4. RESULTS

This chapter presents the results obtained. It is arranged as follows:

- specimen characterisation;
- properties of SiC abrasives;
- results of the wear tests;
- analysis of the wear scars;
- analysis of the SiC abrasive paper;
- analysis of the wear debris.

4.1 Specimen characterization

4.1.1 WC-12wt%Co microstructure

The microstructure of the WC-12wt%Co specimen is shown in figure 4.1 indicating that two phases are present i.e. WC (grey) and Co (black). The WC grains are angular. The micrographs show that the WC grain size is not uniform.

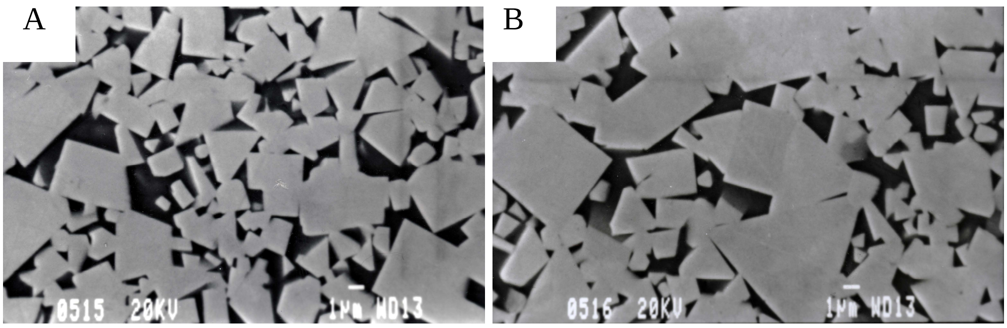


Figure 4.1: SEM micrographs of two different areas from a WC-12wt% Co sample showing that the WC grain size is not uniform.

4.1.2 WC grain size

The WC grain size is important in WC-Co alloys as it affects the hardness and wear resistance of the alloys [3]. Small WC grains lead to harder WC-Co alloys which have a higher resistance to wear. Figure 4.2 is the graph of the cumulative frequency versus WC grain size. The median WC grain size was determined from this graph which was also used to assess the WC grain size distribution. The arithmetic average was taken as the mean size of the WC grains.

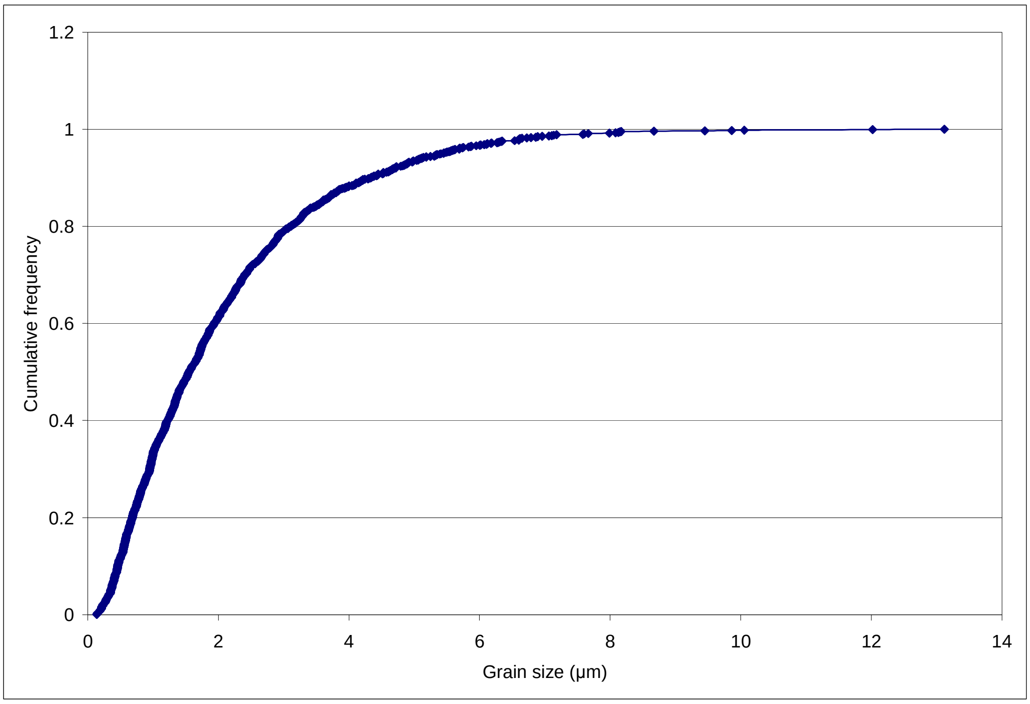


Figure 4.2: Graph of cumulative frequency versus WC grain size.

From figure 4.2, the median WC grain size corresponding to the 0.5 cumulative frequency is 1.55μm. The graph shows that the range of large grains having a grain size greater that 1.55μm is greater then the range of smaller grains. The arithmetic average WC grain size, based on the average of all measured grains, is 2.03 ± 1.67μm.

4.1.3 Co mean free path

The Co mean free path is the average spacing between the WC grains. Figure 4.3 is the graph of cumulative frequency versus Co free path.

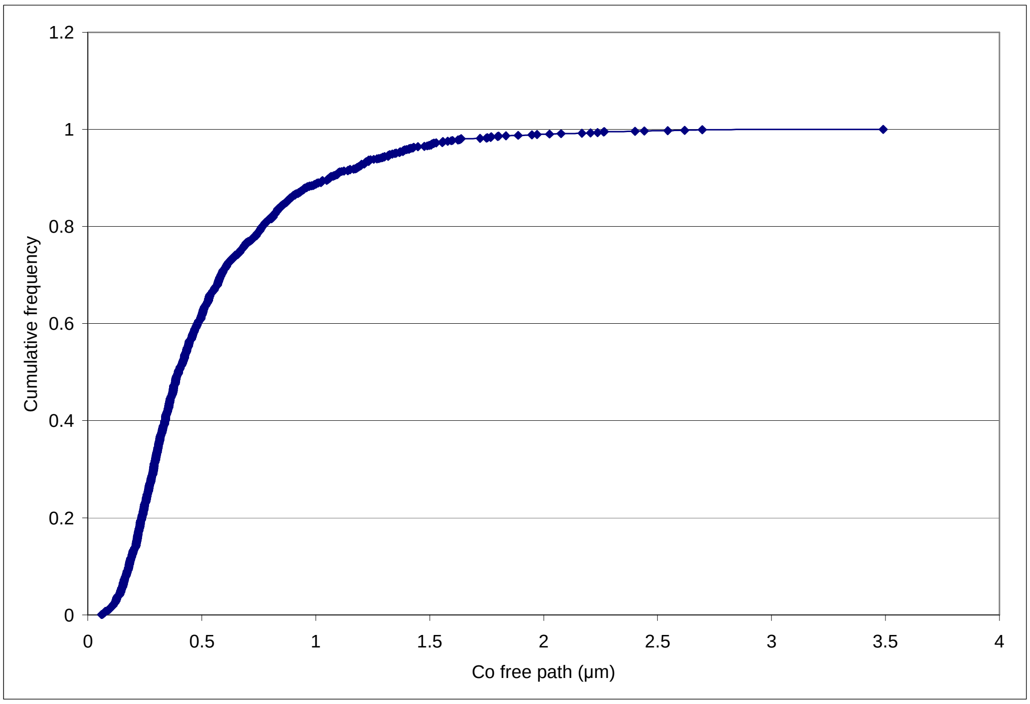


Figure 4.3: Graph of cumulative frequency versus Co free path.

From figure 4.3, the median cobalt free path as obtained from the 0.5 cumulative frequency is 0.4µm but the average of all measured Co free paths is 0.53 ± 0.04µm.

4.1.4 Density

The density of four WC-12wt%Co specimen is given in table 4.1 and the average was taken as the density of the alloy.

Table 4.1: Density of four WC-12wt%Co specimens.

Sample number	**Mass in air (g)**	**Mass in water (g)**	**Density (g/cm^3)**
1	4.9501	4.6315	14.56
2	4.9234	4.5997	14.21
3	4.9276	4.6006	14.10
4	4.9337	4.6106	14.27

The average density of the alloy is 14.29 ± 0.20 g/cm^3. This value is in close agreement with 14.33g/cm^3 given by the supplier.

4.1.5 Calculation of the Co weight percentage

The Co weight percent was calculated from the density of the specimen using equation 3.2.

$$M_{Co} = \left(\frac{M_{WC-12wt\%Co}}{\rho_{WC-12wt\%Co}} - \frac{100}{\rho_{WC}}\right) \Big/ \left(\frac{1}{\rho_{Co}} - \frac{1}{\rho_{WC}}\right)$$

Where: M_{Co} = weight percentage Co in WC-Co alloy
$M_{WC\text{-}12wt\%Co}$ = mass of specimen = 100g
$\rho_{WC\text{-}12wt\%Co}$ = density of WC-12wt%Co = 14.29g/cm^3
ρ_{WC} = density of WC = 15.63 g/cm^3 [9]
ρ_{Co} = density of Co = 8.85g/cm^3 [9]

Therefore, M_{co} = (100/14.29 – 100/15.63) / (1/8.85 – 1/15.63)
= 12.24 wt% Co

This value is in close agreement with the value of 12wt% given by the supplier. Therefore, this confirms that the alloy used is WC-12wt%Co.

4.1.6 Hardness

Table 4.2 shows the results of the Vickers hardness measurements of the WC-12wt%Co alloy.

Table 4.2: Vickers hardness of the WC-12wt%Co alloy.

Tests	1	2	3	4	5	6	7
HV30	1278	1144	1095	1211	1268	1104	1283

The average hardness of the specimen is 1197 ± 82 HV30. This value is close to 1200 HV30 as given by the supplier. The large scatter in the hardness results is probably due to the non uniform grain size shown in figure 4.1. The results of the specimen characterization are tabulated in table 4.3.

Table 4.3: Measured properties of the WC-12wt%Co alloy.

WC grain size (μm)	**Weight % Co**	**Density ($g.cm^{-3}$)**	**Hardness (HV30)**
2.03 ± 0.67	12.24	14.29 ± 0.20	1197 ± 82

4.2 Properties of the SiC abrasives

The abrasive material used was 80-grit SiC grinding paper. Figure 4.4 shows the graph of cumulative frequency versus the SiC grit size.

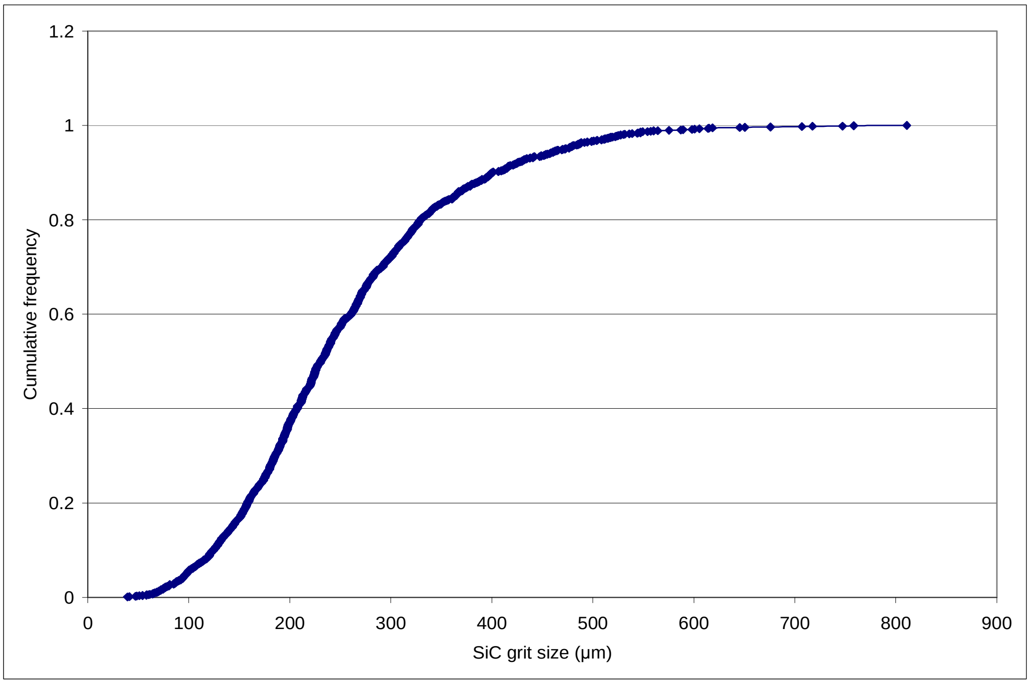


Figure 4.4: Graph of cumulative frequency versus SiC grit size.

From figure 4.4 the median SiC grit size is 230µm and the arithmetic average SiC grit size is 251 ± 112µm. The hardness of the SiC particles was taken from the supplier because of the difficulty in polishing and indenting the SiC abrasive particles. Properties of the SiC abrasive grits are shown in table 4.4.

Table 4.4: Properties of the SiC abrasive grit.

Supplier values		**Experimental values**	
Hardness (kgf/mm^2)	**Average particle size (µm)**	**Average particle size (µm)**	**Median particle size (µm)**
2400	200	251 ± 112	230

4.3 Wear

Specimens were polished to a 0.05µm finish before being worn. This section gives results of the wear tests for three different wear conditions under two different loads.

4.3.1 Wear tests under a load of 2.16N

The load of 2.16N is based on the weight of the sample holder that presses down on the specimen during the test. The load on the specimen was calculated as follows.

Load of 2.16N = mass of sample holder x g
= (220.362/1000) kg x 9.8 ms^{-2}
= 2.16 N, which is the lower of the two loads used for these experiments.

