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DAMAGE PROCESSES EXHIBITED BY WC-CO COMPOSITE IN ROCK DRILLING

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ABSTRACT

A study of the interaction of tungsten carbide-cobalt inserts with rocks and abrasive was carried out using an abrasive wear test and drop weight test. In both tests, it was shown that the major mechanism of wear loss is associated with microfracture and/or fragmentation of WC grains.

The study has also revealed that wear of WC-Co depends on the hardness and abrasiveness of the rock or abrasive. The weight loss was found to be directly proportional to the number of blows during the drop weight test, while in the abrasive wear test , the weight loss was directly proportional to the hold down load and the traverse length. An analysis of the results showed that the major wear process of the WC-Co inserts during rotary percussive drilling is impact damage and the contribution of sliding abrasion to the total wear is insignificant.

INTRODUCTION

Tungsten carbide-cobalt composites are widely used for wear resistant parts and dominate as well in tools and rock drilling operations. From a practical point of view, tool wear is the most important aspect of rock drilling. Knowing that mine productivity is very dependent upon the performance of these drilling materials, it is essential therefore, that there should be an understanding of the manner in which these alloys wear or fracture. It should be borne in mind though that the wear of tools is but one aspect of the overall cutting process.

Percussive drill bits have inserts of cemented carbides on its wear faces. It consists of 5 buttons in the periphery with two buttons on the impact face as shown in Figure 1. There are other designs of rock bit inserts currently in use aside from the hemispherical button shape, which is either a chisel or wedge shape. The resulting wear of WC-Co composite depends on the drilling processes that are being employed. Most drilling is done by rotary, percussive, or rotary-percussive methods. Rotary percussive drilling is a combination of rotary and percussive methods. However, it appears that only Montgomery (1968) has published work on the wear mechanism for this type of drilling process. According to Perrott and Robinson (1974), the wear of carbide tools in rock drilling and cutting applications occurs by abrasive wear, surface impact spalling or thermal fatigue.

The mechanism of abrasive wear of tungsten carbide tools was, until recently, thought to involve the wearing away of the binder which leaves the tungsten carbide grains unsupported and susceptible to fracture and removal. Such mechanism was suggested by Doeg (1960). However, Larsen Basse (1973) postulated a second coexisting mechanism of wear; which involves the nucleation of cracks in the carbide network as a result of the impingement of abrasive particles. Later work by Bailey and Perrott (1974) reported that wear by thermal fatigue, abrasion and surface impact fatigue occurs in all cases by the propagation of intergranular cracks. But the study by Dixon and Wright (1985) shows that WC grains fracture intragranularly, subsequently generating fine WC wear debris.

In another study conducted by Larsen Basse, Perrott and Robinson (1974) using SEM, it was reported that wear of WC-Co composites takes place by a combination of cobalt erosion and microfracture of the carbide skeleton irrespective of the grade. This finding is confirmed by Blomberry, et.al (1974). It was further observed that the removal of cobalt binder appears to lower the fracture strength of the surface layers.

The final aim of this present study was to determine quantitatively the possible contribution of abrasion and impact spalling to the total wear of the insert at the impact face of the drill bit in order to understand what mechanism prevails in the wear of these alloys. Work towards this end has been in progress for some years, and the present work represents part of this effort.

II. MATERIALS AND METHODS

Three different approaches to the problem were employed due to the complexity in observing the operative wear mechanism during actual rotary-percussive drilling. The first approach was to study the bits worn in actual field operation. Worn bits supplied by Sandvik (Sweden) were examined using the optical microscope and scanning electron microscope in order to determine the general characteristics of the worn surfaces. The most helpful correlation in developing a wear test is the comparison of the worn surfaces and wear debris produced in the test to those produced in actual practice.

The second approach was an abrasive wear testing procedure using 180 grit size alumina and garnet abrasives. According to Perrott (1979), these abrasives have been found in the hard metal industry to provide a better basis for empirical correlation with field performance and predictive wear tests. A pin-on-plate high abrasion tester attached to the milling machine was used in the test. Weight loss measurements were conducted after each test including examination of the worn surfaces in the SEM.

