Solve the Hard Problem: Materials Harder than Diamond

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Hypotheses of interest

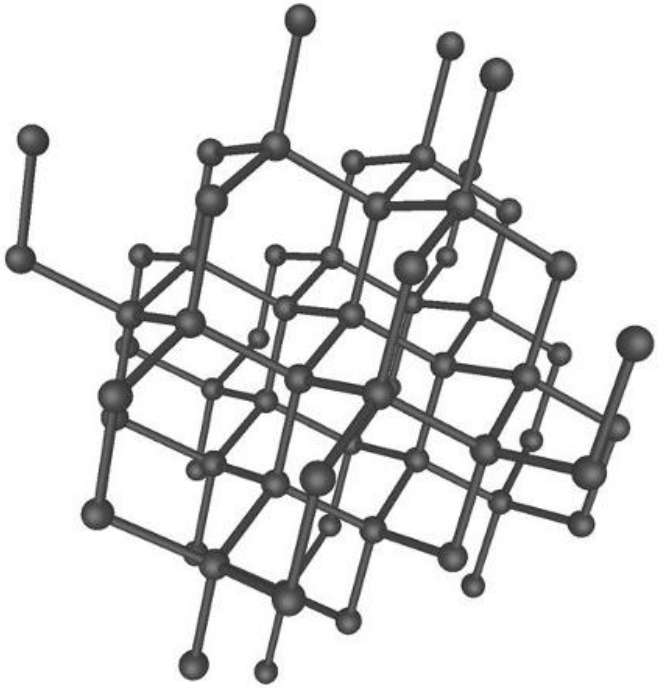
- Hypothesis 1: Materials that are harder than diamond are possible to achieve.

- 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

Diamond



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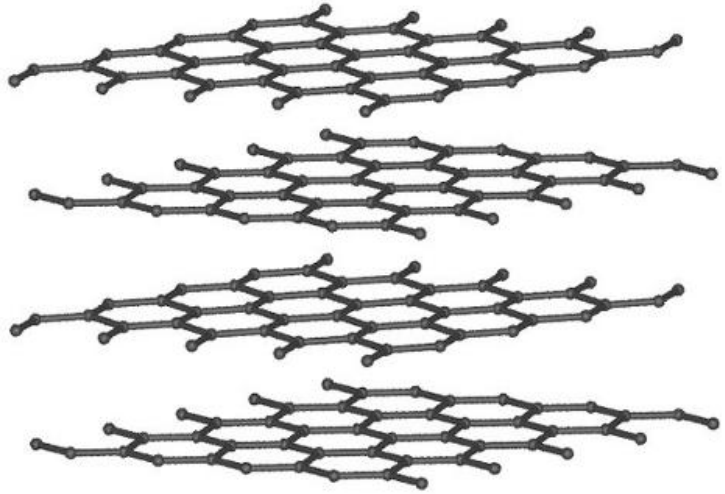


Photo credit: taken from "Eight Allotropes of Carbon" Michael Ströck - Created by Michael Ströck. Licensed under CC BY-SA 3.0 via Wikimedia Commons