The stress which the specimen were subjected to during wear was calculated using the equation:

Stress = Load / Area

The area used is the nominal area of the sample in contact with the abrasive grit.

Area = 9.5mm x 5.1mm

= 48.25×10^{-6}mm^2

Therefore,

Nominal stress = 2.16 N/ 48.25×10^{-6} m^2

= 0.045 MPa

The actual pressure on the specimen is much higher than this since the real area of contact between the specimen and the SiC grits is smaller that the nominal area of contact.

The wear results for each test condition at a load of 2.16N are given in sections 4.3.1.1 to 4.3.1.3.

4.3.1.1 "Ideal" wear condition

Six specimens were worn for approximately 51 seconds (i.e. ≈ 22 test runs) each and one specimen for approximately 120 seconds (i.e. ≈ 50 test runs) under the "ideal" wear condition, i.e. the SiC abrasive paper was replaced after each run thus the specimen were constantly abrading on fresh SiC grits. The WC-12wt%Co mass loss was recorded after each 2.4 second period (i.e. 1 test run) and the wear rate calculated as follows:

Wear rate = cumulative volume loss (cm^3)/ time (sec)

where,

cumulative volume loss = cumulative mass loss (g)/density (g/cm^3)

A graph of the WC-12wt%Co wear rate versus time is shown in figure 4.5. This graph shows the wear rate when the effect of the change in SiC abrasive grit morphology and wear debris is ignored.

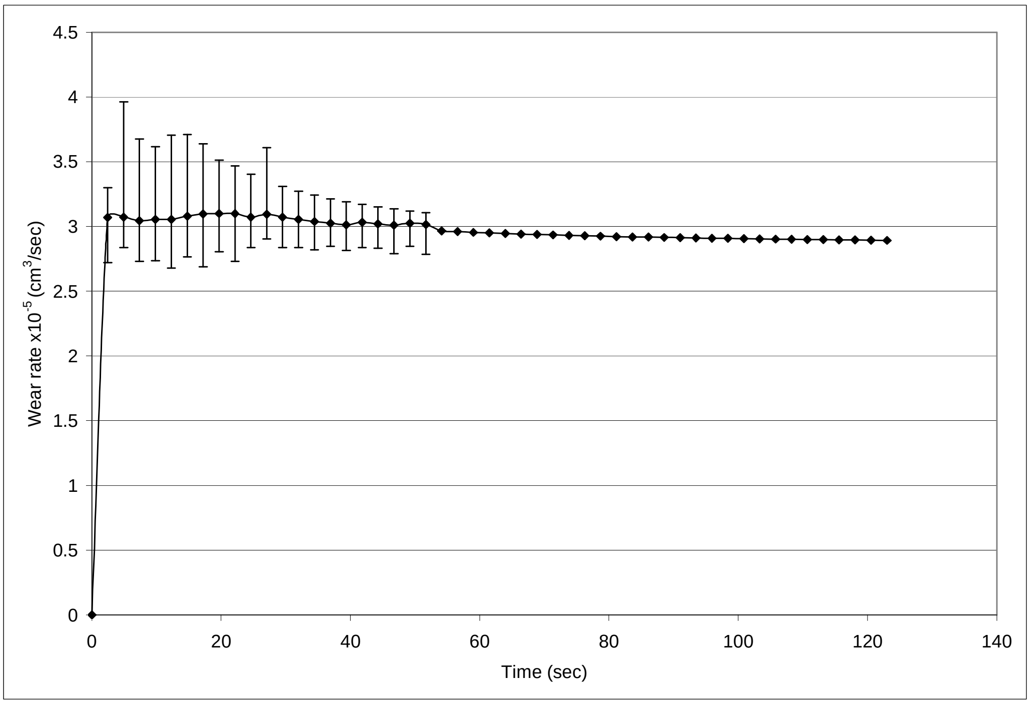


Figure 4.5: Graph of WC-12wt%Co wear rate versus time for the "Ideal" wear condition at 2.16N load. The results for the first 51 seconds are averages of six tests; above 51 seconds only one sample was tested.

According to figure 4.5 the wear rate of WC-12wt%Co is approximately constant with time for the "Ideal" wear condition.

4.3.1.2 "No debris" wear condition

Under this wear condition, nine specimens were worn for about 51 seconds (i.e. ≈ 22 test runs) each and five specimen for approximately 120 seconds (i.e. ≈ 50 test runs). Wear debris was removed after every 2.4 seconds but the same SiC abrasive paper was retained for each complete wear test per specimen. Thus the wear rate is only affected by the change in the SiC grit morphology. Figure 4.6 shows the graph of the WC-12wt%Co wear rate versus time. During the first 20 seconds the wear rate is similar to that of the "Ideal" wear condition (see figure 4.5). After this period there is a steady decrease in wear rate with time until approximately t = 105 seconds after which the wear rate appears to level off. This implies that the effect of SiC grit wear only begins to influence the wear rate after approximately 20 seconds and proves that SiC grit wear reduces the WC-12wt%Co wear rate.

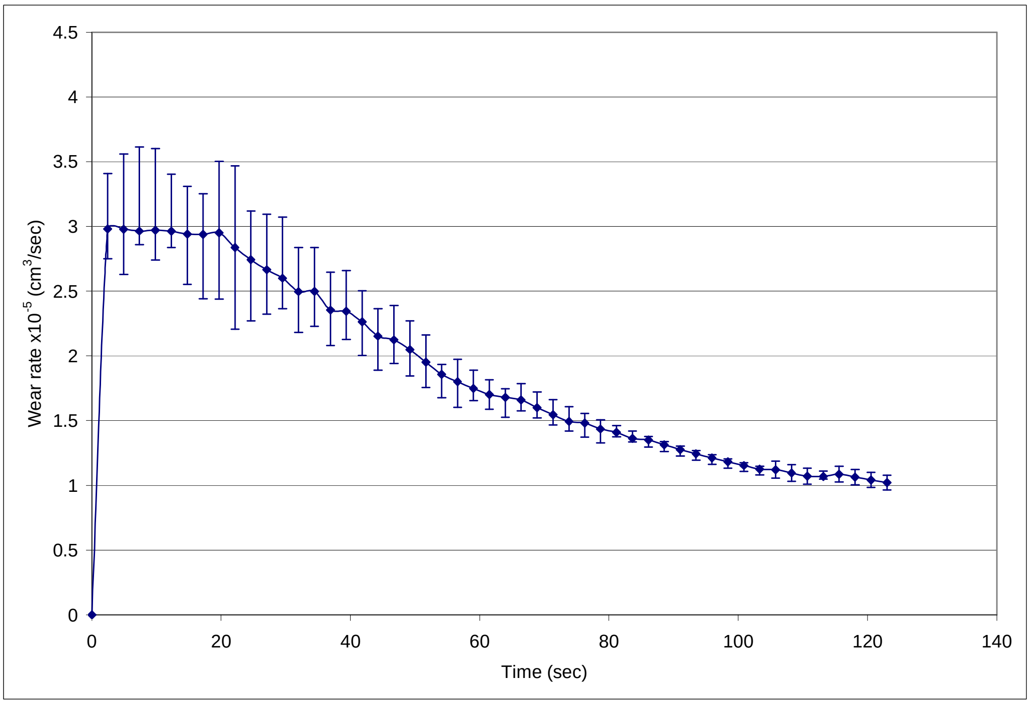


Figure 4.6: Graph of WC-12wt%Co wear rate versus time for the "No debris" wear condition at 2.16N load.

4.3.1.3 "With debris" wear condition

Under this wear condition, six specimens were worn for about 64 seconds (i.e. ≈ 27 test runs) each and three specimen for approximately 120 seconds (i.e. ≈ 50 test runs). The wear debris and the same SiC paper were retained for each complete wear test per specimen. This was done in order to partially simulate a "real" life situation. Figure 4.7 is the graph of the WC-12wt%Co wear rate versus time for the "With debris" wear condition.

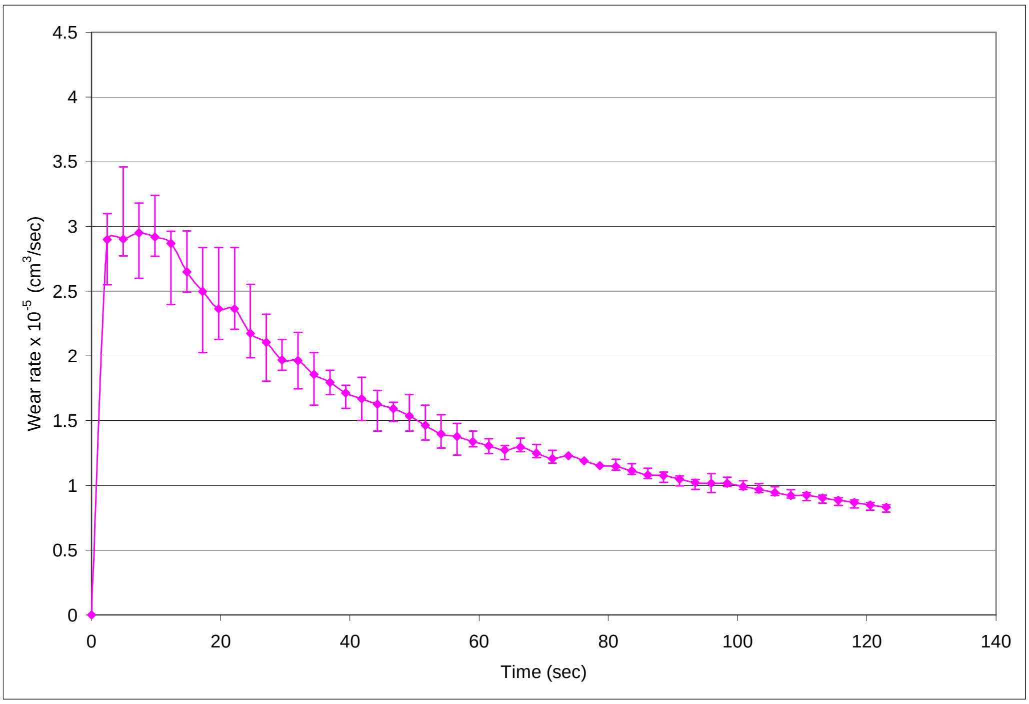


Figure 4.7: Graph of WC-12wt%Co wear rate versus time for the "With debris" wear condition at 2.16N load.

This graph shows a decrease in WC-12wt%Co wear rate with time when the wear debris is retained. This decrease starts after approximately 10 seconds. This time period is 10 seconds shorter that the initial 20 second period recorded in the "No debris" condition. This indicates that the debris is an additional contributor to a reduction in the WC-12wt%Co wear rate.

4.3.1.4 Comparison of the three wear conditions

Combining the graphs for the "Ideal", "No debris" and "With debris" wear conditions one can deduce the effect of SiC grit wear and wear debris on the wear rate of WC-12wt%Co, as shown in figure 4.8.

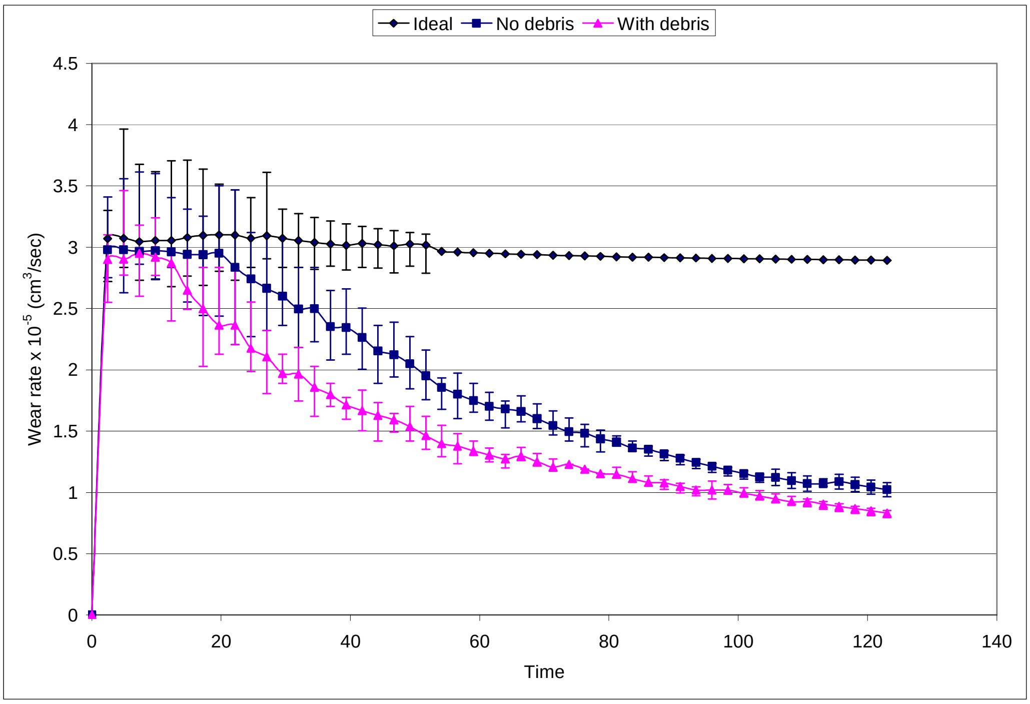


Figure 4.8: Graph of WC-12wt%Co wear rate versus time for the 2.16N load.

It can be deduced that the wear rate of WC-12wt%Co with time is initially constant followed by sharp decreases in the wear rates for the "No debris" and "With debris" wear conditions. The decrease is more pronounced for the "With debris" condition. Possible reasons for the reduction in wear rates include grit blunting and a reduction in the applied stress. The retention of wear debris provides a further reduction of the wear rate. The retained debris increase the effective grit diameter thereby lowering the applied stress resulting in less wear. These results prove that wear debris and SiC grit wear influence measured WC-12wt%Co wear rates. This will be discussed in detail in chapter 5.3.