The last approach was a drop weight test made unto the rock, which could effectively reproduce the percussive action of the bit. Multiple impacts were applied on the flat surface of the rock. SEM examination and weight loss measurements were also conducted after each test.

2.1 Materials

The WC-Co insert contained 5.53% Co and has a density of 15.11 gm/cc. The bulk hardness is 1650 kg/mm^2 and the crack resistance is 0.22 kg/mm, as determined by the Palmqvist method. The inserts were examined using both optical microscopy and SEM over a wide range of magnifications. The examination was generally restricted to the region close to the worn part of the insert. A Mt. Isa rock (85% quarts) and Ashgrove granite rock (25 % quartz) were used in the experiment.

2.2 Methods

2.2.1 Abrasive Wear Test

Tungsten carbide-cobalt specimens were pressed over cloth backed abrasives (Hermes brand) using a pin-on-plate high stress abrasion tester attached to the Maxport milling machine as shown in Figure 2. This tester was fabricated based on the specification of Conroy (1989). The speed of linear translation of the specimen across the abrasive surface was 0.3 m/min and 1 m/min at a load from 4 kgs to 12 kgs. The length of the abrasion path was 280 mm with a maximum of 20 passes which is equivalent to 5.6 meters total traverse length. The specimen diameter was 9 mm and the speed of specimen rotation was 150 rpm.

The stage of the milling machine was adjusted continuously during the operation to ensure that fresh abrasive was always in contact with the specimen. After 20 traverses, the pin specimen was removed from the tester and cleaned with an ultrasonic cleaner with alcohol. After drying, the specimen was weighed in the Sartorius Research Electronic Balance.

2.2.2 Drop Weight Test

A PVC pipe, 50 mm diameter and 600 mm length was used as a guide apparatus for the 2 kg drop mass as shown in Figure 3. The drop mass and drop height was based on the typical percussive drill below energy of 80 joules as reported by Larsen Basse (1973).

The rock to be tested was cut in the diamond wheel in order to have a flat and smooth surface. Each test involved dropping the WC-Co specimen attached to the drop mass a total of 400 times. After dropping the insert several times, the weight loss was taken after every 100 drops until the 400 drops. SEM examination was also conducted after each 100 drop interval to confirm possible cracking of the WC grains, surface spalling, and fracture of the composite.

III. DISCUSSION OF RESULTS

A comparison of the microstructures of the worn inserts taken at the impact face and gauge faces (periphery) of the bit used in drilling showed some differences. Figures 4 and 5 reveal a wear flat which manifested grooving due to grinding abrasion. It is known for a fact that gross grooving of the wear flat in a certain direction usually indicates that the gauge face had less impact. Therefore, we can safely conclude that abrasion is the wear mechanism that is dominant in this button part of the drill bit. In Figures 6 and 7 , the wear flat of the buttons on the impact face does not show any grooving, only WC grains that were fragmented due to brittle fracture during impact. These figures also demonstrate gross removal and pull out of WC grains from different areas of the surface.

3.1 Abrasive wear test results

The results of wear testing carried out against alumina and garnet abrasives using different applied loads and traverse speeds and lengths are shown in Figures 8 and 9 below.

