ABSTRACT

For many years researchers and industries involved in development of wear resistant materials have been searching for a way to produce materials containing diamonds because of their high hardness and wear resistance. Most of these processes use resin or ductile metal binders with pressure or low temperature processes to achieve compaction and usable strength. Higher temperature metals as binders have not been successful until this work, because the diamonds either react with the metal and oxidize or are converted to graphite. If converted to graphite they are no longer strong and hard, and they cannot be used in wear applications.

The primary goals of this research were to determine the feasibility of producing intermetallic-bonded diamond (IBD) composites for use as potential coal mining tool bits materials and to test and compare their wear resistance to current commercial tungsten carbide (WC) bit materials. The embodiment of this work is both unique and proprietary, because after high temperature processing, the diamonds in the IBD composites produced at SIUC remain as diamonds and are not converted to graphite or vaporized by the processes employed. Following wear testing at SIUC, the diamonds in the IBD composites were intact and the IBD composites showed extremely low wear. The IBD composites were further tested by engineers at Robert Bosch Tools Co. They found the IBD materials produced at SIU to be exceptional; in one test they reported the wear resistance of the SIUC IBD to be 800 times more wear resistant that their most wear resistant grade of WC. In the words of the Bosch engineers, “WC tools have been the standard for over 50 years in the mining industry because nothing else has been able to improve on the abrasion resistance and performance of WC. The IBD materials may be the next step in the evolution of better and longer-lasting materials.”

Although, there is much more work to be done to commercially produce IBD composites for coal mining bits, the results of Phase I conclusively established that high temperature intermetallic can be used as a binder for diamonds in producing IBD’s. The diamonds survived the thermal processing conditions and demanding wear testing against cast iron, granite, and diamond grinding wheels and cut-off blades. Phase I was completed ahead of schedule and the Phase II proposal will be submitted, following acceptance of the Phase I final report.

“Pages 1 through 33 contain proprietary information.”
EXECUTIVE SUMMARY

BACKGROUND

It is believed that future coal mining operations can be improved through the development and production of a mining tool bit that maintains its cutting edge and is strong and tough enough to withstand the forces involved in coal mining operations. Advances in recent years in composite, intermetallic matrix materials may be the key to producing this unique tool. Improving coal production with safer and more environmentally friendly methods could also lead to more jobs in the coal industry of Illinois. Developing a new diamond composite tool could also lead to additional manufacturing jobs in Southern Illinois.

Current cutting tools are tungsten carbide (WC) bonded with cobalt (Co). These tools have been used for many years and over the years these cutting bits have been redesigned to take advantage of the hardness and toughness of these cutting tools. Many problems still persist with these cutting tools because of the attack of the Co binding phase, which leads to wear of the tool bit. Also, both W and Co are strategic materials which must be imported, the US would benefit from reduced dependence. For over 30 years, researchers have been looking for a way to embed diamonds into metals to improve their wear resistance and sharpness of tools. The major problem with embedding diamonds is the poor oxidation resistance and thermal stability of the diamonds during the processing of the metal binder. This was proven in numerous experimental and theoretical works where attempts were made to embed diamonds in a Co matrix. Prior to this work, there was no reported technology that allowed the production of diamond composite materials, using high-temperature processing with metal binders.

EXPERIMENTAL AND TESTING

A total of 53 formulations of IBD’s were produced using a combination of alloying elements with the chosen intermetallic, modifying carbide additions, and 6 different sized industrial diamonds. The formulations were all processed by wet milling in solvent, followed by drying, screening and dry pressing. The resulting green discs, 1” in diameter by about 0.25” thick, were then densified by three techniques: the continuous furnace at SIUC in flowing Ar, the vacuum/pressure sintering technique developed by ORNL at their facility, and hot pressing at SIUC in the laboratory of the Center for Advanced Friction Studies (CAFS). X-ray diffraction (XRD), light optical microscopy (LM), and scanning electron microscopy (SEM) were techniques used to confirm the existence of diamonds in the IBD composites, following sintering, and before and after wear testing.

Wear testing was conducted in several ways. The Friction Assessment Screening Test (FAST) used by CAFS to measure friction coefficient was modified to allow testing of full-sized IBD composites. The wear material was gray cast iron and a force of 80 lbs was used. For selected IBD composites, 9 hr FAST tests were conducted. For comparison, a commercial WC disc was also FAST tested for 9 hr.