4.3.2 Wear tests under a load of 2.84N

The effect of load on the wear rate of WC-12wt%Co under three wear conditions was investigated by increasing the load to 2.84N. This was done by loading weights on the sample holder bringing the total mass to 289.466g. This represents a 25% increase in the applied load. The stress on the specimen was calculated to be 0.059MPa. The wear results for each wear condition are given in sections 4.3.2.1 to 4.3.2.3.

4.3.2.1 "Ideal" wear condition

As in the lower load of 2.16N, this condition represents a situation where the specimen are constantly worn by fresh grits and the SiC abrasive paper is replaced after every run. The effect of the SiC grit wear and wear debris is absent. One specimen was worn for approximately 120 seconds and the wear rate illustrated graphically in figure 4.9 was calculated from the cumulative mass loss as was done in section 4.3.2.1.

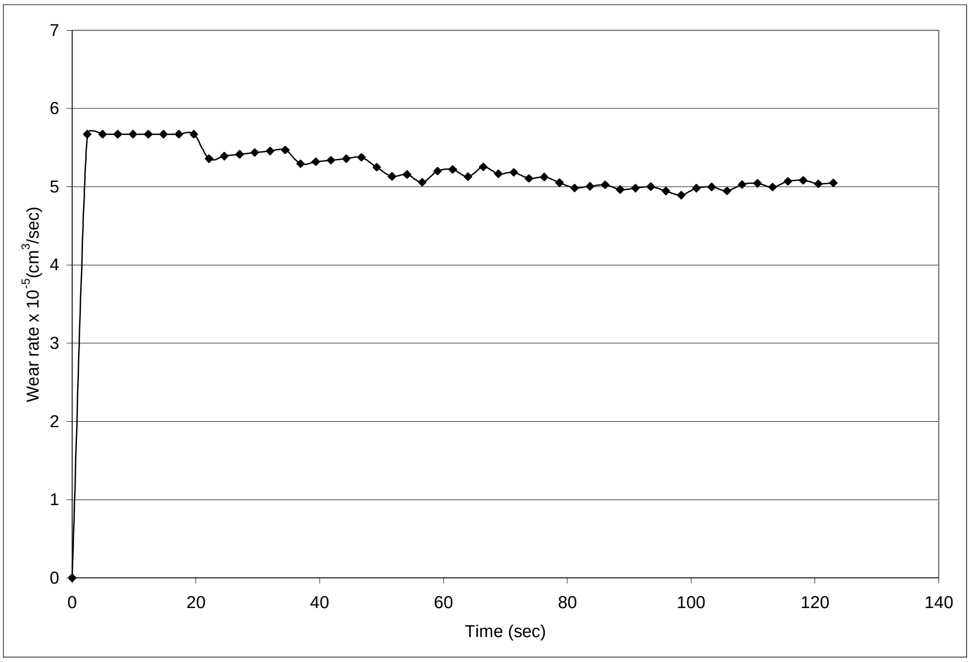


Figure 4.9: Graph of the WC-12wt%Co wear rate versus time for the "Ideal" wear condition with a load of 2.84N.

Compared to the 2.16N load, the WC-12wt%Co wear rate has increased by approximately 43%. This is expected since it is well documented that increasing the load causes an increase in wear rate [10,11,21-24]

4.3.2.2 "No debris" wear condition

Three specimen were worn for approximately 120 seconds with the wear debris removed every 2.4 seconds thereby investigating the effect of the SiC grit wear on the wear rate. Figure 4.10 shows an immediate sharp decrease in the WC-12wt%Co wear rate with time during the first 20 seconds, after which the wear rate gradually slows down. No initial constant region was found compared to the low load (see figure 4.6).

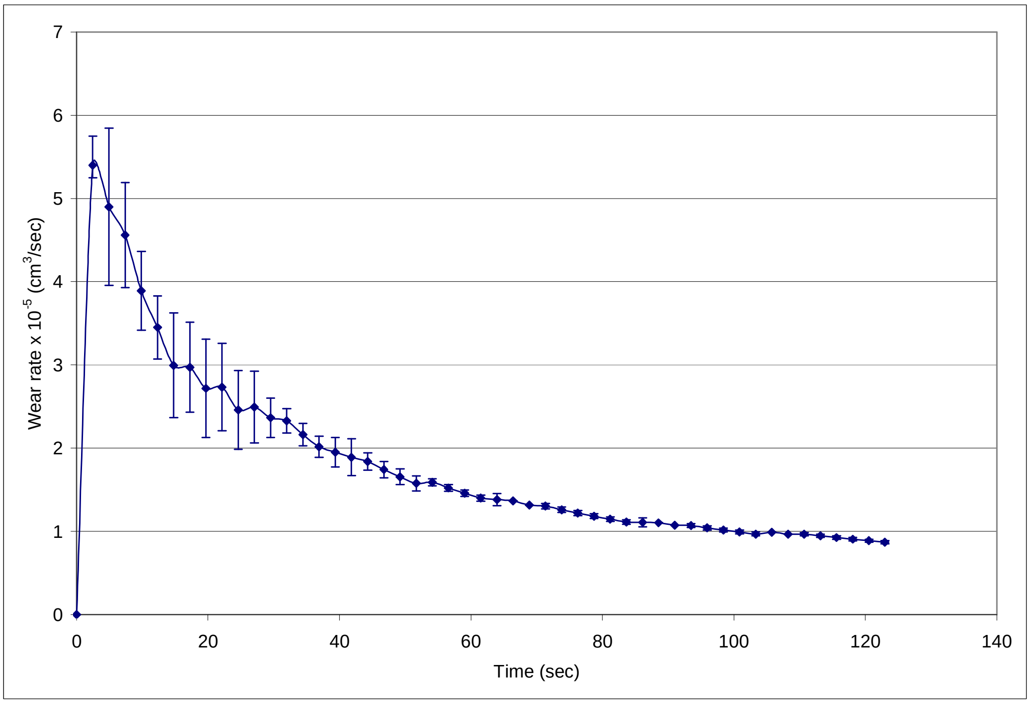


Figure 4.10: Graph of the WC-12wt%Co wear rate versus time for the "No debris" wear condition under a 2.84N load.

4.3.2.3 "With debris" wear condition

Three specimen were worn for approximately 120 seconds. The wear debris and the same SiC paper were retained for the entire wear test per specimen. Figure 4.11 is a graph of WC-12wt%Co wear rate versus time. The graph shows an immediate decrease in WC-12wt%Co wear rate with time similar to the "No debris" wear condition.

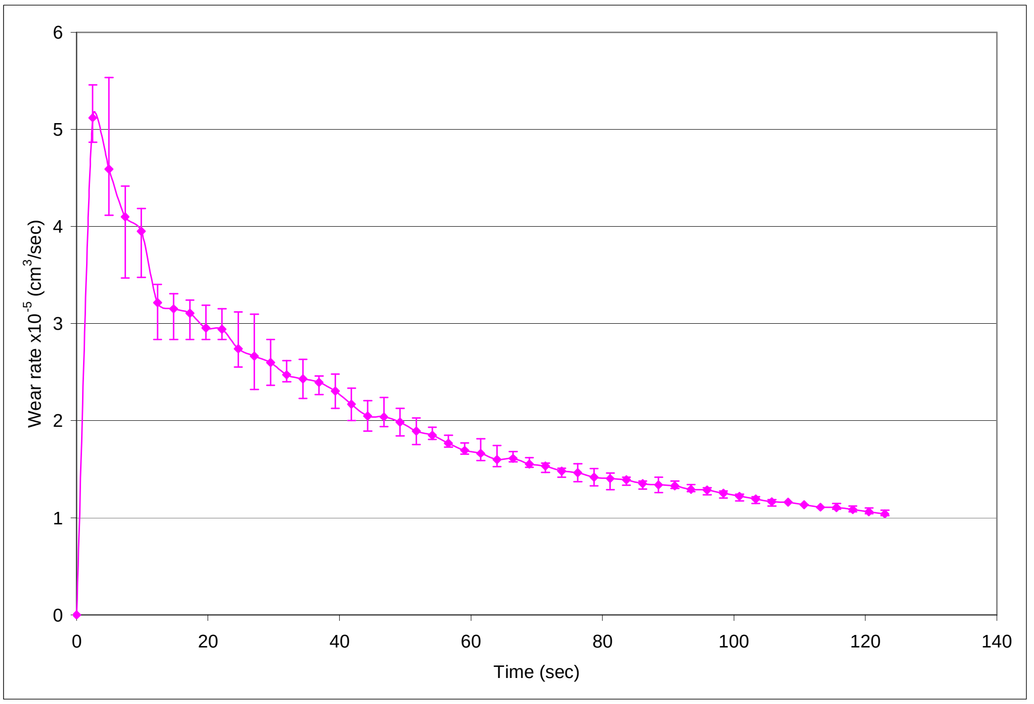


Figure 4.11: Graph of the WC-12wt%Co wear rate versus time for the "With debris" wear condition under 2.84N load.

4.3.2.4 Comparison of the three wear conditions

The effect of SiC grit wear and wear debris on the WC-12wt%Co wear rate can be observed from the graphs in figure 4.12. There is an immediate decrease in WC-12wt%Co wear rate for the "No debris" and the "With debris" conditions compared to the "Ideal" wear condition. This immediate decrease is similar for both conditions. From approximately 50 seconds onwards, the "With debris" wear rate is slightly higher than the "No debris" wear rate. This is opposite from what was expected since wear debris increase the effective grit diameter resulting in decreased wear rates as seen in the low load results.

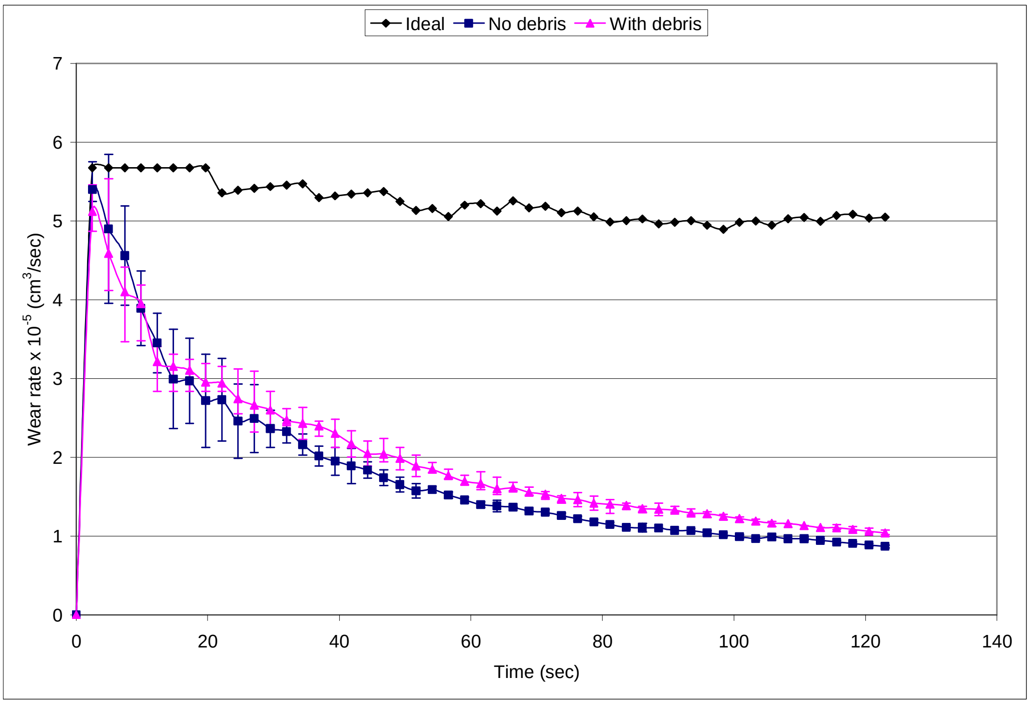


Figure 4.12: Graph of WC-12wt%Co wear rate versus time for the load of 2.84N.

4.4 Microscopic Analysis

The wear scars of the WC-12wt%Co specimen worn for approximately 10 and 120 seconds were examined using different microscopes. Cross-sections of the 120 seconds worn specimen were also examined.

4.4.1 Low Load (2.16N)

4.4.1.1 "Ideal" wear condition

SEM micrographs of the specimen worn for approximately 120 seconds are shown in figures 4.13 to 4.15 (plan view) and figure 4.16 (cross-sections). SEM micrographs of the specimen worn for approximately 10 seconds are shown in figures 4.17 and 4.18 (plan view). These micrographs show wear features characteristic of WC-Co alloys. These features are wear grooves formed by the motion of the abrasive grits, formation of pits due to material removal, material pile-up due to groove formation, cracking and severe fragmentation of WC grains. The dominant mechanism is plowing leading to the formation of grooves (see figure 4.13). The sizes of the grooves vary from 6µm to 51µm. Smearing of the material masked the microstructure in figure 4.14 (a). Regions of high and low groove density were found with each region displaying similar wear features. Figure 4.14 represents a typical high groove density region. Areas with low groove density (figure 4.15) displayed extensive cracking of the WC grains in regions adjacent to the grooves. This feature was not observed in the high groove density regions (compare figure 4.14 to 4.15).The wear features are similar for both the final (120 seconds) and initial (10 seconds) stages of wear however the grooves are fewer and shallower during the initial wear stage. Areas with unworn WC grains were also noted.