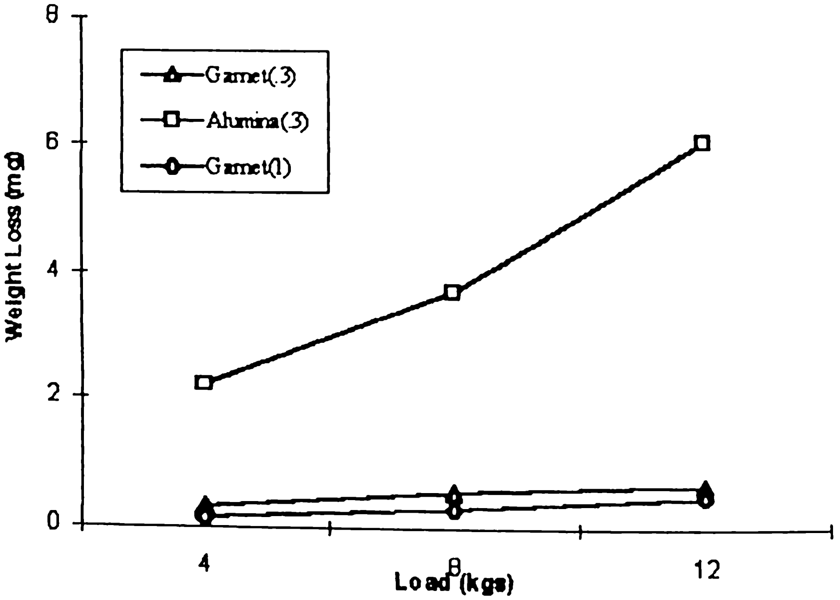

Figure 8. Effect of varying applied load and traverse speed (0.3 m/min and 1 m/min) on weight loss of WC-Co in garnet and alumina abrasive.

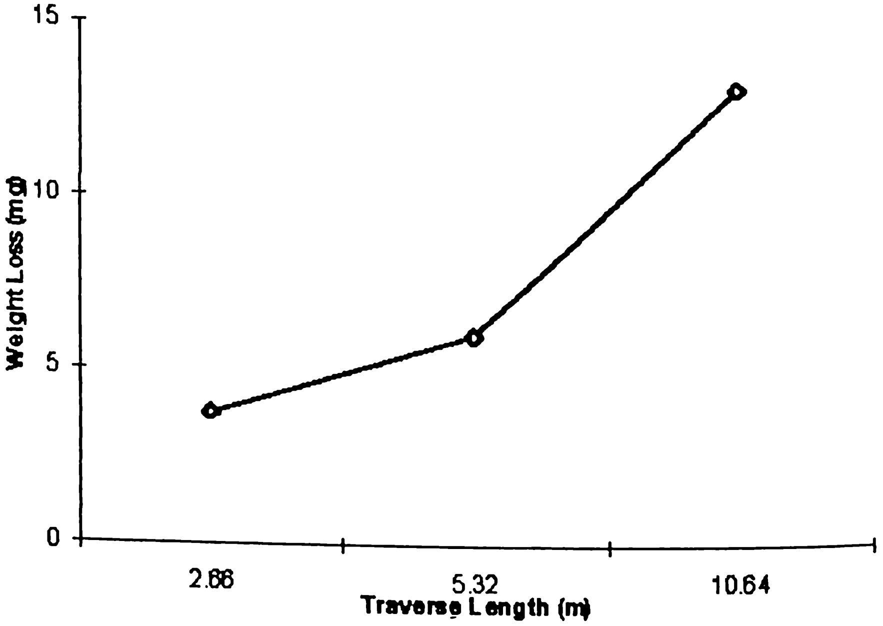

Figure 9. Effect of varying traverse length on weight loss using alumina abrasive at 12 kgs hold down load.

The quantified results of abrasive wear test illustrates a distinctive linear relationship between applied load and weight loss, and traverse length and weight loss. Such relationship thus indicates that the hold down load and sliding distance are important parameters that determine the wear rates during abrasion. However, there is a greater weight loss of the composite in alumina abrasive than in garnet considering that alumina is harder than garnet. The hardness of alumina is approximately 2,000 kg/mm^2 while that of garnet is approximately 1,200 kg/mm^2, with the hardness of WC-Co composite at about 1,650 kg/mm^2. This means that the material removal during abrasive wear also depends on the hardness of the abrasives. A further increase in the hardness of the abrasives leads to higher wear rates because the hard abrasive can scratch the material deeper. In this case, alumina was able to partially cut the composite as shown in Figure 10. Alumina abrasive can cause a gross grooving formation on the surface of the composite considering that it is harder than the composite. Alumina abrasive removed both the binder and the WC grains from the setting while the softer garnet abrasive can cause only a preferential cobalt removal.

According to Doeg (1960), the removal of cobalt binder which causes a release of the compressive stress acting on the WC grains, could be one of the reasons for the formation of transcrystalline cracks. At high levels of compressive stresses, the binder material tends to be extruded from the binder regions because it has lower yield point. The constraining effect of the binder and its associated compressive stresses in the carbide phase decreases to the point where cracks can propagate through the carbide grains. However, it is interesting to note that most cracks occurred on the coarse WC grains that were abraded by the alumina abrasives.

