Indentation load size effect in boron-based ceramics

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Introduction

It is the goal of ARL to protect the lives of those who protect yours. To improve the performance of ballistic plates, ARL is working to identify which boron-based ceramic is the hardest. Six different ceramics were chosen for testing, and the hypothesis was that one would display significantly better impact resistance making it the best material to use in ballistic vests. A greater hardness will deform the bullet projectile so that it does not pierce the vest, but instead shatters the projectile. Studies have been around for decades trying to determine which material weighs the least, but provides the most protection to incoming projectiles. Ceramics are regarded as one of the best materials to fit that description, and boron-based ceramics are particularly impressive in this regard. Many tests have been developed to best examine the hardness of ceramics, but the most widely accepted test, and the one used in this experiment was the Knoop hardness test (See Figures 1 and 2).

By analyzing the indentation's length, depth, and adjacent cracking, the hardness of the material can be determined. In an article by Vargas-Gonzalez et al. (2009), it was concluded that even armor approved by the United States government can feature significant differences in hardness. This study could be very beneficial to United States military and local police forces because if their vests are made of a tougher, lighter material, it could save many lives.

Materials and Methods

A hardness test was used to compare the materials, which requires a hardness testing machine and uses an indenter, typically made of diamond, being driven into the material with a known load and duration. The hardness testing was done on a Wilson Tukon 2100B hardness testing machine following ASTM guidelines C1326 (2013). A Scanning Electron Microscope (SEM) and an optical microscope were used to measure the resulting indentations. Six different ceramics; SiC-N, BAM ($AlMgB_{14}$), BAM with TiB_2 additive, B_6O, B_6O with 1% volume SiO_2, and B_6O with 5% volume SiO_2 were all tested. Lastly epoxy mounting was secured to the backs of each specimen to provide a parallel body that they did not rock or shift during testing. In this experiment, in accordance to ASTM standards C1326 (2013), each load was administered for a duration of 15 seconds.

Materials and Methods (cont.)

To calculate the hardness, the lengths of each indent were measured in micrometers using optical microscopy and inputted into the equation,

$$HK = (0.014299)\left(\frac{F}{d^2}\right)$$

where F is the load and d is length. At least 10 good indents were needed to calculate an average for each material at each load. There were 8 loads ranging from 100 to 10,000 gF (gram force) tested in each material. Once an average hardness at each load was calculated, the data was graphed. By comparing the horizontal asymptotes of each graph using exponential regression models (See Graphs 1-6), the hardness of each material where it is independent of load could be quantified and then ranked.

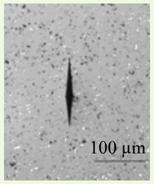


Figure 1: 5 kg indentation on BAM with TiB_2 additive which features no adjacent cracking or spalling (material ejection due to impact).

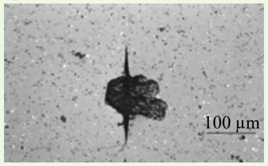
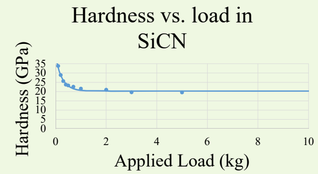
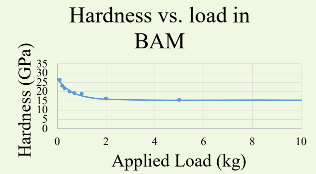


Figure 2: 5 kg indentation on BAM which features heavy spalling.

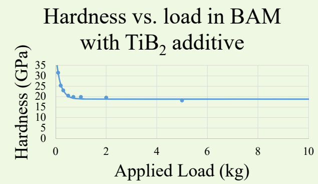
Results



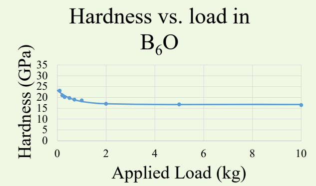
Graph 1: Exponential regression model of SiC-N, asymptote at hardness 20.3 GPa



Graph 2: Exponential regression model of BAM, asymptote at hardness 15.3 GPa

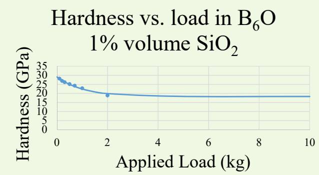


Graph 3: Exponential regression model of BAM with TiB_2 additive, asymptote at hardness 18.8 GPa

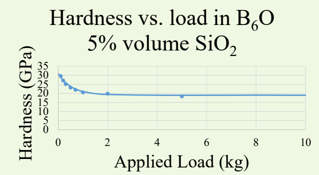


Graph 4: Exponential regression model of B_60, asymptote at hardness 16.7 GPa

Results (cont.)



Graph 5: Exponential regression model of B_6O with 1% Volume SiO_2, asymptote at hardness 18.3 GPa



Graph 6: Exponential regression model of B_6O with 5% Volume SiO_2, asymptote at hardness 19.0 GPa

The horizontal asymptotes were approximated (See Graphs 1-6). SiC-N had the highest apparent hardness as load increased, while BAM ($AlMgB_{14}$) had the lowest apparent hardness. SiC-N reached its asymptote 7% higher than any other material tested. BAM reached its asymptote 9% lower than any other material tested. These differences are enough to drastically change the performance of a vest. Noticeable abnormalities observed while testing included the consistent spalling of SiC-N samples, as well as small lateral cracks formed in all B_6O 5% volume SiO_2 samples. All of the other samples observed standard cracking mechanisms.

Conclusion

The purpose of this project was to identify which ceramic was the hardest, and if possible identify any cracking mechanisms observant in the materials that directly link with hardness. The hardest material was SiC-N, which was the control group, because it is one of the most well-studied ceramics in the field of material science. One pattern noticed was the positive effect SiO_2 has on hardness when combined with B_6O. In the future, the research of this project can be expanded by exploring further the effect SiO_2 has on other boron-based materials.

References

ASTM International. (2013). *Standard test method for Knoop indentation of advanced ceramics* (C1326). West Conshocken, PA.

Campbell, J., Vargas-Gonzalez, L., & Speyer, R. (2009). Recommendations for determining the hardness of armor ceramics. *International Journal of Applied Ceramic Technology, 7* [5] 643–651.