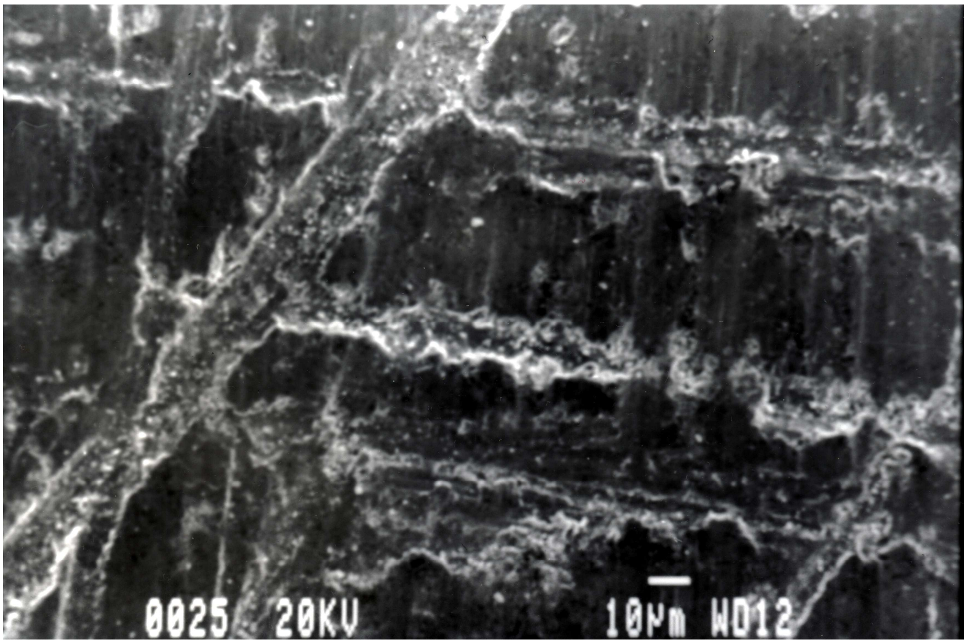
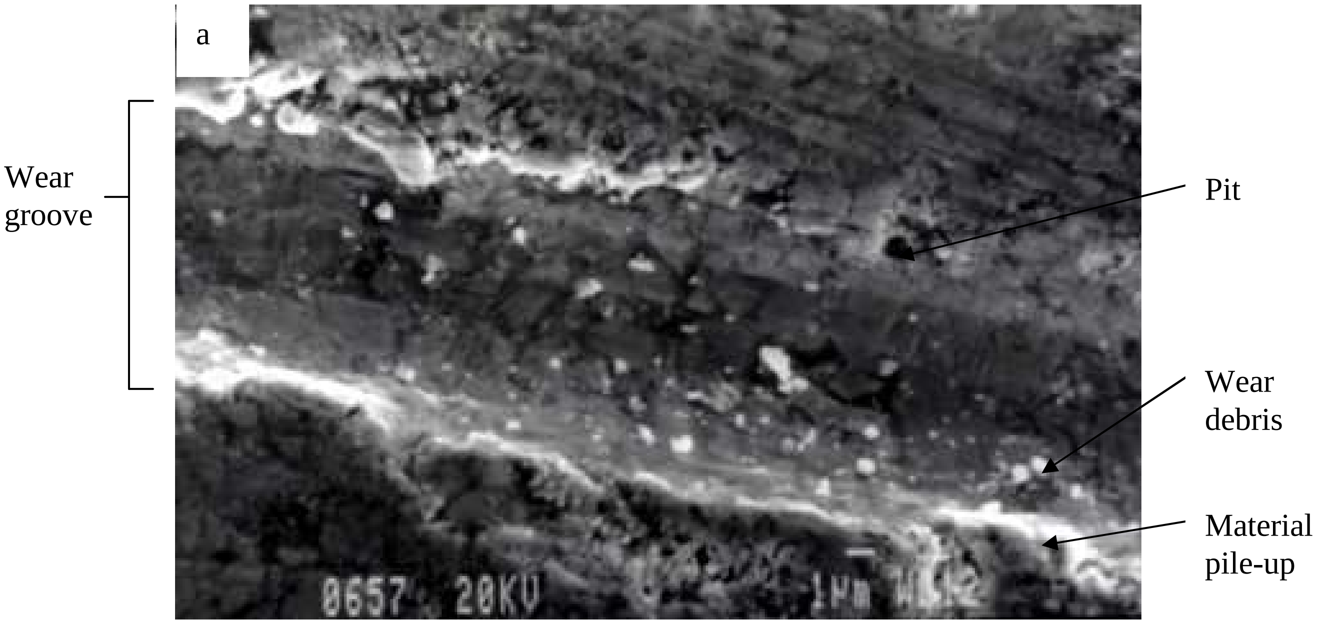


Figure 4.13: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 second under 2.16N load in "Ideal" wear condition showing wear grooves formed in varying directions.



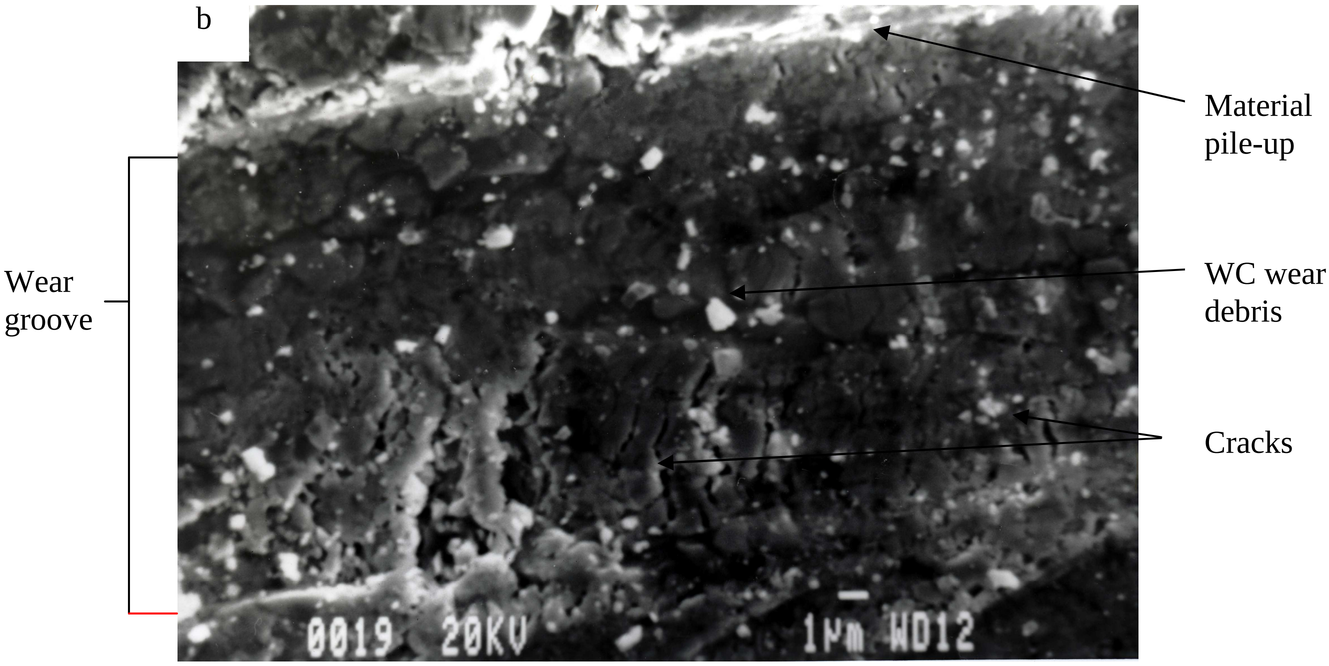


Figure 4.14: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "Ideal" wear condition showing (a) narrow and (b) wide wear grooves. Pits, material pile-up, wear debris and surface cracking occur within the grooves. These features were typical for the "Ideal" wear condition especially in areas with high groove density.

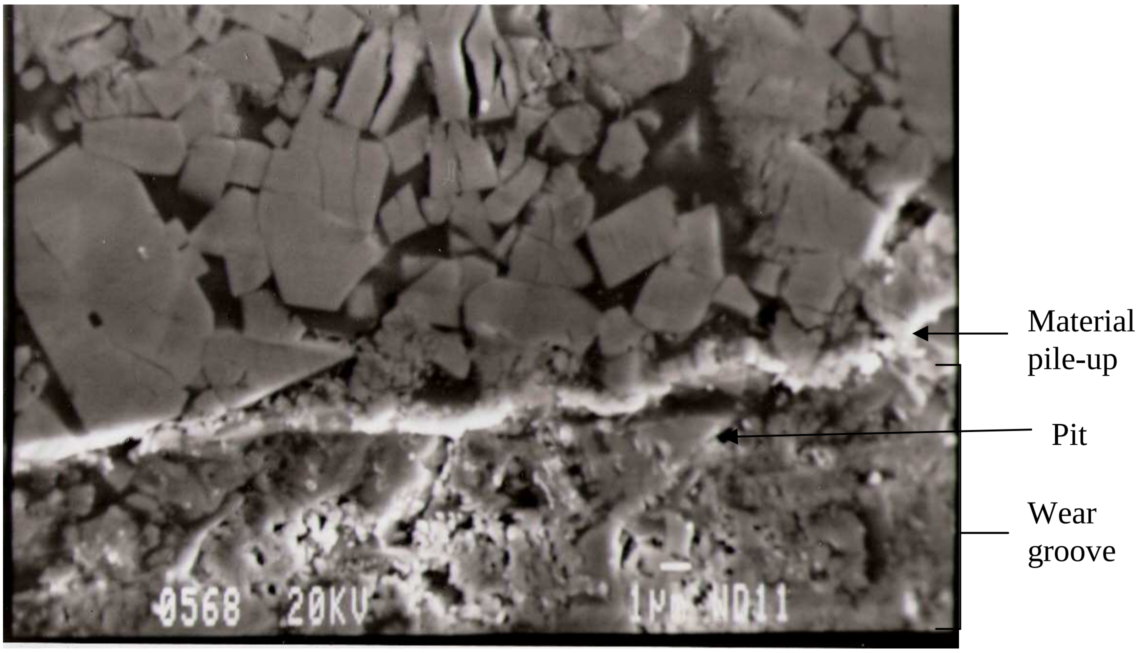


Figure 4.15: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "Ideal" condition showing wear groove, cracked WC grains and material pile-up. These features were specific to areas with low groove density.

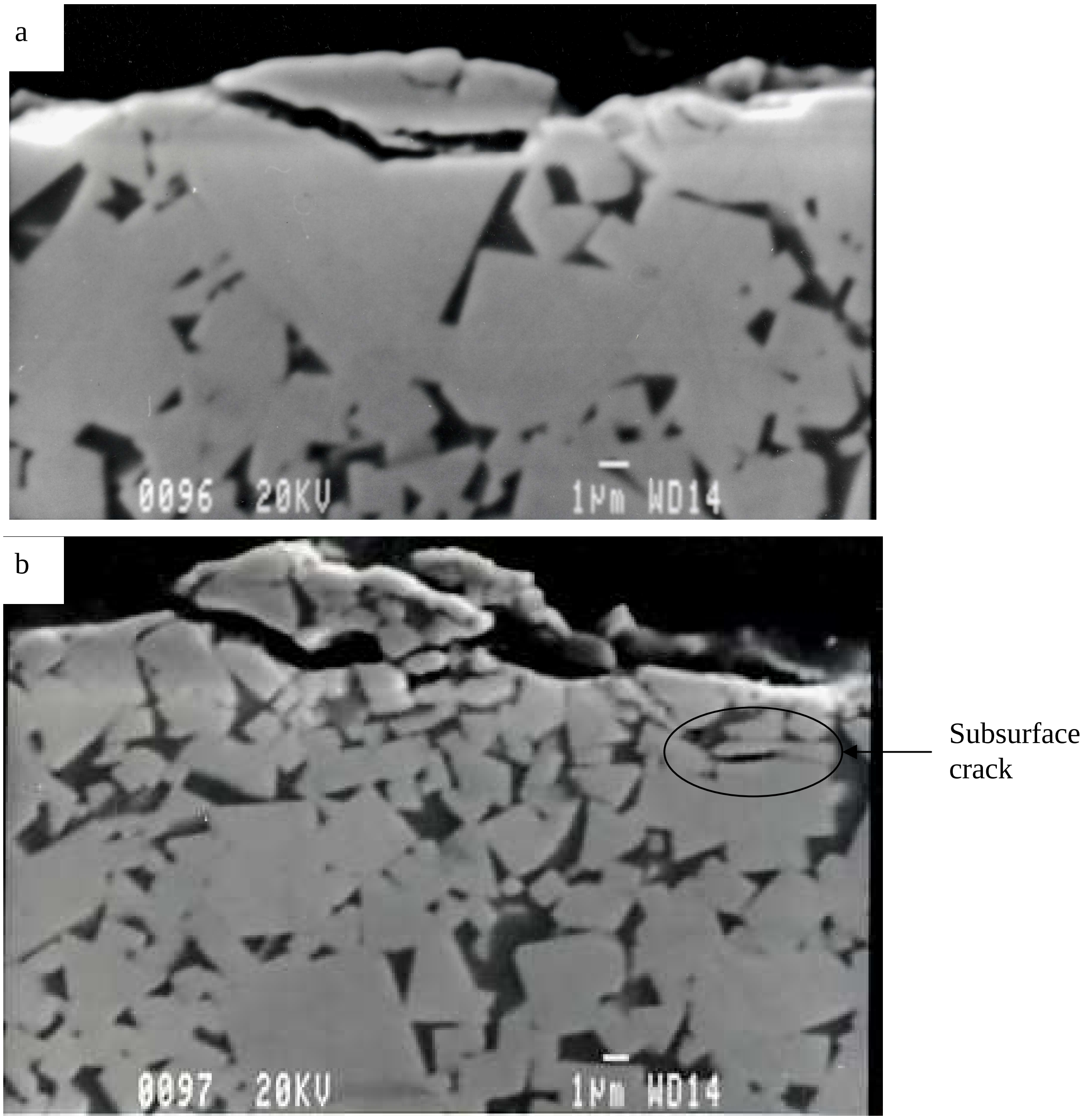


Figure 4.16: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in “Ideal” wear condition showing (a) & (b) cracking of WC grains parallel to the worn surface, (b) chipping of the worn layer and subsurface cracks.