3.2 Drop weight test results

Table 1 shows that there was higher weight loss of the composite when dropped on Mt. Isa rock. Studies by Perrott and Robinson (1974) have shown that the wear rates of WC-Co composites increase with the blow energy and rock hardness. The quartz content determines the mechanical properties of the rock, particularly its hardness. Mt. Isa rock has 85 % quartz compared to only 25 % in Ashgrove granite.

Table 1

Comparison of the effect of varying the number of drops on the weight loss of WC-Co composite at a constant blow energy of 11.76 joules on rocks

No. of Drops	Ashgrove Granite Weight Loss(mg)	Mt. Isa Rock Weight Loss(mg)
100	0.63	1.28
200	1.25	2.09
300	1.76	3.33
400	2.55	4.51

Figure 11 shows that there were adherent particles of debris, most of which were fragmented WC grains. These fragmented WC grains together with some rock debris penetrated between the WC grains and acted as wedges to cause WC pull out and fragmentation during impact. The material removal in Ashgrove granite as shown in Figure 12 indicated that there was less fragmentation of WC grains and that pull out of the grains was predominant. This was probably caused by the removal of the binder that was squeezed out due to impact, leaving the WC grains unsupported. Osborne (1969) reported that cobalt removal itself cannot account for appreciable weight loss but it promotes removal of entire surface layers through a microspalling type of failure.

The adherent particle of debris which are evidently fragmented WC grains showed that surface impact spalling is a process of fracture on WC grains. The brittleness of the WC grains would contribute to higher wear rates during impact. It was also observed that the rate of microfracture was strongly dependent on the hardness of the rock. The wear rate of WC-Co during impact on the Mt. Isa rock was higher because it is harder than the Ashgrove granite.

3.3 Contribution of impact and abrasion on the total wear

This segment of the results is an attempt to estimate the contribution of each wear mechanism to the WC-Co inserts at the impact face of the bit, based on the results from abrasive wear tests and drop weight tests. During actual drilling operation, the drill rotates at a speed such that the inserts at the impact face have a sliding velocity between 0.05 - 0.08 m/s. This sliding velocity of the inserts can be reproduced in the milling machine if we consider the rotation and the linear translation of the specimen during the wear test. To quantify the total distance travelled, this would be the sum of the distance of the linear and rotation travel, as shown in the formula below:

$$\text{Total traverse length} = (TS \text{ x } t) + (R \text{ x } 2\pi r \text{ x } t)$$

where: Ts = traverse speed (1 m/min, 0.3 m/min)
t = time (5.8 min, 20 min)
R = speed of specimen rotation (150 rpm)
r = effective radius of the specimen (3.18 mm)

According to Larsen Basse (1973), the hold down load for percussive drilling is about 30 kgs per button. By varying the applied load during an abrasive test, it is possible to extrapolate the wear loss at 30 kgs load. This extrapolation hinges on the simple theory that wear is proportional to load (Blickensderfer and Laird, 1988). Table 2 shows the weight loss by abrasion at 30 kg hold down load. The loss rate at higher speed of linear translation was larger because of greater possibility of contact with fresh abrasive. The abrasive particles degraded significantly when WC-Co specimen traveled at a slower speed.

Table 2
Weight loss of WC-Co insert at different speed of linear translation

Abrasive Type	Linear Translation (m/min)	Traverse Time (min)	Weight Loss (mg)	Loss rate (mg/min)
Garnet	1.0	5.8	1.23	0.20
Garnet	0.3	20.0	1.40	0.07
Alumina	0.3	20.0	14.50	0.72

In the drop weight test, the drop mass of 2 kgs at a height of 0.6 m represents the actual percussive impact energy of 11.67 joules/button. From Table 1, the average wear loss per impact in the two types of rock was 0.0062 mg/drop and 0.0114 mg/drop in Ashgrove granite and Mt. Isa rock, respectively. According to Larsen Basse (1973), the typical impact frequency of a percussive drill bit is 1800 impacts/min and the drill bit is in contact with the rock for less than 10 per cent of the time or about 3 milliseconds per impact which is spent on indexing and forward movements. From this information, the calculated wear rate of WC-Co composite during drop weight test on Ashgrove granite and Mt. Isa rock were 11.16 mg/min and 20.52 mg/min, respectively.

