this mechanism is obtained by comparing the value of the parameter $A$ ($= 10^4$ s$^{-1}$) derived from the fracture toughness results with those for various slip and fracture modes. It is found that best agreement is obtained with that for prism slip, where $A$ ranges between $10^2$ to $10^3$ s$^{-1}$ [17]. This suggests that the rate controlling mechanism during the fracture toughness of beryllium sheet is prism slip, which is in accord with the fact that this is the major slip system active during the plastic flow of sheet specimens [18].

Fracture Mode—SEM Observations

An important feature of the SEM observations is that a transition region between the precrack and the final fast fracture regions was not found in the hot pressed specimen which had fractured during fatigue and in the sheet specimen with an as-machined notch. Both of these specimens exhibited a lower fracture toughness than specimens which were first fatigued precracked, unloaded, and then tested to failure in tension. This suggests that the reinitiation of the fatigue precrack may be important in the fracture toughness testing of beryllium. Whether a transition region is absent in precracks produced by the wedge-opening method is of interest; it is expected that the fracture mode during this type of precracking is similar to that during the ultimate fast fracture. More work is needed on the subject of the relationship between the fracture mode and the fracture toughness value for beryllium.

Comparison of the Fracture Toughness of Beryllium with Other Materials

The relatively low fracture toughness values for beryllium are in accord with its generally low three-dimensional ductility. Comparisons of the ratio of $(K_{IC}/\epsilon_f)^{1/2}$, which is a measure of the critical flaw size at the yield stress, for beryllium with other engineering materials are given in Fig. 16 [19]. It is seen that the value of $(K_{IC}/\epsilon_f)^{1/2}$ for beryllium as a function of yield strength-to-density ratio is similar to that for certain steels and titanium alloys.

References

[1] Brush Wellman Data, present investigation.