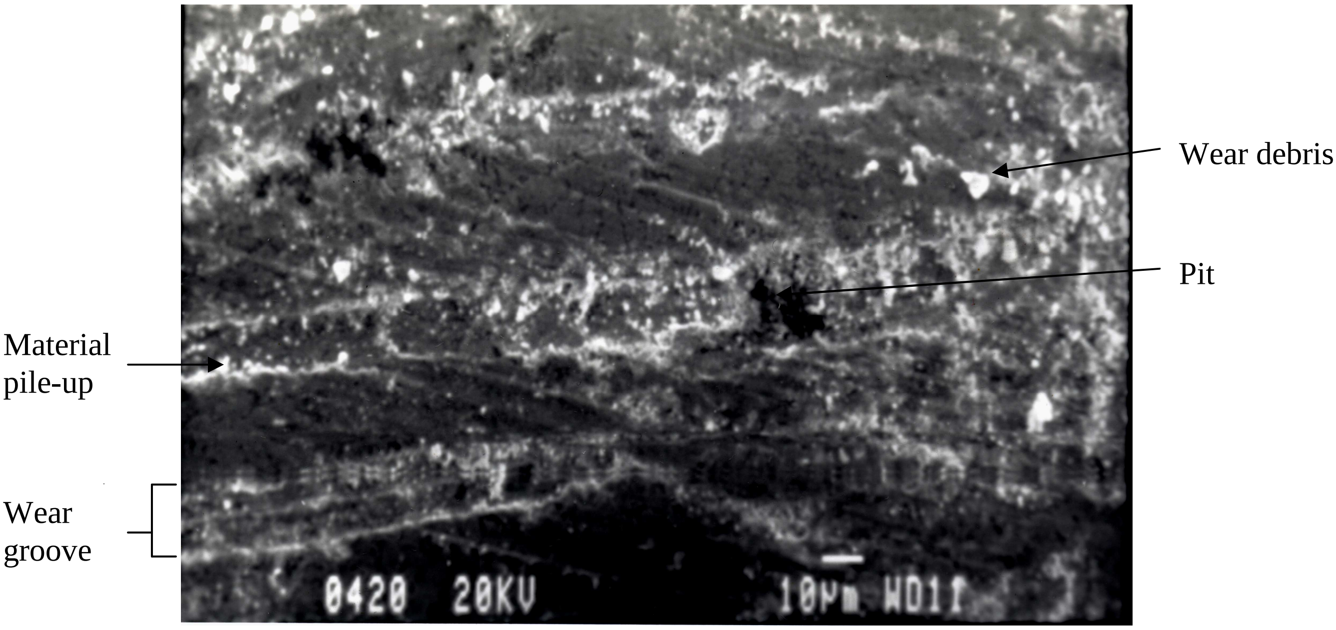


Figure 4.17: SEM micrograph of WC-12wt%Co specimen worn for approximately 10 seconds under 2.16N load in "Ideal" wear condition showing wear grooves, material pile-up, wear debris and pits at low magnification.

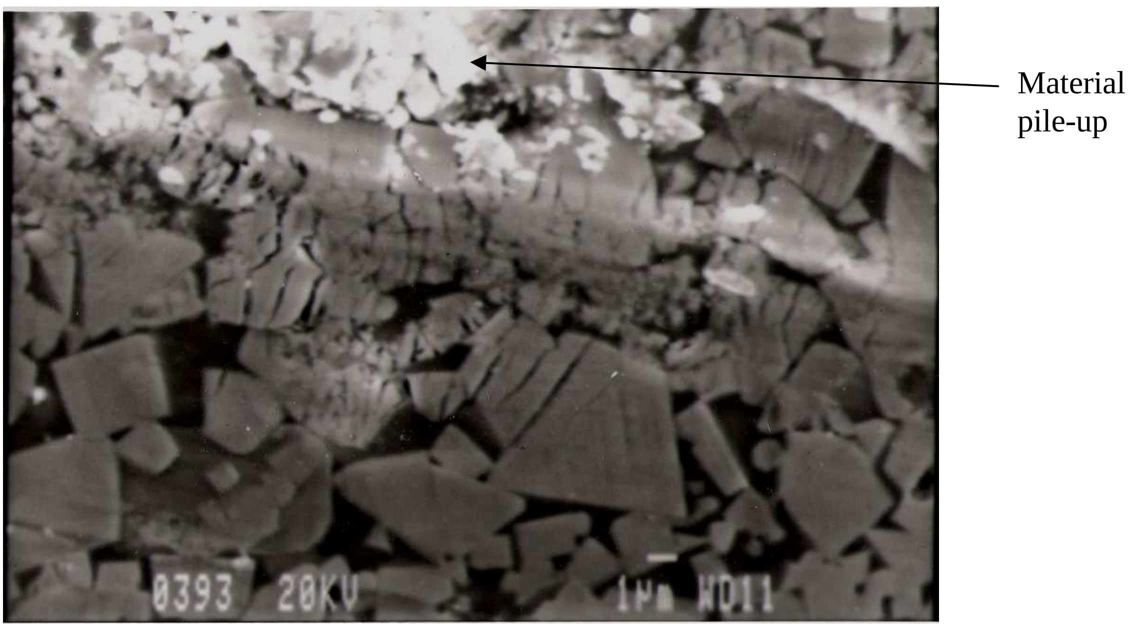


Figure 4.18: SEM micrograph of WC-12wt%Co specimen worn for approximately 10 seconds under 2.16N load in "Ideal" wear condition showing cracked WC grains and material pile-up. The micrograph was taken along the edge of a groove.

4.4.1.2 "No debris" wear condition

SEM micrographs of specimens worn for approximately 120 seconds are shown in figures 4.19 and 4.20 (plan view) and figure 4.21 (cross-section). An SEM micrograph of WC-12wt%Co specimen worn for approximately 10 seconds is shown in figure 4.24. WC cracking and fragmentation is more severe compared to the "Ideal" wear condition (see figure 4.20). The dominant wear features along the edges of the grooves were cracking and fragmentation of WC grains (figure 4.20). Cracking also occurred inside the grooves (figure 4.23). These features occur because of Co removal by extrusion. Co removal leads to relieved compressive stresses in the WC grains causing them to crack. Due to Co removal, the WC grains are more visible in figure 4.20.

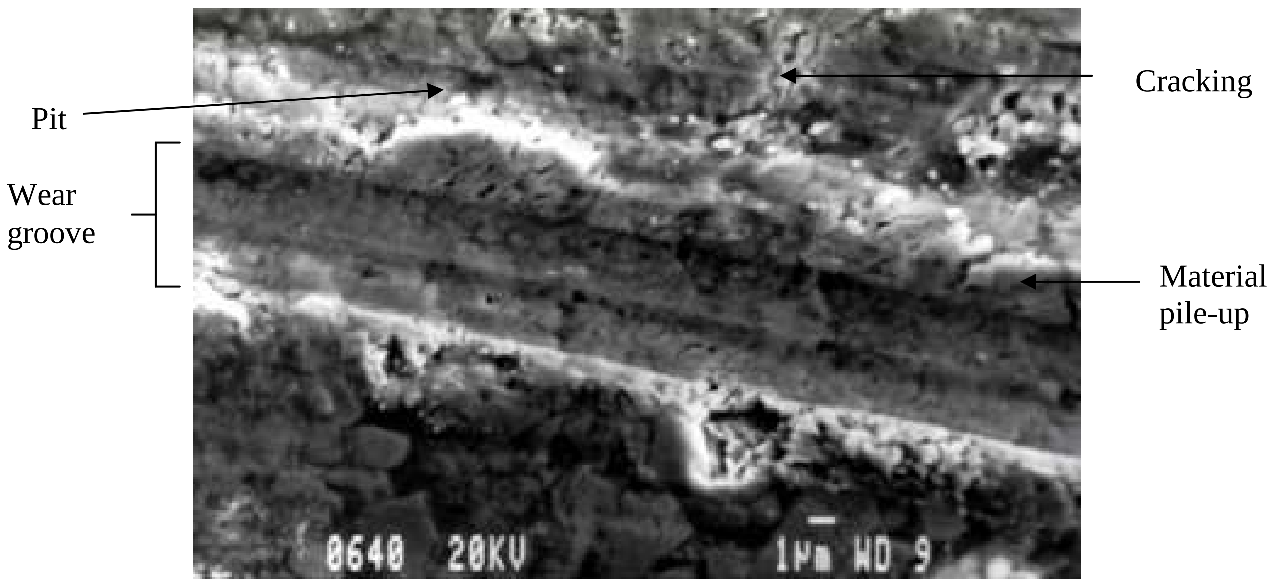


Figure 4.19: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "No debris" wear condition showing a narrow wear groove, cracks, pits and material pile-up.

Figure 4.20: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "No debris" wear condition showing severely cracked WC grains, WC grain fragments and pits. The micrograph was taken along the edge of a groove and represents typical wear of the "No debris" condition.

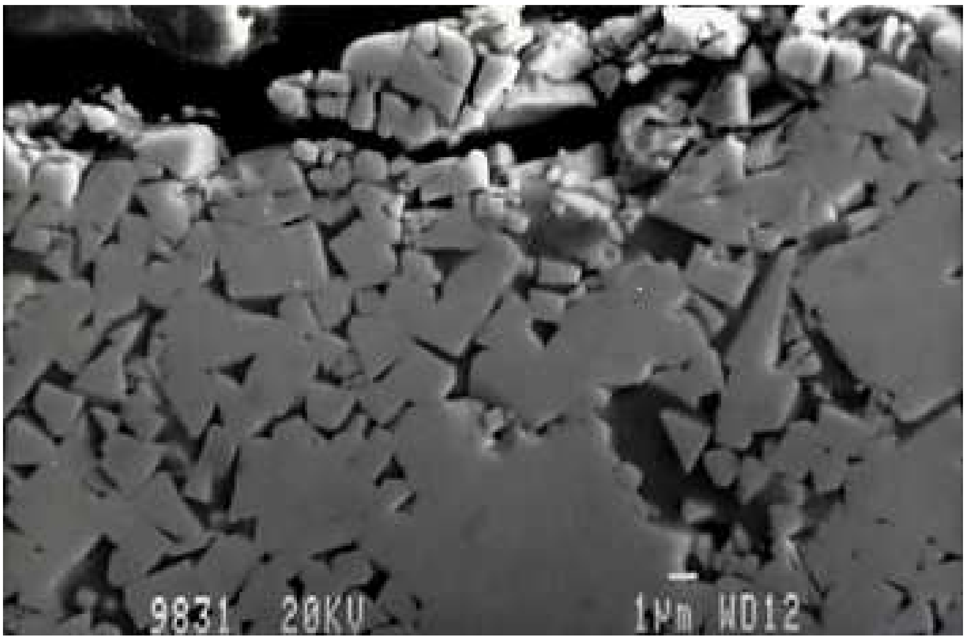


Figure 4.21: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "No debris" wear condition showing partial detachment of the surface layer.

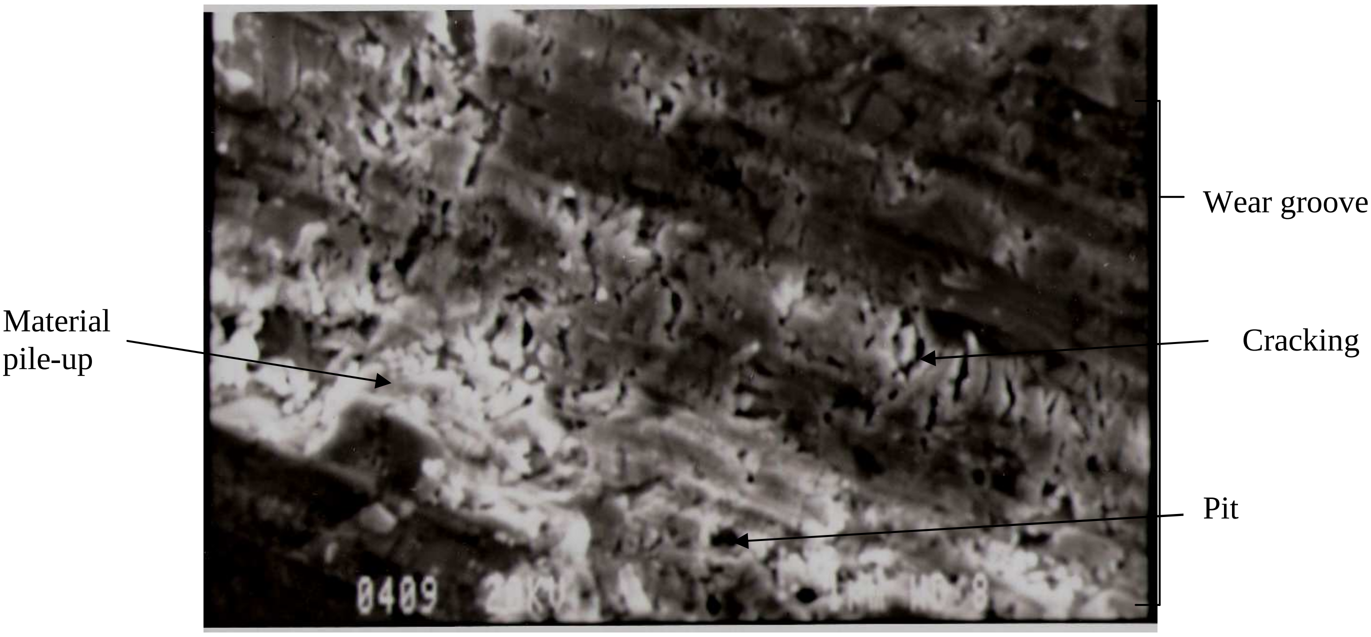


Figure 4.22: SEM micrograph a WC-12wt%Co specimen worn for approximately 10 seconds under 2.16N load in "No debris" wear condition showing wear groove, cracks perpendicular to the wear groove, pits and material pile-up.