The abrasion loss per minute was calculated using the formula: Abrasion Loss = 1800 impacts/min x 0.003 seconds/impact x 1/60 x loss rate in Table 2. From this formula, the calculated wear rates of the composite during abrasion test on garnet (1 m/min), garnet (0.3 m/min), and alumina (0.3 m/min) were 0.018 mg/min, 0.0063 mg/min, and 0.06 mg/min, respectively. The contribution of abrasion and impact on the total wear loss of WC-Co composite can be estimated by combining the results from the drop weight tests and the abrasive wear tests as shown in Table 3.

Table 3

Estimated contribution of abrasion and impact on total wear loss of WC-Co composite in rock drilling

Rock/Abrasive	Impact (%)	Abrasion (%)
Ashgrove granite/ Garnet abrasive (1m/min)	99.84	0.16
Ashgrove granite/ Garnet abrasive (0.3m/min)	99.94	0.06
Ashgrove granite/ Alumina abrasive	99.5	0.50
Mt. Isa rock/Garnet abrasive (1m/min)	99.92	0.08
Mt. Isa rock/Garnet abrasive (0.3m/min)	99.96	0.04
Mt. Isa rock/Garnet abrasive	99.7	0.3

The comparison of the wear rate data in the abrasion test and drop weight test indicated that the contribution of abrasion to the total wear of the WC-Co insert is less than one percent. However, when abrasion and impact are combined, the wear due to abrasion may be higher but is probably just a minor change.

The above findings support the work of Montgomery (1968), who published the only detailed work on wear in simulated percussive drilling. He also estimated the contribution of abrasion to be about 4 percent of the total wear. This signifies that the contribution of sliding wear and hold down force is minor. However, according to Larsen Basse (1973), this estimate by

Montgomery was based mainly upon the simulated rotary-percussive drilling. Nevertheless, it should be emphasized that the present work and that of Montgomery's appear to be the only reported investigations that separate impact damage from abrasive wear on WC-Co inserts during rotary-percussive drilling. Both investigations have shown that impact damage is the prime source of wear, thus further work should be carried out under conditions that rigorously simulate exact drilling conditions. It is recommended that design and manufacture of equipment to perform abrasion and impact must be undertaken in order to simulate effectively the rotary-percussive drilling operations.

SEM observations of wear scar supported this general conclusion. Electron scanning micrographs of the worn insert at the impact face used in percussive drilling showed similarity with the wear scar of the insert used in drop weight test. Figures 7 and 12 showed that some of the grains at the impact face were fragmented and others were pulled out from their setting which is an indication of fatigue damage accumulated over many blows durlng impact. However, it is recommended that retrieval of wear debris of the WC-Co composite during laboratory testing and actual drilling operations should be included in the wear experiments. The processes must include the examinations of the debris in the early stages of wear, observations of the progressive changes on the surface of the composite and comparison of the worn surfaces and wear debris produced in the test.

IV. CONCLUSIONS

1. The primary contribution to wear of WC-Co insert in rotary-percussive drilling is impact damage. The contribution of abrasion to the total wear of the insert at the impact face of the bit is insignificant as confirmed by scanning electron micrographs of worn insert.
2. The wear of WC-Co insert due to abrasion and impact fatigue depends upon the hardness or abrasiveness of the rock. Both wear mechanisms exhibit fragmentation of WC grains.
3. The wear of WC-Co inserts in both drop weight test and abrasion test was directly proportional to the number of impacts and to the traverse length and hold down load, respectively.
4. Fragmented WC grains which adhere to the surface of the cemented carbides contribute to high wear rates of the composites. The wear debris consist of fine WC fragments loosely bonded by cobalt.
5. Preferential cobalt removal is one possible mechanism that contributes to the wear loss of WC-Co insert. However, Co removal itself cannot account for appreciable weight loss but promotes removal of the entire surface layer when WC grains are no longer supported.