Harder than diamond

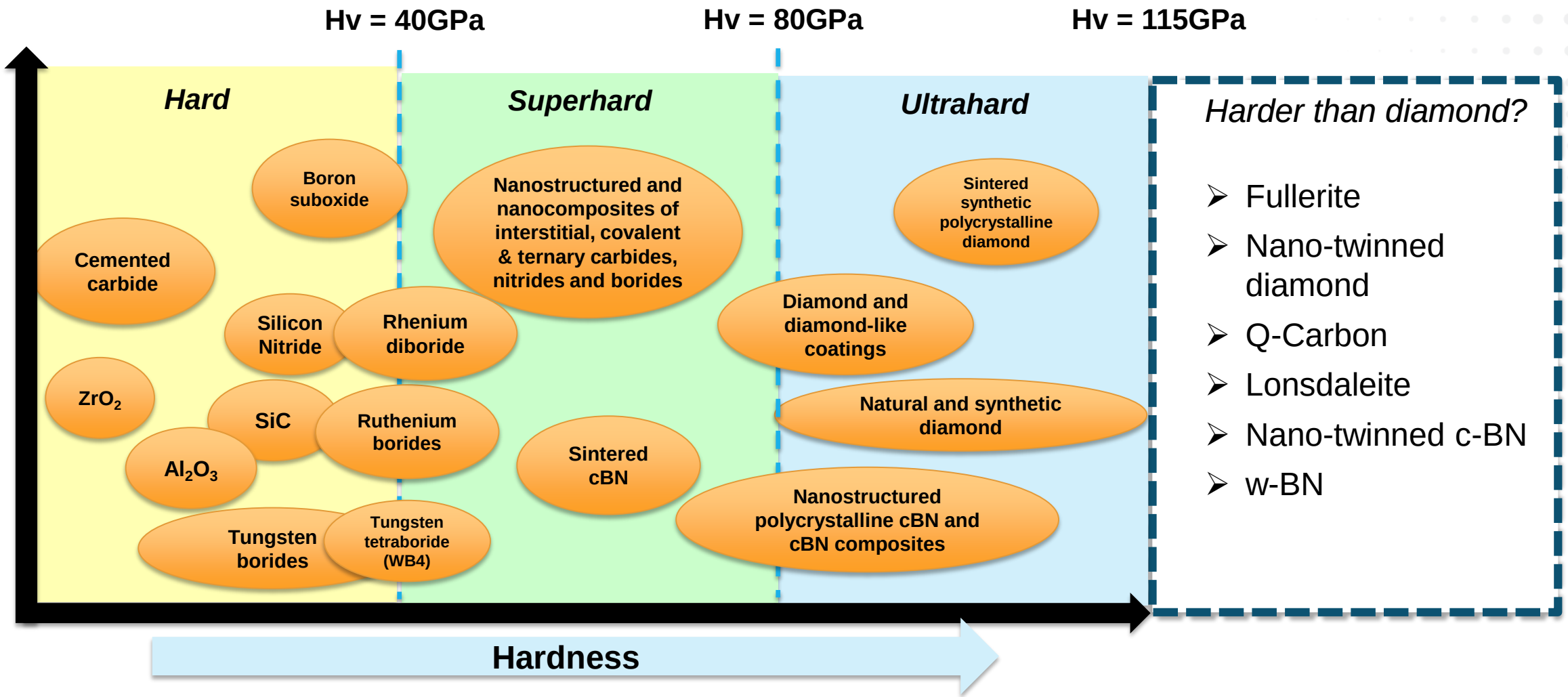


Figure adapted from: Kanyanta, Valentine. "Hard, Superhard and Ultrahard Materials: An Overview." *Microstructure-Property Correlations for Hard, Superhard, and Ultrahard Materials*. Springer International Publishing, 2016. 1-23.

Emerging “harder than diamond” materials show promise?

Material	Vickers Hardness (GPa)	Stage of Verification
Fullerite	200 - 300[1]	Experimental
Nano-twinned diamond	200[2]	Experimental
Q-Carbon	60% harder than diamond[3]	Extrapolated from theory and nano-indentation experimentation on filament samples
Lonsdaleite	152[4]	Theoretical
Diamond	115[4]	
Nano-twinned c-BN	About as hard as diamond[5]	Experimental
w-BN	About as hard as diamond[6]	Experimental

Harder than diamond?