4.4.1.3 "With debris" wear condition

SEM micrographs of WC-12wt%Co specimen worn for approximately 120 seconds are shown in figures 4.23 and 4.24 (plan view) and figures 4.25 and 4.26 (cross-sections). SEM micrographs of specimen worn for approximately 10 seconds are shown in figures 4.27 and 4.28. The dominant wear features along the edge of the grooves were cracking and fragmentation of WC grains which probably occurred due to binder removal by abrasive action of fragments of abrasive and carbide grains [22]. Cracking was also observed inside the grooves (figure 4.23). Figure 4.28 shows that SiC grits did not always groove the material as there were areas of unworn WC grains.

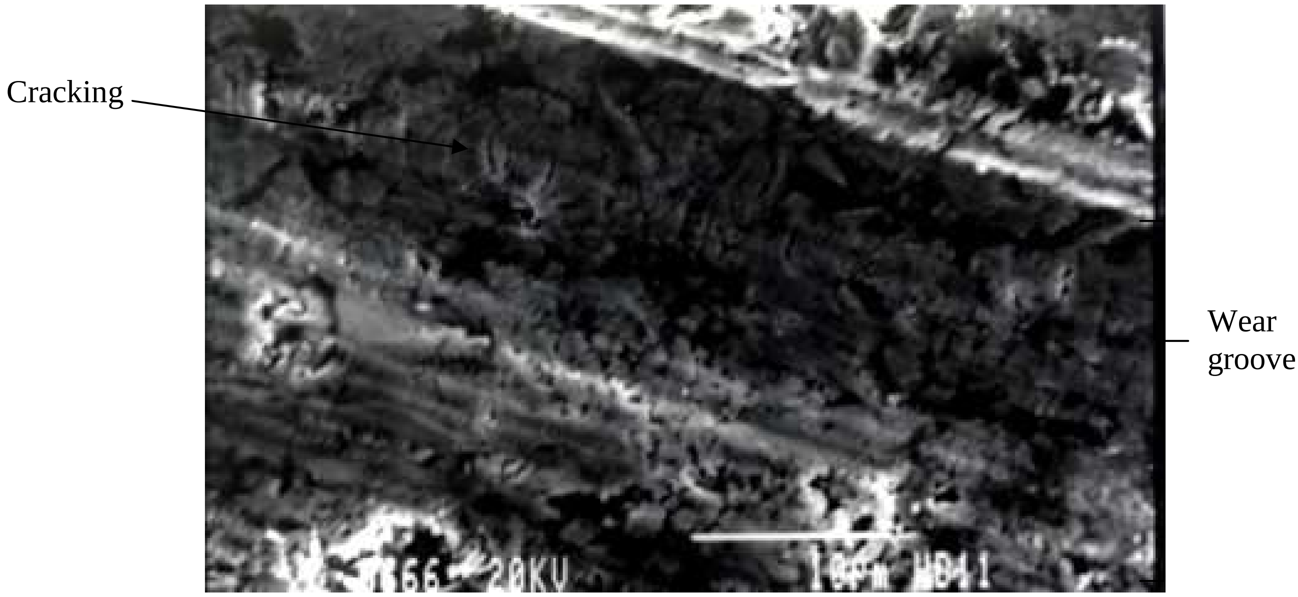


Figure 4.23: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "With debris" wear condition showing a large wear groove, cracked WC grains perpendicular to the groove, pits and material pile-up.

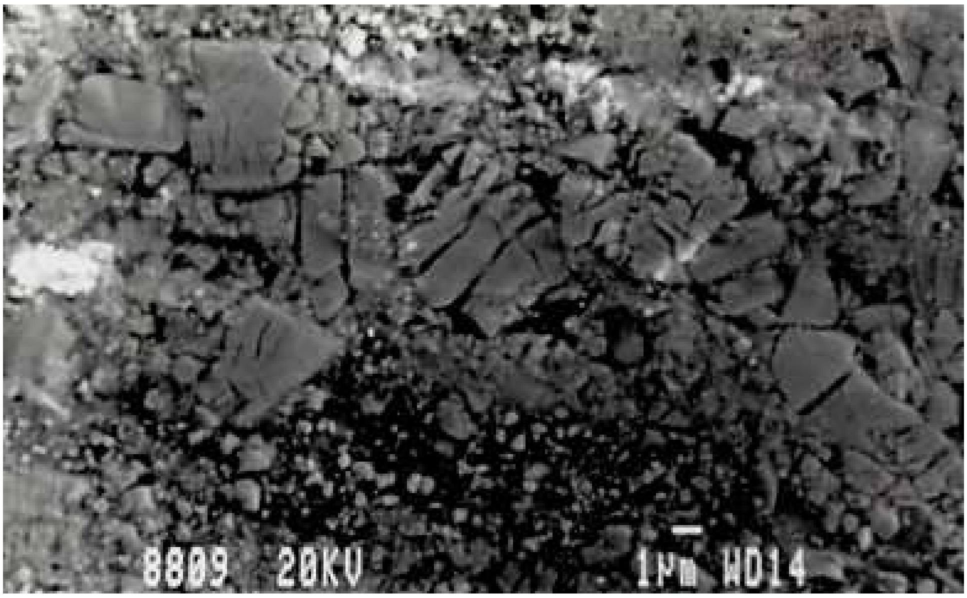


Figure 4.24: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "With debris" wear condition showing severely cracked WC grains and WC grain fragments. The micrograph was taken along the edge of a groove and represents typical wear features of the "With debris condition.

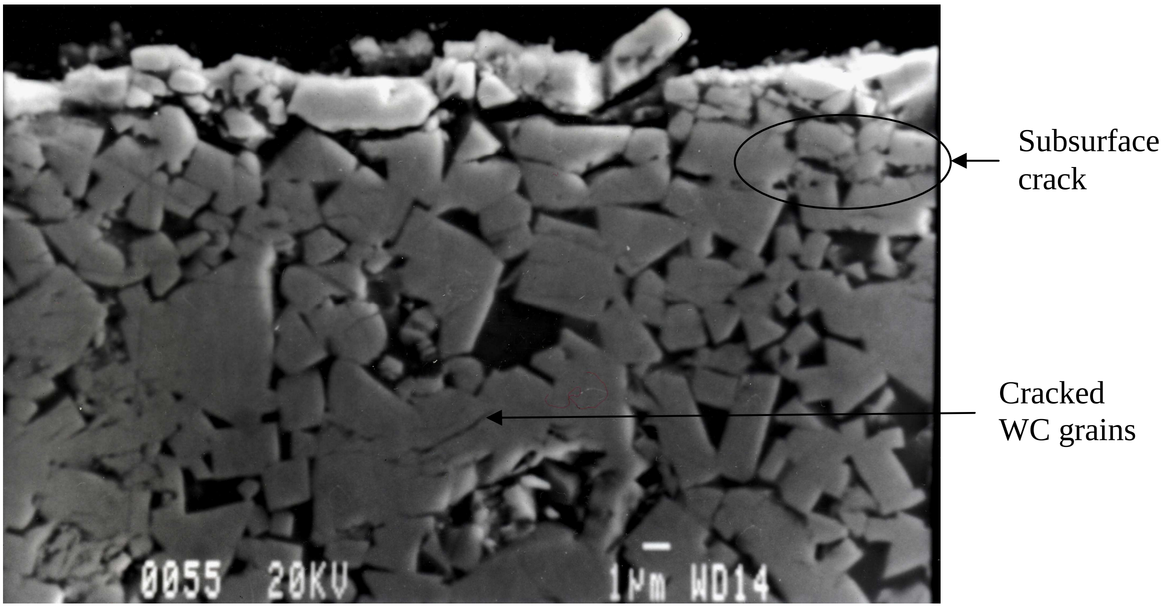


Figure 4.25: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "With debris" wear condition showing subsurface cracking.

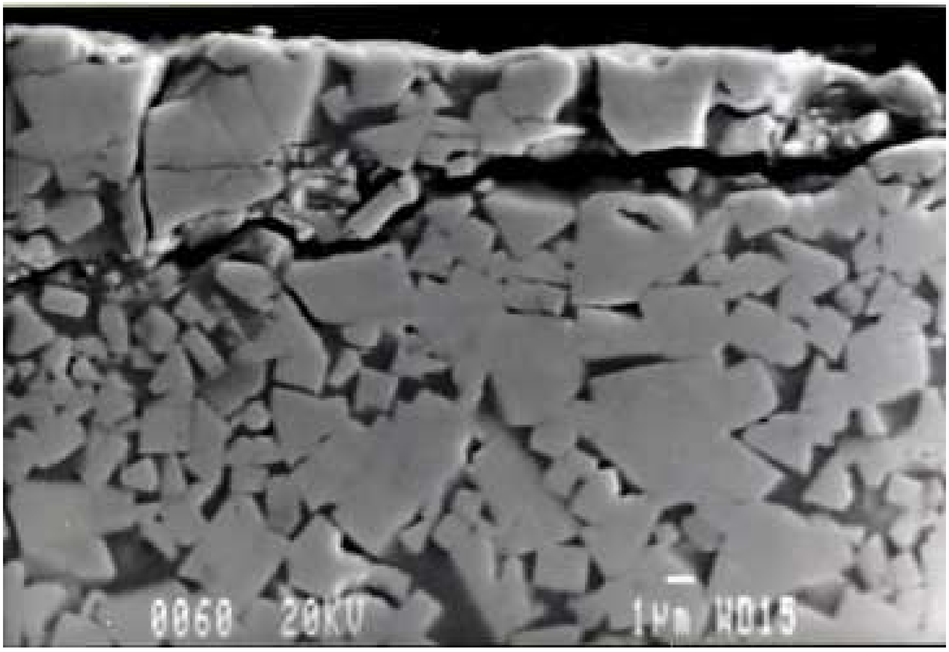


Figure 4.26: An SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.16N load in "With debris" wear condition showing a large subsurface crack.

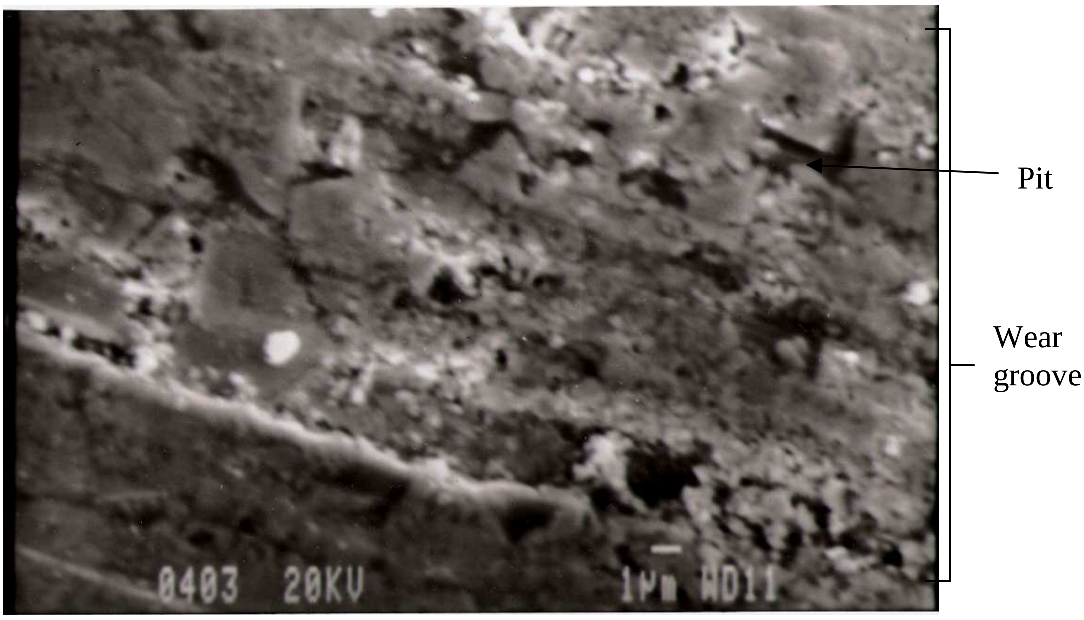


Figure 4.27: SEM micrograph of a WC-12wt%Co specimen worn for approximately 10 seconds under 2.16N load in "With debris" wear condition showing wear groove and pits.

