ABSTRACT

The original work was initiated to investigate a new material that may prove advantageous in coal mining, gas and oil drilling, excavating, and other industries where hard materials like tungsten carbide (WC) and polycrystalline diamond compacts (PDC) are used. In coal mining this is especially a problem in both mining and handling the coal where dust and the corrosive environment can create problems. A cutting tool that stays sharp and can last longer would improve both the mining health environment and production costs.

The work in the Phase I research showed the feasibility of producing diamond composites bonded with an intermetallic compound composed of nickel and aluminum, termed IBD. Phase II concentrated on the optimization of the processing methods and formulations, the investigation of alternative densification mechanisms, the investigation of successful bonding methods to other materials, and continued wear and performance testing. The Phase III work concentrated on prototype development, scale-up of the processing equipment, and actual field testing of IBD prototypes. A no-cost extension was granted to the project because of delays in delivery of a larger capacity hot press prevented task completion. New die designs allowed the production of conformal shapes for bits used in coal mining bits, limestone crushing equipment and down-hole drills. Field testing has provided information to improve the IBD formulations and testing conditions. Conical bits for testing in an Illinois coal mine were produced, but the mine where testing was to occur has been shut down. Additional bits for testing in another mine were produced and tested using the new equipment in the no-cost extension period.

A new hot press was ordered and installed in order to allow the production of more than one composite tip at a time in newly designed multi-component die sets. More than 6 different types of bits were produced. One set of these bits was tested in an Illinois coal mine, however the test met with limited success because of the tempering of the steel bodies during brazing of the tips. This was overcome by developing an interference fit between the steel body and IBD tip and another set of tips was prepared. Mine strikes prevented testing of these tips and an alternate test mine was found. The final set of 12 IBD tipped bits were tested in October 2007 at the Crown III Mine near Farmersville, IL. Only 2 IBD bits were available for comparison to the WC bits, but clearly the wear of the IBD composite was less by 3 to 5 times compared to that of the WC. Failure of the WC was by brittle failure while the IBD wore continuously, exposing fresh diamonds.
EXECUTIVE SUMMARY

The major objectives of this research were to develop a net-shape process for producing sufficient quantities of IBD composite tool bits for continuous mining equipment and to conduct preliminary and full-scale mining tests in local Illinois coal mines.

The following 4 tasks were targeted for completion during this project phase:
Task 1. Install Hot Press
Task 2. Design Graphite Die Sets
Task 3. Preliminary Mine Screening Tests
Task 4. Full-Scale Mine Testing

As reported in previous reports, coal mining can potentially benefit from improvements in the technology used to mine and handle coal. The development and production of a mining tool bit that maintains its cutting edge longer than current materials and is strong and tough enough to withstand the forces involved in coal mining operations would be of great benefit to the mining industry. These sharper tool bits are expected to also produce less dust, which has obvious health and safety advantages, and tools that last much longer than conventional tools will decrease coal production costs. As mentioned in prior reports, SIU has a patent pending that covers processing and production of IBD composites. In 2007 an option for a license was executed between SIU and a major company fully capable of commercialization of the invention. This agreement precludes SIU from working with any other company on the fields of interest covered by the agreement. No disclosure of details related to this agreement will be made because of confidentiality.

In both Phase I and II of this project, supported by ICCI, the feasibility of producing Intermetallic-Bonded Diamond (IBD) composites was proven. Over 130 IBD composite formulations were made, densified and tested. Hot pressing was found to be the best method for densification. An industrial partner, Robert Bosch Tool Co., reported that some of the IBD composites selected had 800 times greater wear resistance when compared with their most wear resistant WC. During Phase II, IBD formulations containing 30 and 50 vol% intermetallic were identified as having the most promise for mining related applications. In addition the hot pressing conditions were optimized to improve densification. Bonding of IBD composites to alternate materials was successfully investigated. IBD composites were bonded by self-diffusion and brazing to the base intermetallic and to other IBD formulations containing lower amounts of diamond.