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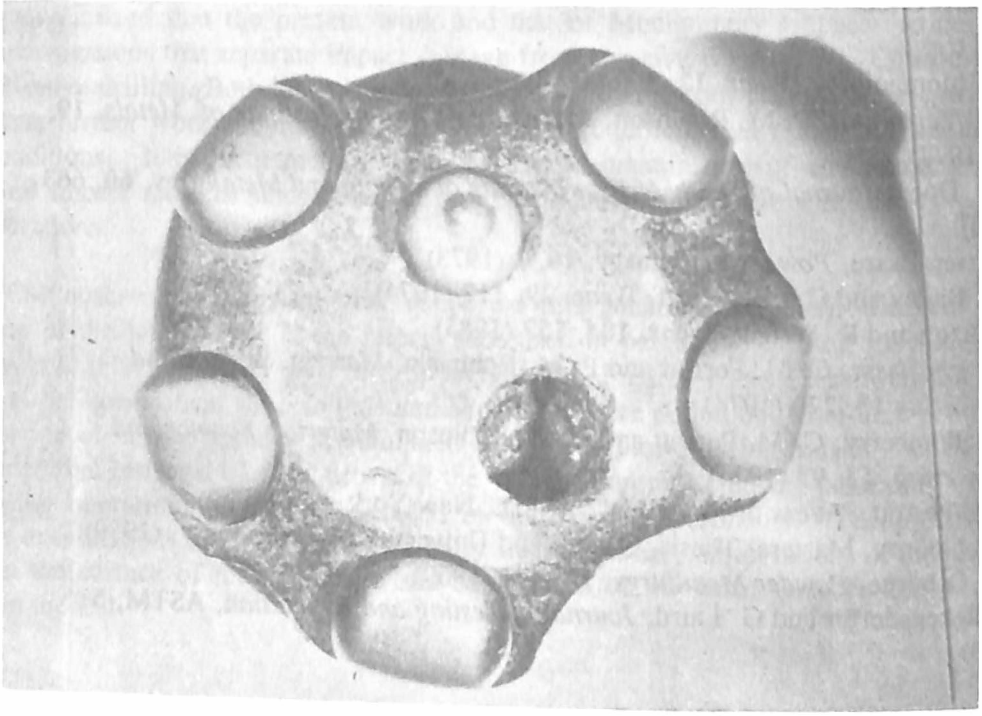