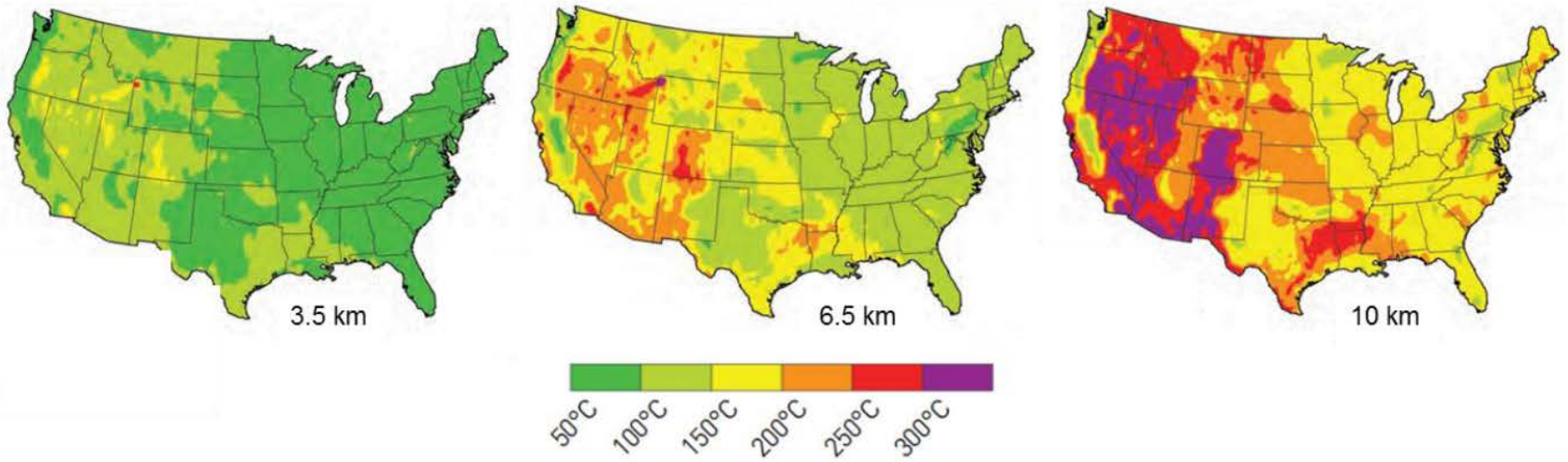
- Fullerite
- Nano-twinned diamond
- Q-Carbon
- Lonsdaleite
- Nano-twinned c-BN
- w-BN

1: Popov, M., et al. "Synthesis of ultrahard fullerite with a catalytic 3D polymerization reaction of C 60." Carbon 76 (2014): 250-256.
2: Huang, Quan, et al. "Nanotwinned diamond with unprecedented hardness and stability." Nature 510.7504 (2014): 250-253.
3: Narayan, Jagdish, and Anagh Bhaumik. "Novel phase of carbon, ferromagnetism, and conversion into diamond." Journal of Applied Physics 118.21 (2015): 215303.
4: Kanyanta, Valentine. "Microstructure-Property Correlations for Hard, Superhard, and Ultrahard Materials." (2016).
5: Tian, Yongjun, et al. "Ultrahard nanotwinned cubic boron nitride." Nature 493.7432 (2013): 385-388.
6: Pan, Zicheng, et al. "Harder than diamond: superior indentation strength of wurtzite BN and lonsdaleite." Physical review letters 102.5 (2009): 055503

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[1]

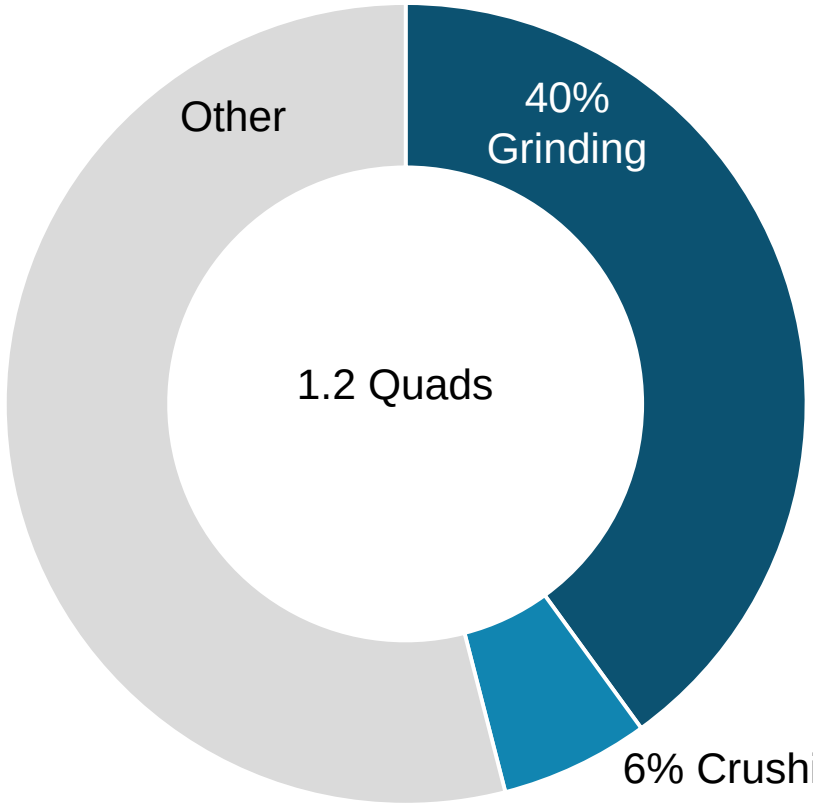
40%
of EGS costs
are for drilling[2]