The major component of Phase III was prototype production and field testing of mine bits containing IBD and WC tips. Production of the IBD tips required the installation of a larger capacity hot press. Delays were experienced that required a no-cost extension that was granted, resulting in a new end date of February 28, 2007. Further delays in mine closings and scheduling mine testing caused even more problems in completing Phase III.

The hot press was installed and several sets of bits were completed for the proposed mine tests. Each mine used a different style bit, so 4 different style IBD tips were designed...
and produced for testing in the Liberty (Figures 1 and 2), Wabash (2 sizes shown in Figures 3 and 4) and Crown III (Figure 5) mines. Tests planned for the Liberty mine were cancelled due to the mine closing. Testing was then planned for the Wabash coal mine and two different bits sizes were prepared. The larger bits (Figure 3) were produced first but were not tested due to equipment problems and the smaller bits (Figure 4) were tested in February 2007. The Crown III bits were finally tested in October of 2007.

The testing in the Wabash coal mine met with limited success due to problems with the steel bodies holding the IBD tips. During the brazing operation, the steel bodies were annealed which made them very ductile, as seen in Figure 6. Some of the steel bodies survived the testing and did not deform to the same extent. These were comparable to the WC tipped bits that are commercially used in mining. Figure 7 shows two of the WC tipped bits after the Wabash testing, where the bit on the left does not show much damage, while the bit on the right was cracked and destroyed. In contrast, the IBD bits shown in Figure 8 do not show any signs of cracking or wear. This is significant because toughness of the IBD tip to this type of impact is an important property.

Annealing of the steel was thought to be solved by using an interference (shrink fit) to install tips into the bits for testing in the Crown III mine near Farmersville, IL. The steel body was a different design and so was the IBD tip. The results from testing at the Crown III mine were again affected by the process used to remove the original WC tip from the steel body. Several of the bits were not fully heat treated and the steel bodies were severely deformed. The IBD tipped bits that were properly heat treated did not deform and out performed the WC tipped bits in this test (Figure 9). Because of problems related to removing the WC tips from the steel bodies, results of mine testing were not fully conclusive. However, based on limited data, the IBD tips clearly out performed the WC tips in wear and failure mode. Only 2 IBD bits were available for comparison to the WC bits, but clearly the wear of the IBD composite was less by 3 to 5 times compared to that of the WC. Failure of the WC was by brittle failure while the IBD wore continuously, exposing fresh diamonds.

The major conclusions from Phase III were:

- IBD was shown to outperform WC in both wear and failure mode;
- IBD tipped bits can survive in conditions where rock is present;
- IBD tips can be attached to steel bodies by interference fit without requiring a heat treating step after attachment but require either virgin steel bodies or additional heat treatment during fabrication.
Figure 1. IBD tip on left and original WC tip from Liberty mining bit.

Figure 2. Set of IDB tipped bits for Liberty mining test, after brazing.

Figure 3. Large bits for Wabash mine test.

Figure 4. Small bits for Wabash mine test.

Figure 5. Twelve IBD tipped mining bits for testing in Crown United coal mine.
Figure 6. Bits after Wabash testing.

Figure 7. WC tipped bits after Wabash testing.

Figure 8. IBD tipped bits after Wabash testing show little damage to the IBD.

Figure 9. IBD tips on left and WC tips on right after Crown III test show less damage to IBD.

This research was made possible by the Illinois Department of Commerce and Economic Opportunity through the Office of Coal Development and the Illinois Clean Coal Institute.
OBJECTIVES

The major objectives of this proposal were to develop a net-shape process for producing sufficient quantities of IBD composite tool bits for continuous mining equipment and to conduct preliminary and full-scale mining tests in local Illinois coal mines.

The following tasks were targeted for completion during this project phase:

Task 1. Install Hot Press

This task required the specification, purchase and installation of a 50 ton hot press. A larger hot press was required to allow for multi-component die and larger part production.