Figure 1. Typical worn drill bit with WC-Co button inserts

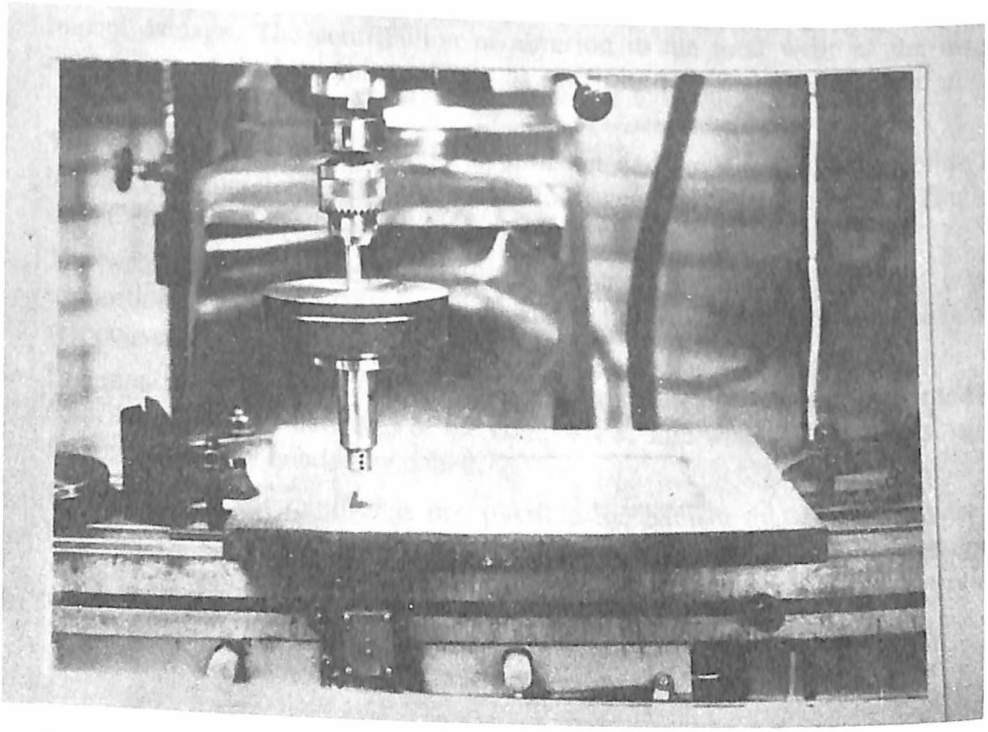

Figure 2. Pin on plate high stress abrasion tester attached to the milling machine