Worn bit after removal at ~2000 ft [3]

1: Renner, J. L. The Future of Geothermal Energy. No. INL/EXT-06-11746. Idaho National Laboratory (INL), 2006.
2: Kipsang, Carolyn. "Cost model for geothermal wells." (2014).
3: Bit image from: Raymond, David, et al. "PDC Bits Outperform Conventional Bit in Geothermal Drilling Project." Geothermal Resources Council Transactions 36 (2012): 307-316.

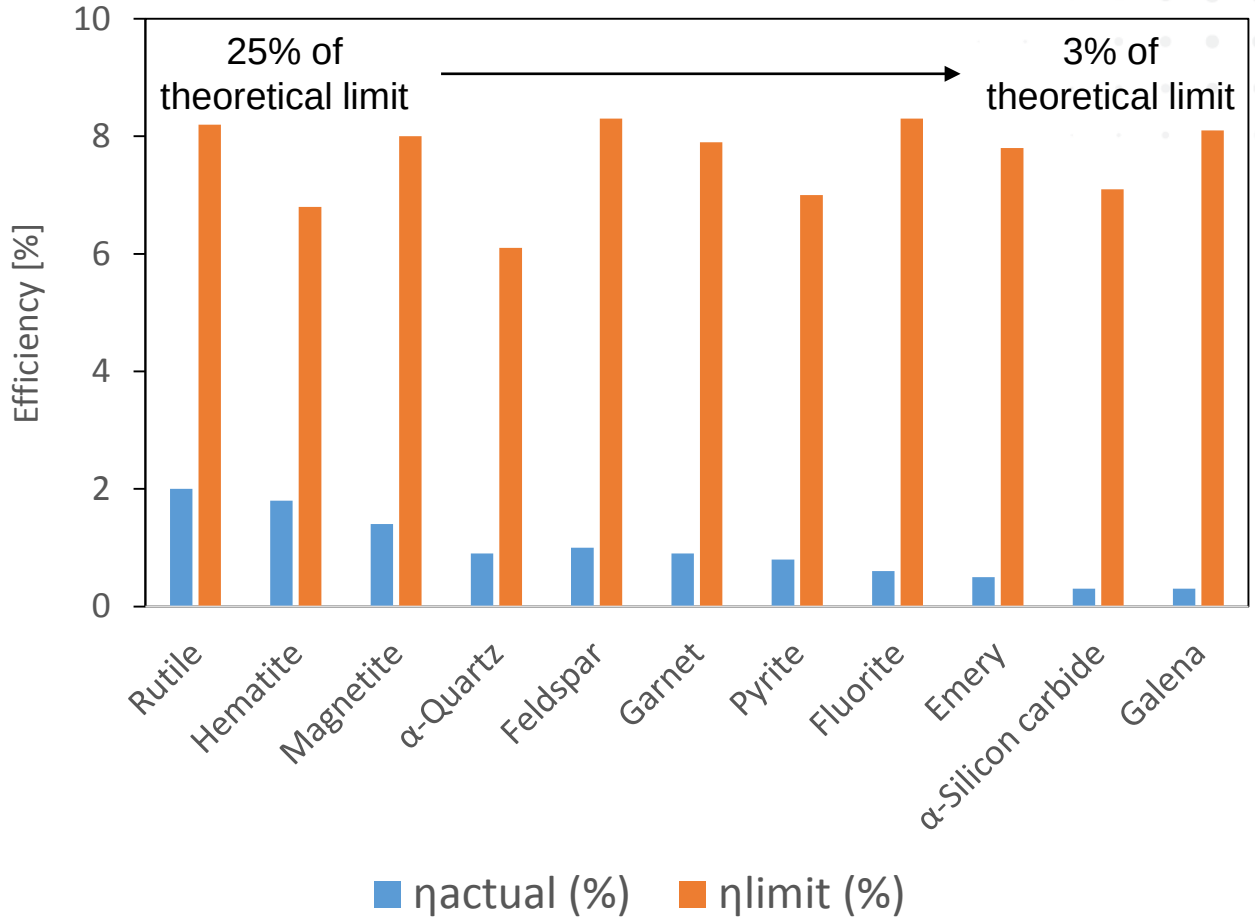
Mining comminution is energy intensive and inefficient