Task 2. Design Graphite Die Sets

The design and fabrication of multi-component die sets will allow going from producing bits one at a time to producing several in one pressing.

Task 3. Preliminary Mine Screening Tests

This task was designed to allow the initial screening of several IBD composite tool formulations and formations in limited laboratory and field testing.

Task 4. Full-Scale Mine Testing

Full-scale testing at an Illinois coal mine.

BACKGROUND

As reported in previous reports for Phase I and Phase II, coal mining can potentially benefit from improvements in the technology used to mine and handle coal. The development and production of a mining tool bit that maintains its cutting edge longer than current materials and is strong and tough enough to withstand the forces involved in coal mining operations would be of great benefit to the mining industry. These sharper tool bits are expected to also produce less dust, which has obvious health and safety advantages, and tools that last much longer than conventional tools will decrease coal production costs. There is also the benefit from reduced downtime to replace the mining bits. Tools that wear instead of fracturing also would be much safer and potentially reduce mine accidents due to the current WC bits acting like projectiles when they fracture. Recent advances in intermetallic matrix materials that contain diamonds (IBD) have spawned a potentially new generation of hard materials. Development and production of a new IBD mining tool could also eventually lead to the development of a small business and the creation of additional manufacturing jobs in Southern Illinois. Licensing of the technology is currently bringing rewards to the State of Illinois through revenue generated for SIU, through licensing fees and potential future royalties. In
2007, an option agreement for a license was executed with a major company fully capable of commercialization of the invention. This agreement precludes SIU from working with any other company on the fields of interest covered by the agreement. No disclosure of details related to this agreement will be made in this report because of confidentiality.

In both Phase I and Phase II of this project, supported by the ICCI, the feasibility of producing IBD composites was proven. Over 130 IBD composite formulations were made, densified and tested. Hot pressing was found to be the best method for densification. An industrial partner, Robert Bosch Tool Co., reported that some of the IBD composites selected had **800 times greater wear resistance** when compared with their most wear resistant WC. During Phase II, IBD formulations containing 30 and 50 vol% intermetallic were identified as having the most promise for mining related applications. In addition the hot pressing conditions were optimized to improve densification. Bonding of IBD composites to alternate materials was successfully investigated. IBD composites were bonded by self-diffusion and brazing to the base intermetallic and to other IBD formulations containing lower amounts of diamond.

The major component of Phase III was related to the prototype production and field testing that required the installation of a larger capacity hot press. Because of production problems the hot press was delivered almost 5 months after the quoted date. This delay required that a no-cost extension be granted. Further delays in mine closings and scheduling mine testing caused even more problems in completing this task, resulting in a new end date of February 28, 2007. The hot press was installed and several sets of bits were completed to accommodate 4 different mine tests. Because of problems previously mentioned, only 2 of these tests were completed in FY07. Because of problems related to removing the WC tips from the steel bodies, results of mine testing were not fully conclusive. However, based on limited data, the IBD tips clearly out performed the WC tips in wear and failure mode.

**EXPERIMENTAL PROCEDURES**

Based on previous results from field testing, techniques previously reported were used to produce mine bit tips using the IBD composites containing 30 vol% intermetallic, a carbide phase and diamond. Four different style IBD tips were designed and produced for testing in the Liberty (Figures 1 and 2), Wabash (2 sizes shown in Figures 3 and 4) and Crown III (Figure 5) coal mines. The tips for the Liberty bits were prepared in the old hot press and all other bit tips were prepared in the new higher-capacity hot press (Figure 10) that was installed in January 2007. Higher pressures of over 10,000 psi were used to process the tips in the new hot press, compared with 3500 psi in the old hot press. The Wabash tips were pressed in multi-component dies with a single die cavity (Figure 11). Multi-component dies contained the die body, conformal tip plunger, base profiler, and bottom plunger. A multi-component, multi-cavity die set was designed (Figure 12 and 13) and used for the bit prepared for the Crown mine testing, three tips were pressed simultaneously (Figure 14) with this multi-cavity die set to produce a total of 12 bits.
Tests planned for the Liberty mine were cancelled due to the mine closing. Testing was then planned for the Wabash coal mine and two different bits sizes were prepared. The larger bits (Figure 3) were produced first but were not tested due to equipment problems at the mine and the smaller bits (Figure 4) were tested at the Wabash mine in February 2007. The IBD tips were vacuum brazed into the steel bodies for this testing. Subsequent IBD tips prepared for testing in the Crown III coal mine were attached to the steel bodies by interference fit, as shown in Figure 15.