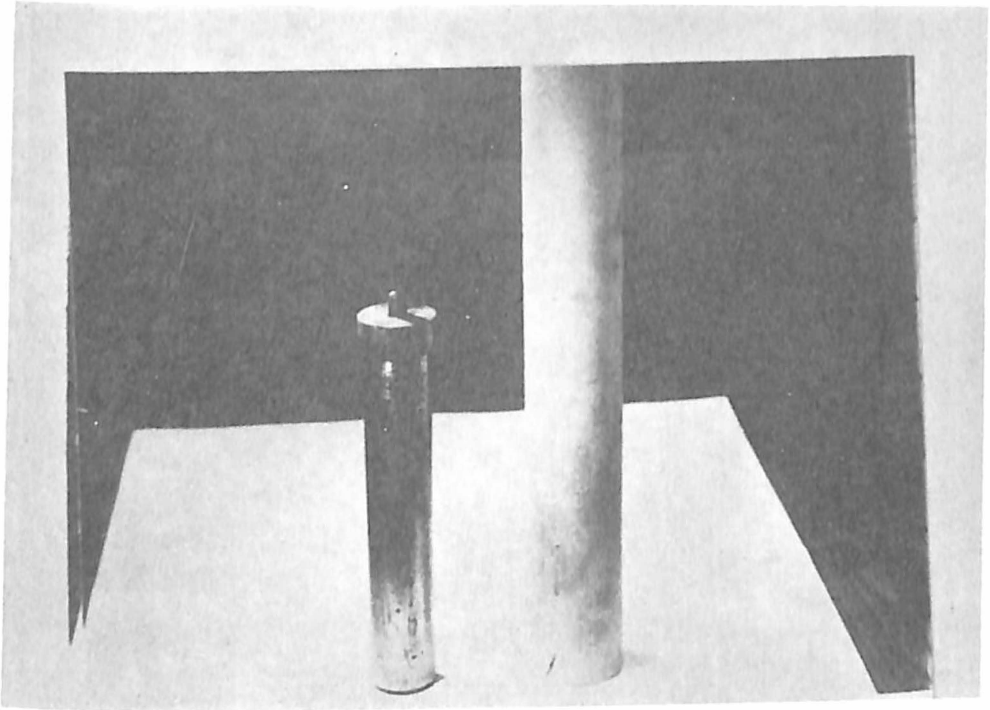

Figure 3. WC-Co insert attached to the drop mass and a drop test guide apparatus

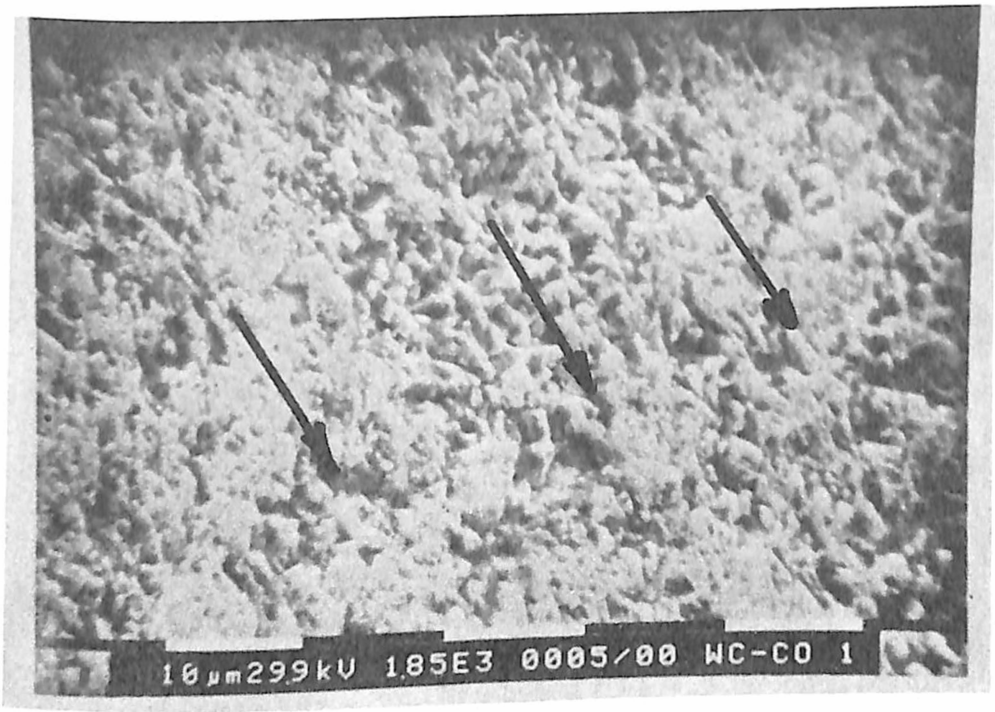

Figure 4. SEM of worn insert taken from the periphery of the drill bit which manifests grinding abrasion

Figure 5. Wear scar of the insert showing abraded surface and gross grooving in certain direction

Figure 6. SEM of worn insert taken from the impact face of the percussive drill bit showing fragmented WC grains

Figure 7. Wear scar of the insert showing gross pull out of WC grains due to impact fatigue

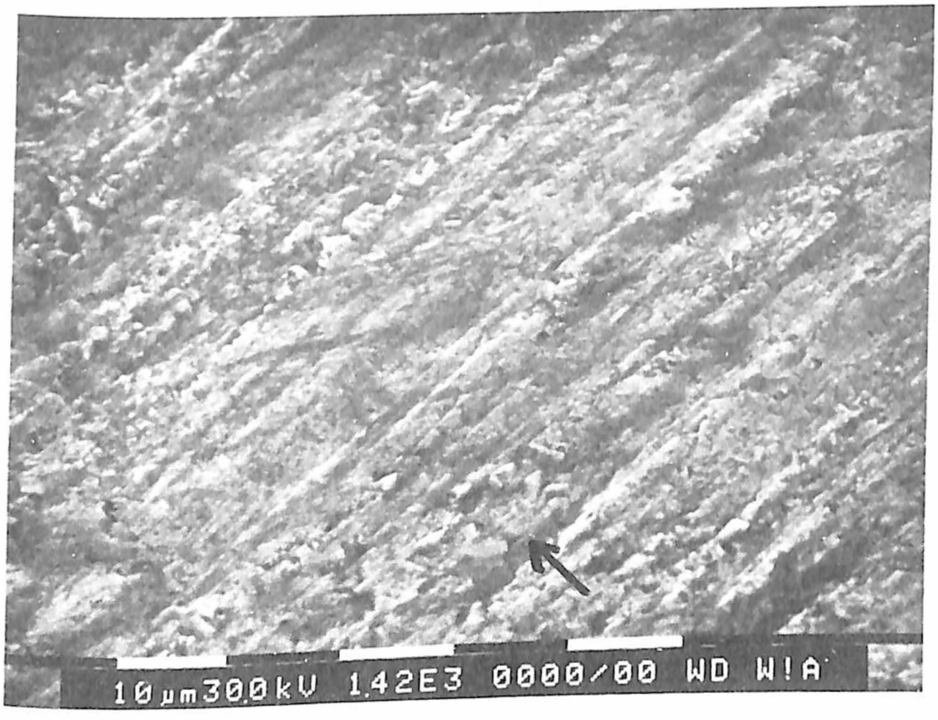

Figure 10. SEM micrograph showing partially cut WC-Co composite after abrasion with alumina abrasive.