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



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

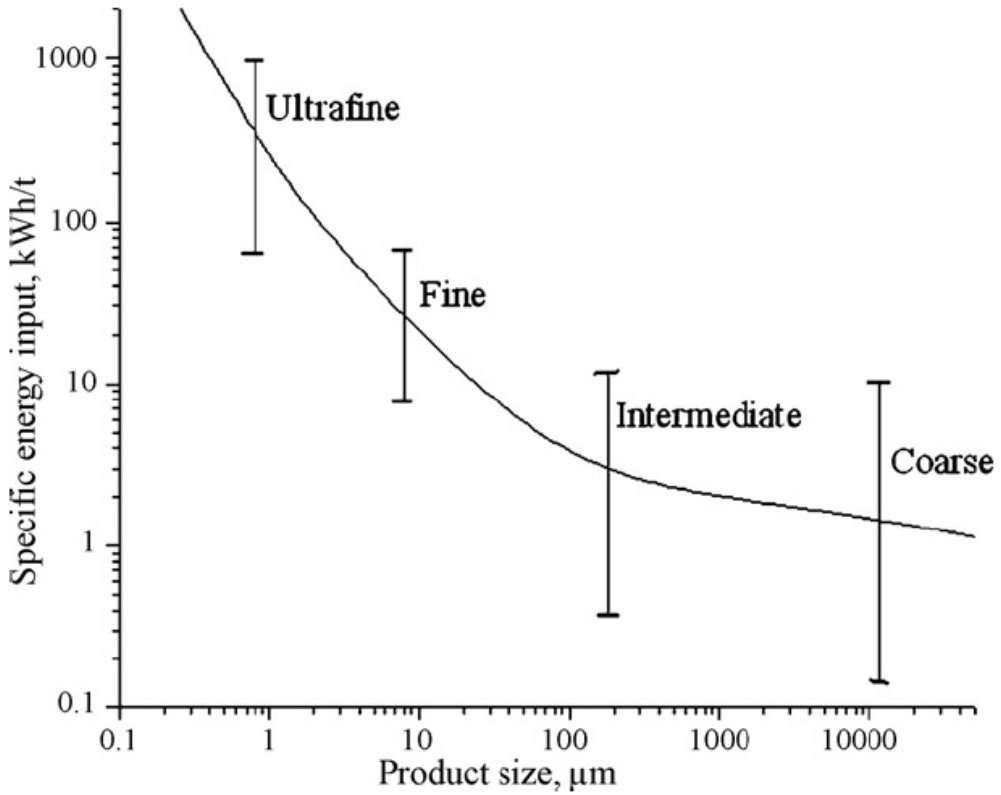
These operations are very inefficient with significant room for improvement[2]



1: DOE, US. "Mining industry energy bandwidth study." US Department of Energy, Washington, DC (2007).
2: Tromans, Desmond. "Mineral comminution: energy efficiency considerations." Minerals engineering 21.8 (2008): 613-620.