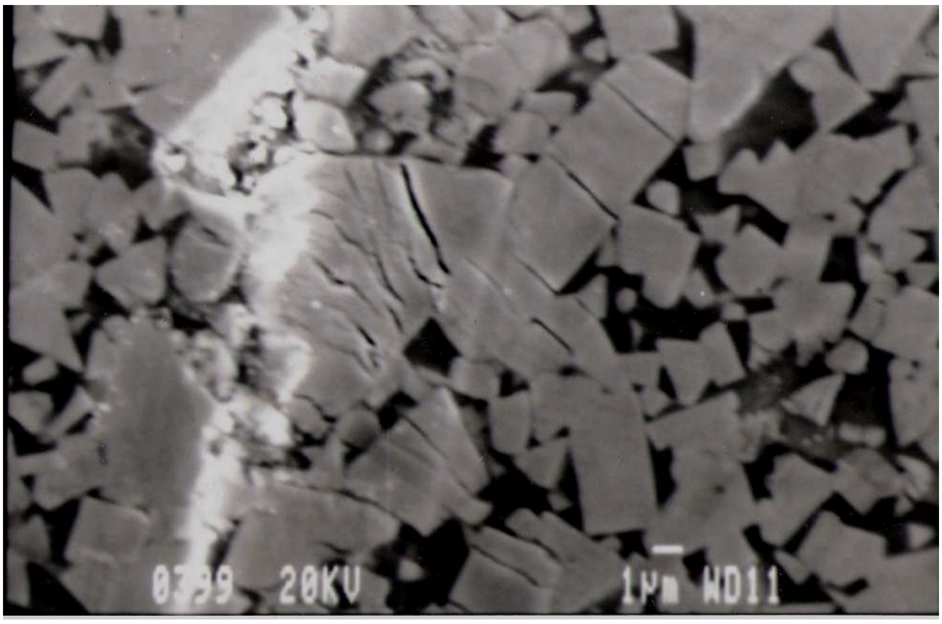


Figure 4.28: SEM micrograph of a WC-12wt%Co specimen worn for approximately 10 seconds under 2.16N load in "With debris" wear condition showing selectively cracked WC grain and areas of unworn WC grains.

To show that the chipping was not caused during sectioning of the specimen, a cross section was prepared from a polished specimen and SEM micrographs taken (see figure 4.29). A clean cut is obtained.

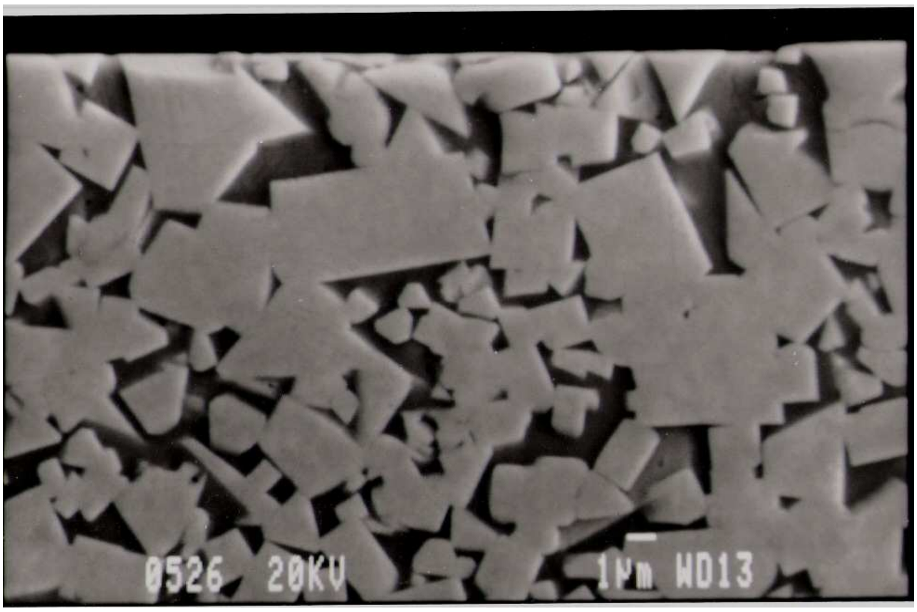


Figure 4.29: SEM micrograph of the cross section of a polished WC-12wt%Co specimen.

4.4.2 High load (2.84N)

4.4.2.1 "Ideal" wear condition

SEM micrographs of WC-12wt%Co specimen worn for approximately 120 seconds are shown in figures 4.30 and 4.31 (plan view) and figure 4.32 (cross-section). SEM micrograph of WC-12wt%Co specimen worn for approximately 10 seconds is shown in figure 4.33 (plan view). Similar wear features to those observed under the 2.16N load were observed. These features are the wear grooves formed by the motion of the abrasive grits, formation of pits due to material removal, material pile-up from the material removed during groove formation, cracking of WC grains and fragmented WC grains. Groove formation, cracking (inside and along the edge of the grooves) and fragmentation of WC grains were dominant wear features.

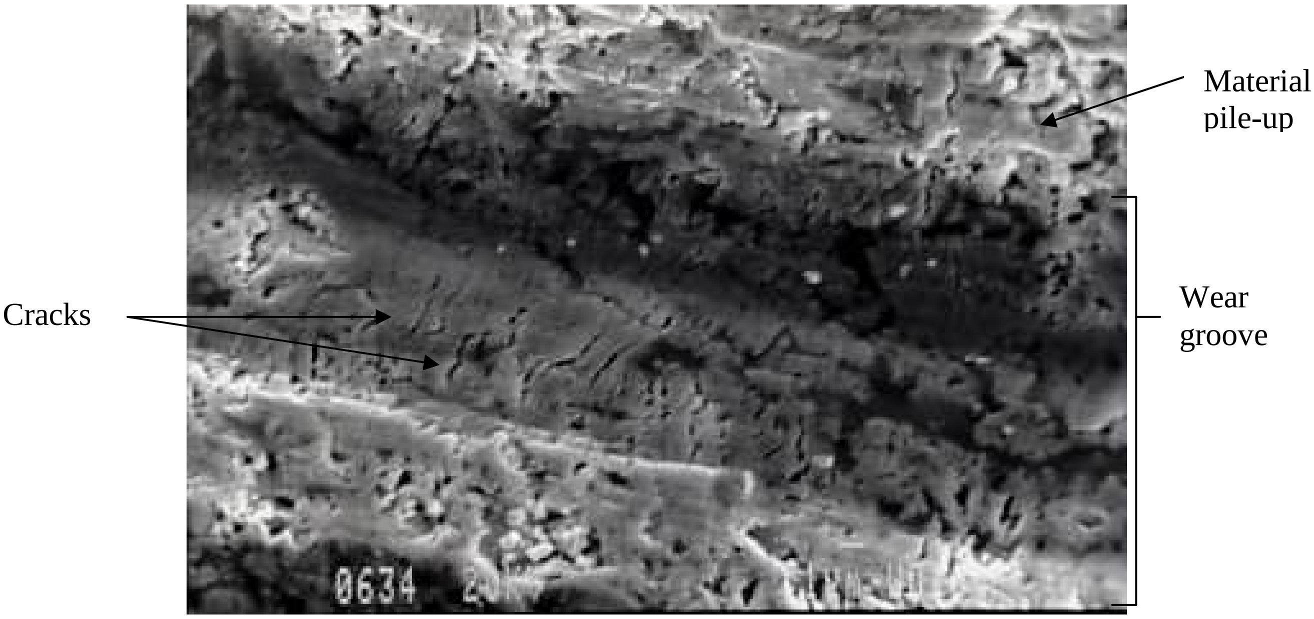


Figure 4.30: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "Ideal" wear condition showing a groove, material pile-up and cracks perpendicular to the wear groove.

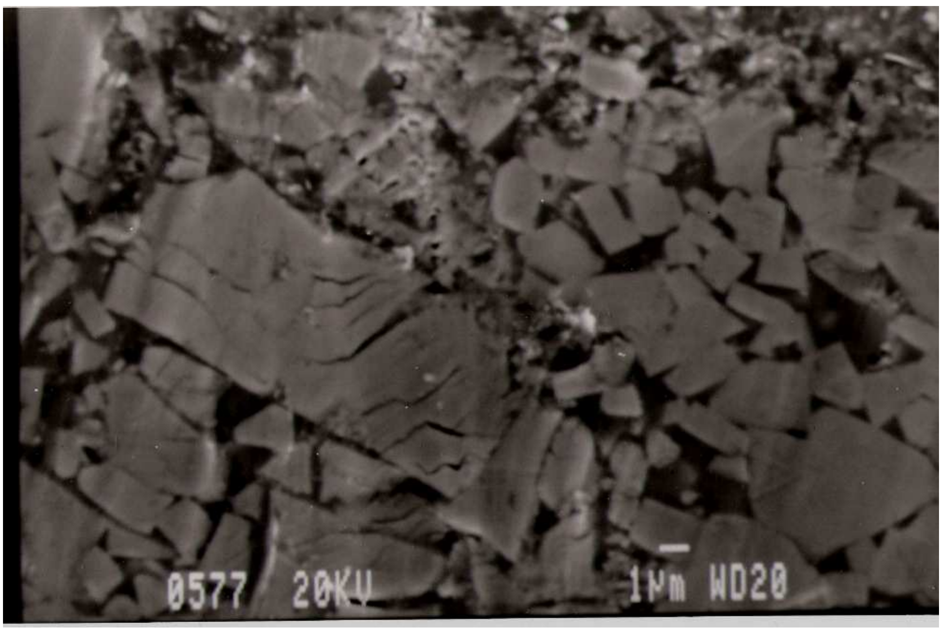


Figure 4.31: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "Ideal" wear condition showing cracked WC grains and fragmented WC grains. The micrograph was taken along the edge of a groove.

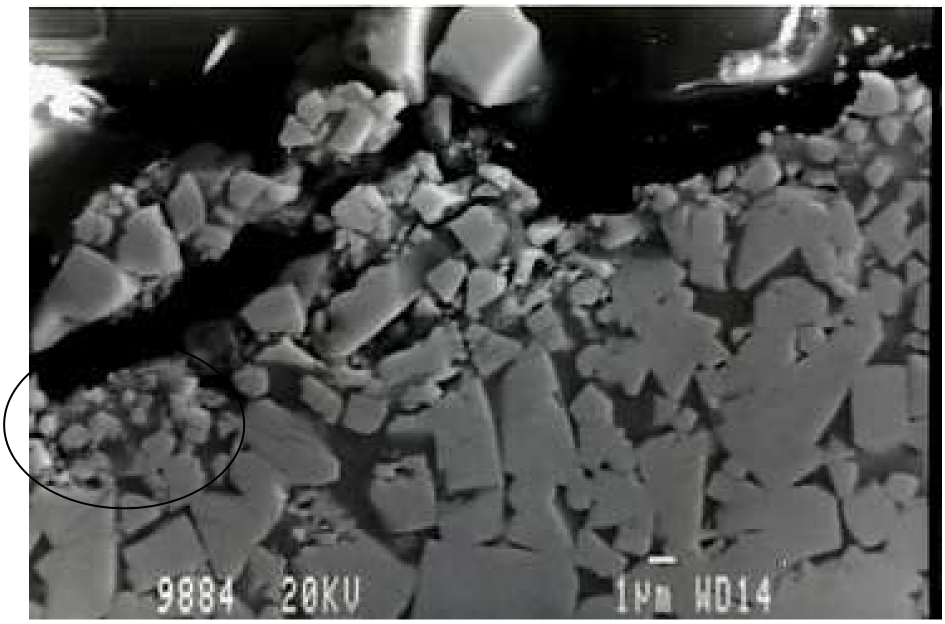


Figure 4.32: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "Ideal" wear condition showing fragmented WC grains in surface layer or tribofim.

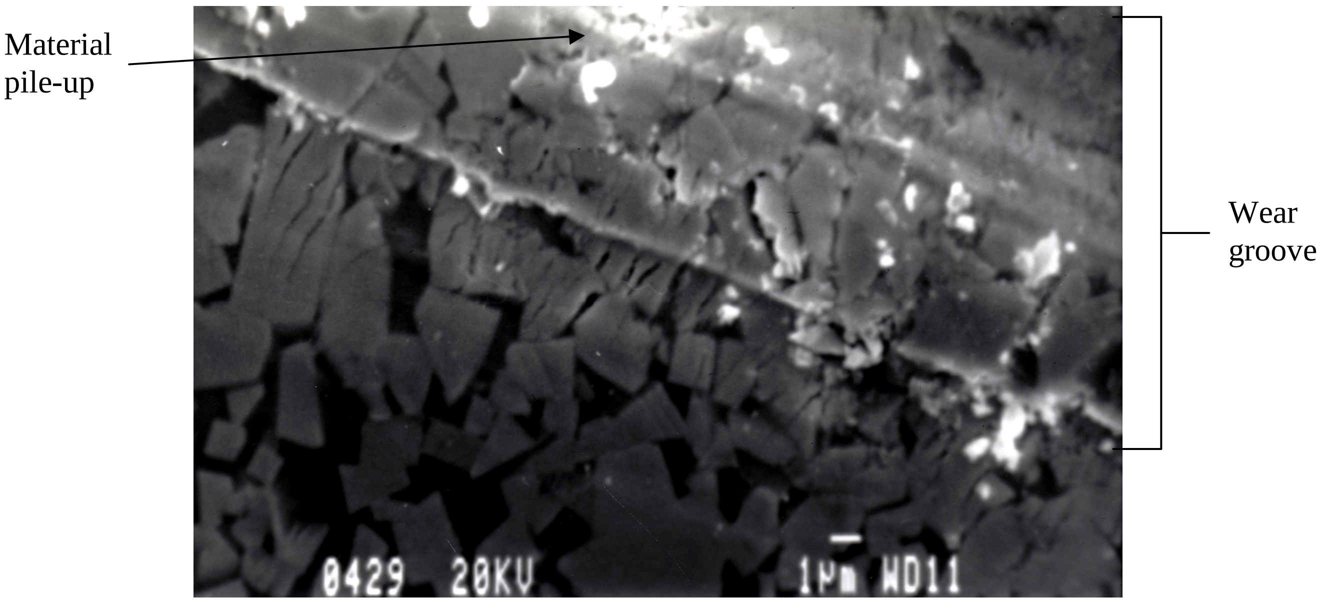


Figure 4.33: SEM micrograph of a WC-12wt%Co specimen worn for approximately 10 seconds under 2.84N load in the "Ideal" wear condition showing a wear groove, material pile-up and cracked WC grains. The micrograph was taken along the edge of a groove.