![Figure 10. Hot press and control cabinet SIUC.](image10)
![Figure 11. Large single cavity die in new hot press.](image11)

<table>
<thead>
<tr>
<th>Parts List</th>
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<td>ITEM</td>
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<td>4</td>
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![Figure 12. Six inch diameter die drawing to press 3 IBD tips simultaneously.](image12)
RESULTS AND DISCUSSION

Task 1. Install Hot Press

There was significant delay in the purchase and installation of the new 50 ton hot press (Figure 10). The installation went smoothly and production of test bits started immediately thereafter. The large press easily contained the large multi-component, multi-cavity die set and the brazing set up to do 12 bits at one time (Figure 4).

Task 2. Design Graphite Die Sets

As mentioned previously, the design and fabrication of multi-component, multi-cavity die sets allowed the production of 3 bits at a time. This design could be modified to accept
up to 12 independent die cavities, thereby increasing production by a factor of 12 over using a single die cavity design. The design and die set are shown respectively in Figures 12 and 13.

Task 3. Preliminary Mine Screening Tests

The preliminary mine screening test of the IBD tipped bits was performed on February 16, 2007 at the Wabash Mine. This mine is a room-and-pillar underground operation located in Wabash County in the Illinois Basin East of Keensburg, IL. The goal of the underground mine test was to compare the performance of the current commercially available WC/Co bits with the newly developed IBD tipped bits made at SIUC. Evan Sink representing the Mineworkers Union, Bill Hoback from the Illinois Department of Commerce and Economic Opportunity, Francois Botha from the Illinois Clean Coal Institute and Peter Filip from the Center for Advanced Friction Studies at the College of Engineering at SIU Carbondale were present at the testing. The test was made possible after arrangements were made by Bill Hoback and the Wabash Mine Land manager Bill Kelly. The assistant manager Keith Mills was present and arranged the testing, Francois Botha picked up the retrieved samples from the manager Michael Meighen on Monday February, 19, 2007 for evaluation at SIUC.

A total of 11 of the 12 IBD tipped bits and three WC/Co bits used on the same miner were recovered from the testing. Figure 6 shows all of the bits after the test, where it is obvious that the steel bodies containing the IBD were heavily plastically deformed as a result of interaction between rock and the miner. This deformation was because of the annealing that occurred during the vacuum brazing of the tips in the steel bodies. Annealing and grain growth of the steel was responsible for lowering of yield stress.