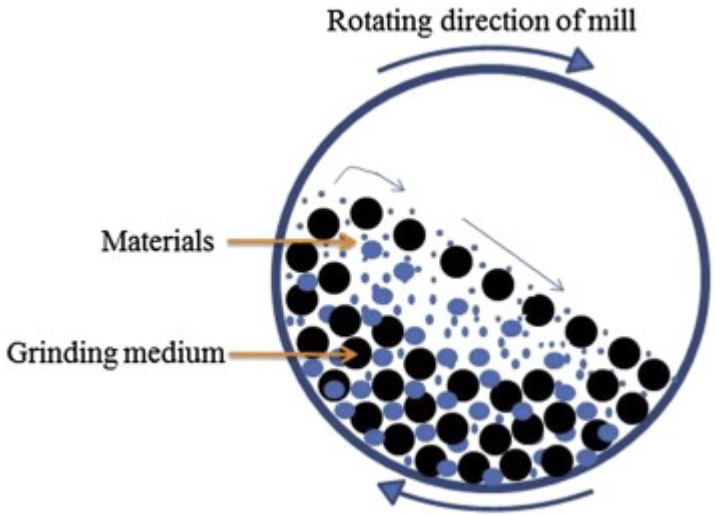
Can HTD materials lead to more efficient comminution?

Energy use increases exponentially as smaller final particle sizes are required[1]



Required energy for size reduction in comminution

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



1: Wang, Yanmin, and Eric Forssberg. "Enhancement of energy efficiency for mechanical production of fine and ultra-fine particles in comminution." China Particuology 5.3 (2007): 193-201.
2: Crushing image credit: "Infographic - Counting the Cost of Comminution." Mining Technology. N.p., n.d. Web. 23 Feb. 2017.
3: Grinding image credit: Khadka, Prakash, et al. "Pharmaceutical particle technologies: an approach to improve drug solubility, dissolution and bioavailability." asian journal of pharmaceutical sciences 9.6 (2014): 304-316.

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

Significant increase in titanium usage in aircraft…

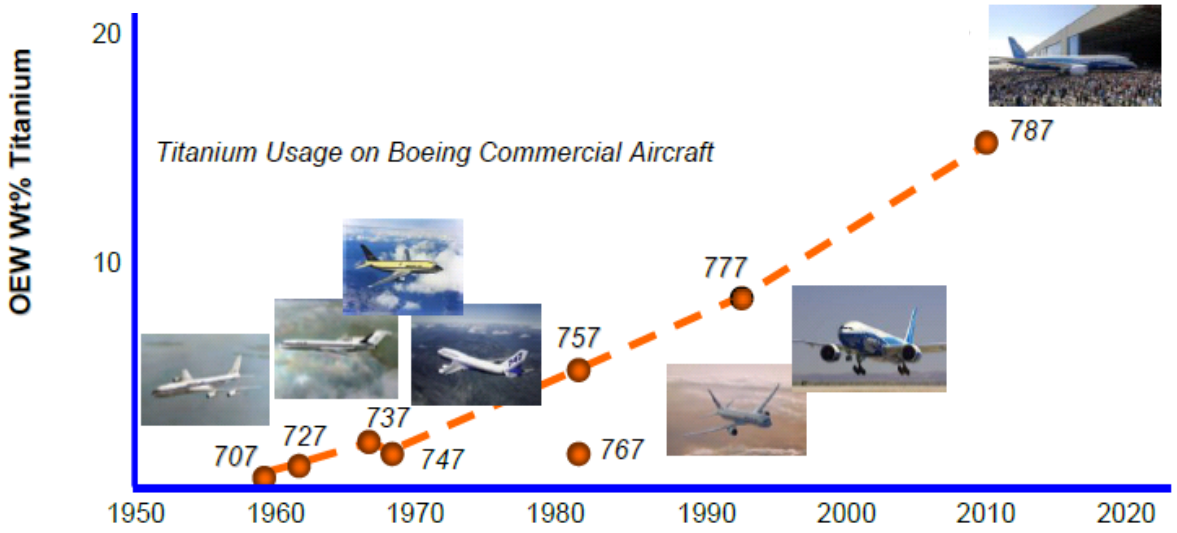


Figure adapted from: Bowden, David M., and William H. Peter. *Near-net shape fabrication using low-cost titanium alloy powders*. The Boeing Company, 2012.

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

Siler, Steve. "2015 Ford F-150 Brings Aluminum and LEDs to the 2014 Detroit Auto Show."*NY Daily News*. N.p., 13 Jan. 2014.

- 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 [2]
- 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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