Solve the Hard Problem: Materials Harder than Diamond

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Hypotheses of interest

- Hypothesis 1: Materials that are harder than diamond are possible to achieve.

- Hypothesis 2: If one or more harder than diamond materials existed, there would be high impact energy applications for them.
What is hardness?

- Metrics associated with hardness
  - Wear resistance
  - Ductility
  - Strength
  - Stiffness

- How is it measured?
  - Indentation size & depth
  - Scratch
  - Rebound

Photo credit: taken from “Eight Allotropes of Carbon” Michael Ströck - Created by Michael Ströck. Licensed under CC BY-SA 3.0 via Wikimedia Commons
Harder than diamond?

- Fullerite
- Nano-twinned diamond
- Q-Carbon
- Lonsdaleite
- Nano-twinned c-BN
- w-BN

Emerging “harder than diamond” materials show promise?

<table>
<thead>
<tr>
<th>Material</th>
<th>Vickers Hardness (GPa)</th>
<th>Stage of Verification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fullerite</td>
<td>200 - 300(^1)</td>
<td>Experimental</td>
</tr>
<tr>
<td>Nano-twinned diamond</td>
<td>200(^2)</td>
<td>Experimental</td>
</tr>
<tr>
<td>Q-Carbon</td>
<td>60% harder than diamond(^3)</td>
<td>Extrapolated from theory and nano-indentation experimentation on filament samples</td>
</tr>
<tr>
<td>Lonsdaleite</td>
<td>152(^4)</td>
<td>Theoretical</td>
</tr>
<tr>
<td>Diamond</td>
<td>115(^4)</td>
<td></td>
</tr>
<tr>
<td>Nano-twinced c-BN</td>
<td>About as hard as diamond(^5)</td>
<td>Experimental</td>
</tr>
<tr>
<td>w-BN</td>
<td>About as hard as diamond(^6)</td>
<td>Experimental</td>
</tr>
</tbody>
</table>

**Harder than diamond?**
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If HTD materials were successfully developed, what energy applications would they impact?

- Hypotheses:
  - Drilling (Geothermal, O&G)
  - Mining comminution and grinding
  - Cutting tools for vehicle lightweighting materials
  - Vehicle powertrain low friction, wear resistant coatings
  - Others?
Better (hotter) geothermal resources tend to be deeper. The combination of deeper and hotter is challenging for drill bits.

Temperatures of geothermal resources at various depths in the continental U.S.

40% of EGS costs are for drilling

Worn bit after removal at ~2000 ft

Mining comminution is energy intensive and inefficient

Grinding and crushing operations consume a significant amount of energy (~0.6Q)\(^1\)

These operations are very inefficient with significant room for improvement\(^2\)

U.S. mining industry energy consumption by process in 2006

Can HTD materials lead to more efficient comminution?

Energy use increases exponentially as smaller final particle sizes are required\(^1\)

Can harder than diamond materials improve the efficiency of crushing and/or grinding?

![Graph showing required energy for size reduction in comminution](image)

Automotive & aerospace industries aim for lightweighting, which would have large energy impact

Significant increase in titanium usage in aircraft…

…& aluminum in automotive vehicles (e.g. Ford F150)

- Advanced tool insert materials (PCD) have a limited tool life
- High stresses and elevated temperatures at the cutting region
- 80% of the heat of cutting Ti is transferred to the tool
- Reduce machining time and lubricant requirements
- Cutting costs may be reduced by 15-30%3,4

* Based on analysis in ARPA-E METALS FOA. Replacement constrained by achieving equivalent bending stress. Only use phase is considered in fuel savings, not energy embedded in metals themselves.
Call to action!

- We want your input!
  - Emerging materials “harder than diamond”
  - Fundamental limitation to reaching low cost
  - Identified energy impact applications
  - Other energy applications utilizing HTD materials

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