In addition to annealing, the machining of a larger hole for inserting the IBD tip into the steel body decreased the effective cross-section of the steel supporting body. As easily seen from Figure 6, bending and heavy plastic deformation of the steel body was often responsible for a total damage of the mining bits. However, not all bit tips were destroyed and the performed test indicated surprisingly high toughness of the IBD bit tips. Figure 16 shows the WC/Co bit (left) and the IBD bit (right) in a situation when the steel body was worn off to similar extent. While the currently available WC/Co tip is heavily damaged (left in Fig. 16), the IBD tip (right in Fig. 16) survived without significant wear. When observing the fracturing mode of the IBD tipped bits, it was found that the cracks were initiated and progressed in the tensile region of a bent tip and after reaching the critical length, the bit tip was broken and the “soft steel body” was easily cut and smeared in the wear process against the coal and rock. This occurred in the bits that went through two brazing cycles because of overheating during the first braze cycle. Proper post-brazing heat treatment by oil quenching could have prevented the improper annealing of the steel bit bodies; however, the equipment to do a proper oil quench was not available at SIU.
When the bits were not heavily plastically deformed, and if the WC tips were not fractured (as shown in Fig.16) there was significant difference between the wear of the WC/Co and the IBD tips observed during the first field test, as demonstrated in Figures 7, 8 and 17. In some cases there was no apparent significant wear of the WC but if there was damage, then the damage was catastrophic. The results for the IBD are shown best in Figure 8 where there is no significant wear or damage to the tips. Any wear was found to be gradual and did not result in catastrophic fracture of the IBD tip. In Figure 17, the left bit is the WC material, while those with the residual orange paint contained the IBD tips. This was very encouraging because this demonstrated that the IBD material has toughness, strength and wear resistance necessary to operate where the WC has shown a tendency to fracture.

Task 4. Full-scale Mine Testing

Full scale testing of the IBD bits at an Illinois coal mine was arranged by Bill Hoback and Dan Wheeler (DCEO) at the Crown III coal mine near Farmville on October 23, 2007. Dan Wheeler, Joe Hirschi, and Francois Botha (ICCI), and Peter Filip (CAFS SIU) were present during the testing. The testing was performed using a continuous miner, Model 12CM12, made by Joy Manufacturing Co. The IBD bits were placed as follows:
2 on the left side of the drum, 2 on the right side of the drum, and 8 in the central part of the drum. The IBD bits were always surrounded by new WC bits, which allowed for comparative evaluation. The miner was cutting both flint and coal (about 30/70) and only ran for about 25 minutes on the first run. After this time all but 2 of the IBD bits were removed along with the adjoining WC tipped bits. The remaining IBD bits cut another 25 – 26 minutes before the miner was again stopped and the remaining IBD bits and surrounding WC bits were removed.

Figure 18 shows the IBD bits after the test. It is obvious that only two out of twelve bits provided reasonable results. The remaining IBD bits failed because of steel body failure; to a lesser extent compared to the Wabash test performed in February 2007. It is clear that the hardness of the steel body was not recovered after the WC tip removal. Two of the 12 IBD bits had undergone double heat/quench cycles and these were bits 9 and 11. Both of these bits survived because the steel was hardened by the double quench and are used for performance comparative purposes against the WC bits taken from the same region of the miner drum.

Figure 18. IBD bits after test. The 10 bits to the left failed because of softened steel body. The 2 bits shown on the right-hand side, #9 and #11 were used for comparative analysis.

Figure 19 shows the two good IBD bits in comparison with two neighboring WC bits. In addition a new WC bit was added to obtain better information about wear process of the WC. Bit #11 and WC 1 run bit were removed after one run and the IBD bit #9 and the WC 2 runs bit were removed after two runs.

Figure 19. The IBD and WC bits loaded at identical conditions and removed after one or two runs.
The wear data were obtained from comparison of initial and final mass of each bit. Wear was calculated as the mass loss in % and the data are summarized in Table I. The mass loss represents the amount of worn material from bit tip only (the mass of the steel body was not taken into consideration). The total wear observed for the two IBD bits removed after one and two runs, respectively, was almost equal and lower than 3 wt %, while the wear of WC bit was considerably higher, 21.3 wt% and increased with the second run, 37.2%. Obviously, the wear of WC bits was significantly higher compared to IBD samples. On a volume bases, the WC bits lost 3 to 5 times more volume than the IBD and more importantly the wear mechanism was entirely different. The IBD bits had continuous wear and exposure of fresh diamond surfaces while the WC bits failed by intensive fracture and break out. While preparing the bits for analyses, it was found that the WC bit that survived 2 runs was severely fractured inside of the steel body. Fracture of the IBD bits was not observed and it should be noted that the method for inserting IBD bits without brazing seems to be very reliable. Further tests are necessary to make more general conclusions about wear and reliability of this braze-less method of tip insertion.