In order to simulate tool wear in rock, selected IBD’s were tested using the CAFS sub-scale dynamometer using granite as the substrate. The sub-scale dynamometer was operated at 1,000 rpm with normal clamping forces of 50 lbs, 100 lbs and 200 lbs for the
duration of 20 minutes at each of the three loading conditions. The granite was significantly worn with minimal wear or damage to the IBD composites.

To provide an even more severe wear test, the IBD composites were tested against a diamond polishing wheel at SIUC and by the Multi-Metals Division of Robert Bosch Tool Co. At SIUC, three IBD composites were mounted face down in an automated polishing fixture and run against a 250 micron diamond wheel at 400 rpm and 50 lbs of down force for 30 hours. At Bosch, one IBD composite at a time and one WC standard were tested against a new 250 micron diamond wheel at 400 rpm and 60 lbs of down force for 2 min or until they wore to the backing plate. In addition, Bosch ran a cutting test using a diamond saw and measured the penetration of the saw into the IBD composites and compared the IBD composites against their most wear resistant WC.

RESULTS AND CONCLUSIONS

Diamonds were found to survive the processing and sintering of the IBD composites, as shown in Figure 1. This was true for the intermetallic-carbide-diamond composites with and without alloying modifications. The best density results to date were achieved by hot pressing. Hot pressing was also challenging because of the temperature and pressure sensitivity of the intermetallic and reaction with the diamond powder surface and the effect of the additions and alloying elements. Smaller diamonds had greater reactivity, while the larger diamonds investigated had significantly reduced activity. Continuous sintering and sintering using the ORNL vacuum/pressure cycle did not produce high density; therefore performance was reduced, however, the larger diamonds did survive sintering at high temperatures.

Wear testing, measured by the FAST test, showed the IBD composites to have higher coefficient of friction than WC and similar weight loss. Depending on the diamond size and concentration, the friction coefficient was found to be between 0.30 and 0.45. The wear of the gray cast iron was significant because the IBD composites showed minimal wear while the cast iron was being easily machined.

In sub-scale dynamometer testing, the IBDs showed exceptional performance against granite (Figure 2). Cutting rate was high and IBD wear was extremely low. At the highest force, the IBDs turned red hot and so much friction was developed that the granite exploded due to thermal expansion. The IBD composites showed exceptional wear in testing against diamond. In the face wear testing at SIUC the composites survived 30 hours, resulting in more wear on the diamond polishing disc than the IBD’s (Figure 3). In edge wear tests conducted by Bosch against diamond, the dense IBDs were more than 4 times resistant to wear than the most wear resistant WC. In diamond cutting tests by Bosch, the dense IBDs displayed an astonishing 800 times greater wear resistance (Table I) than their most wear resistant grade of WC. These results have generated enthusiastic support of Bosch towards the future development and commercialization of IBDs, and support of Phase II.
Figure 1. SEM images of IBDs following sintering, showing that the diamonds (dark particles) survived the high-temperature environment during sintering.

Figure 2. IBD after three dyno runs.

Figure 3. IBDs after 30 hr diamond wear test.

Table I. Diamond cut-off wheel test results from Robert Bosch Tool Co.

<table>
<thead>
<tr>
<th>LABEL</th>
<th>SIU SAMPLE ID</th>
<th>SAMPLE THICKNESS</th>
<th>AVE. DEPTH of CUT</th>
<th>AREA of CUT</th>
<th>CUTTING TIME</th>
<th>PENETRATION RATE x10^3</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>F33HP FAST</td>
<td>0.275 in</td>
<td>0.489 in</td>
<td>0.134 in²</td>
<td>30:00 min</td>
<td>4.5 in²/min</td>
</tr>
<tr>
<td>B</td>
<td>NAT35E35</td>
<td>0.274 in</td>
<td>0.150 in</td>
<td>0.041 in²</td>
<td>30:00 min</td>
<td>1.4 in²/min</td>
</tr>
<tr>
<td>C</td>
<td>E33HP</td>
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<td>0.036 in</td>
<td>0.008 in²</td>
<td>30:00 min</td>
<td>0.3 in²/min</td>
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<tr>
<td>D</td>
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<td>0.034 in</td>
<td>0.009 in²</td>
<td>30:00 min</td>
<td>0.3 in²/min</td>
</tr>
<tr>
<td>E</td>
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<td>0.912 in</td>
<td>0.324 in²</td>
<td>1:15 min</td>
<td>259.2 in²/min</td>
</tr>
</tbody>
</table>

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