### Table I. Summary of wear data from comparative bits.

<table>
<thead>
<tr>
<th>Coal Bit ID</th>
<th>Original mass $M_i$ [g]</th>
<th>Mass after test $M_f$ [g]</th>
<th>Loss $\Delta M = M_i - M_f$ [g]</th>
<th>Wear [wt %]</th>
</tr>
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<tr>
<td>IBD#9, 2 runs</td>
<td>19.329</td>
<td>18.853</td>
<td>0.476</td>
<td>2.5</td>
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<tr>
<td>WC, 2 runs</td>
<td>20.000</td>
<td>12.560</td>
<td>7.440</td>
<td>37.2</td>
</tr>
<tr>
<td>IBD #11, 1 run</td>
<td>19.325</td>
<td>18.796</td>
<td>0.539</td>
<td>2.7</td>
</tr>
<tr>
<td>WC, 1 run</td>
<td>20.260</td>
<td>15.945</td>
<td>4.315</td>
<td>21.3</td>
</tr>
</tbody>
</table>

The SEM images of the retrieved tips revealed the fundamental mechanisms of wear of the individual bits. Figure 20 shows the characteristic surface morphology observed in the WC bits. The major factor contributing to accelerated wear of the WC was fracturing of considerable “chunks” of WC as easily seen in Fig. 20 (a). The wear process occurred in the direction from the bottom to the top of the image and the removed “chunk” of WC composite caused abrasive wear which is visible as a “tail” in the upward direction. The details of the WC surface observed in Fig. 20 (b) show that individual WC particles were also fractured by this severe impact and wear process.

In contrast, the IBD samples demonstrated better integrity, which can be ascribed to a stronger matrix. Importantly, the diamonds present survived the harsh impact and wear conditions better than the WC and they are visible in Figure 21. Figure 21 (a) is a low magnification back-scattered electron image taken from the surface of the used IBD tip and shows the presence of the diamonds (black particles). Figure 21 (b) is a detail image of the IBD surface, clearly demonstrating that diamond tips point upwards (marked by arrows) and the tool remained sharp. This is an important factor creating potential for dust elimination as discussed earlier in Phase I and Phase II reports, when laboratory tests were evaluated. It is important to mention that both laboratory and field tests led to identical conclusions regarding diamond survival and capacity to make diamond tools that stay sharp.
Figure 20. Surface of the WC tip after 2 runs in the mining test. (a) shows the release of a “chunk” of WC composite with abrasive action, and (b) a detailed image showing fracturing of the WC particles in the WC bit.

Figure 21. Surface of the IBD bit after 2 runs in the Crown III mine test: (a) diamonds (black areas) survived the severe loads, and (b) diamonds (marked by arrows) remain sharp on the surface of the IBD tip.
CONCLUSIONS AND RECOMMENDATIONS

The major conclusions for this phase were:

- IBD tipped bits involved in coal mining, including the presence of rock, survived testing.

- Standard brazing can not be used for attaching steel bodies without a heat treating step following the brazing operation. This capability is not present at SIU.

- IBD tips can be attached to steel bodies by interference fit without requiring a heat treating step after attachment. Care has to be taken to properly remove the bit from the steel body, followed by subsequent heating and quenching. This could be completely eliminated if a source were found for the steel bodies without WC tips.

Recommendations for future work:

- To involve the company that has licensed the patent from SIU to become involved in future testing in Illinois coal mines when they are ready to proceed.

- The IBD tips for future testing to be installed in newly forged steel bodies without the need for removing WC tips by torch heating. This will allow for proper shrink fitting without compromise of the steel toughness and wear resistance.
DISCLAIMER STATEMENT

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