4.4.2.2 “No debris” wear condition

SEM micrographs of WC-12wt%Co specimen worn for 120 seconds are shown in figures 4.34 and 4.35 (plan view) and figure 4.36 (cross-section). A SEM micrograph of a WC-12wt%Co specimen worn for 10 seconds is shown in figure 4.37 (plan view). The wear features are similar to those observed at 2.16N for the same wear condition and the dominant features were grooving, severe cracking and fragmentation of WC grains.

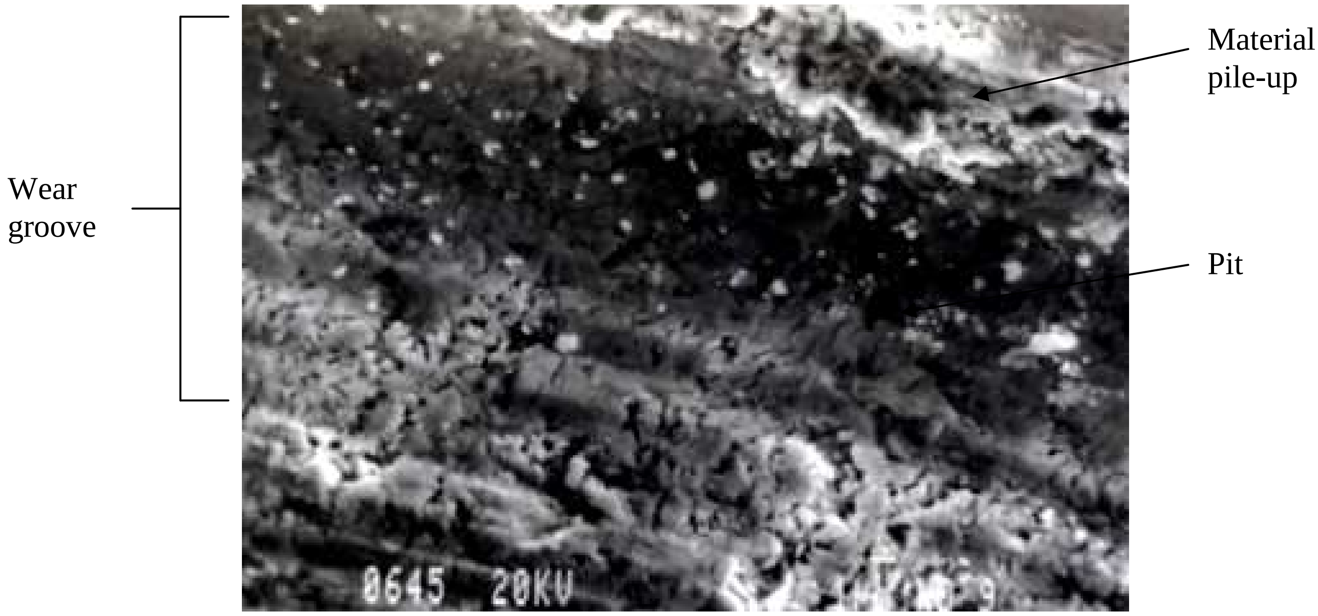


Figure 4.34: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the “No debris” wear condition showing a large groove, cracks perpendicular to the groove, pits and material pile-up.

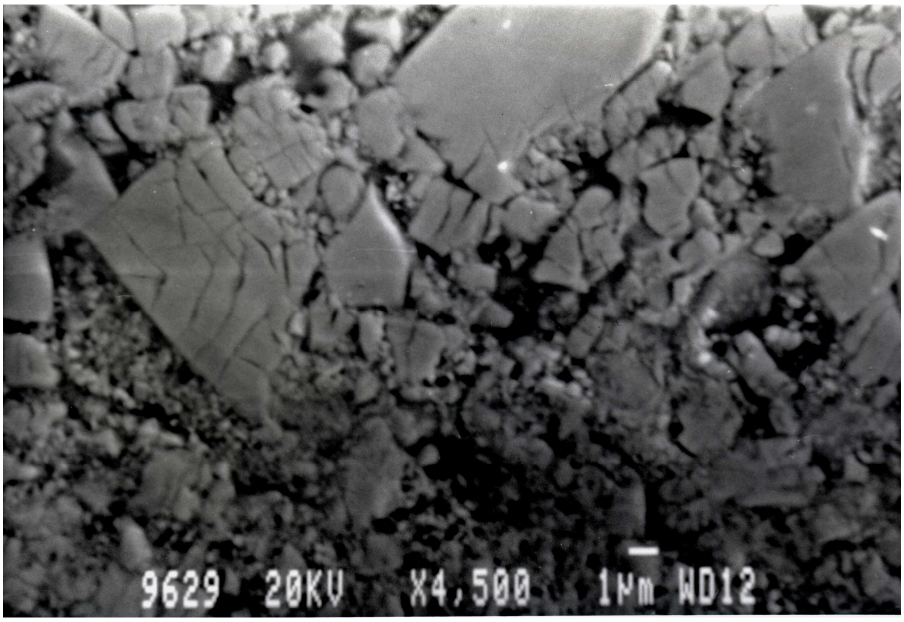


Figure 4.35: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "No debris" wear condition showing severely cracked WC grains, pits and fragmented WC grains.

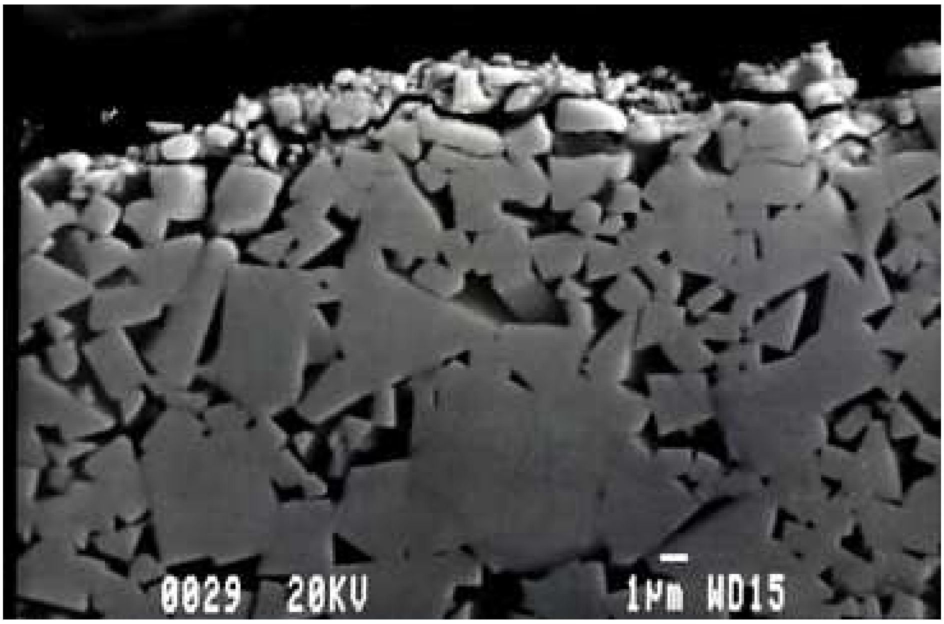


Figure 4.36: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "No debris" wear condition showing subsurface cracking.

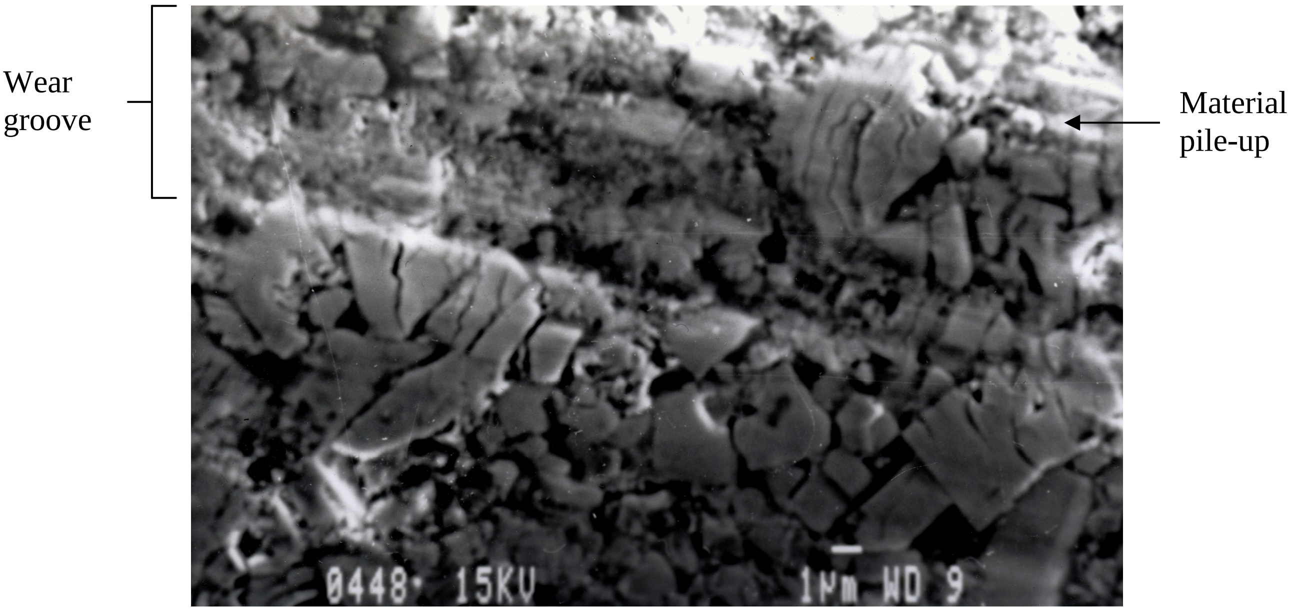


Figure 4.37: SEM micrograph of a WC-12wt%Co specimen worn for approximately 10 seconds under 2.84N load in the "No debris" wear condition showing a wear groove, cracked WC grains, pits and material pile-up.

4.4.2.3 "With debris" wear condition

SEM micrographs of WC-12wt%Co specimen worn for 120 seconds are shown in figures 4.38 and 4.39 (plan view) and figure 4.40 (cross-section). A SEM micrograph of a WC-12wt%Co specimen worn for 120 seconds is shown in figures 4.41 (plan view). The wear features are similar to those observed at 2.16N for the same wear condition and the dominant features were grooving, severe cracking and fragmentation of WC grains.

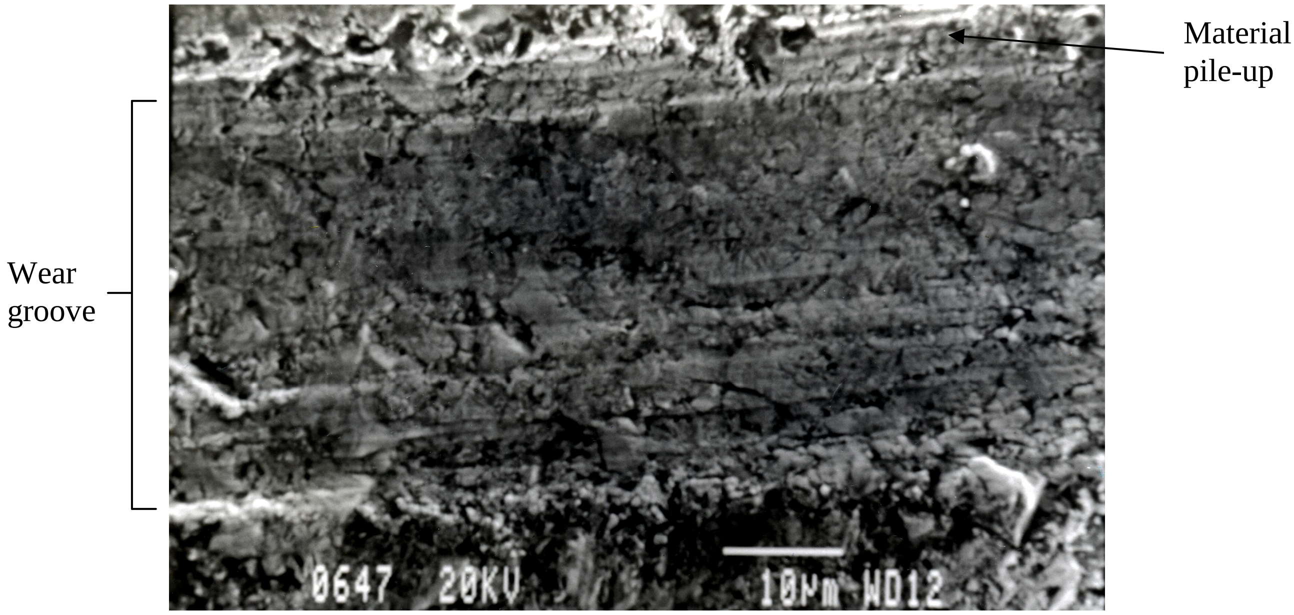


Figure 4.38: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "With debris" wear condition showing a large groove, pits, material pile-up and surface cracking within the groove.

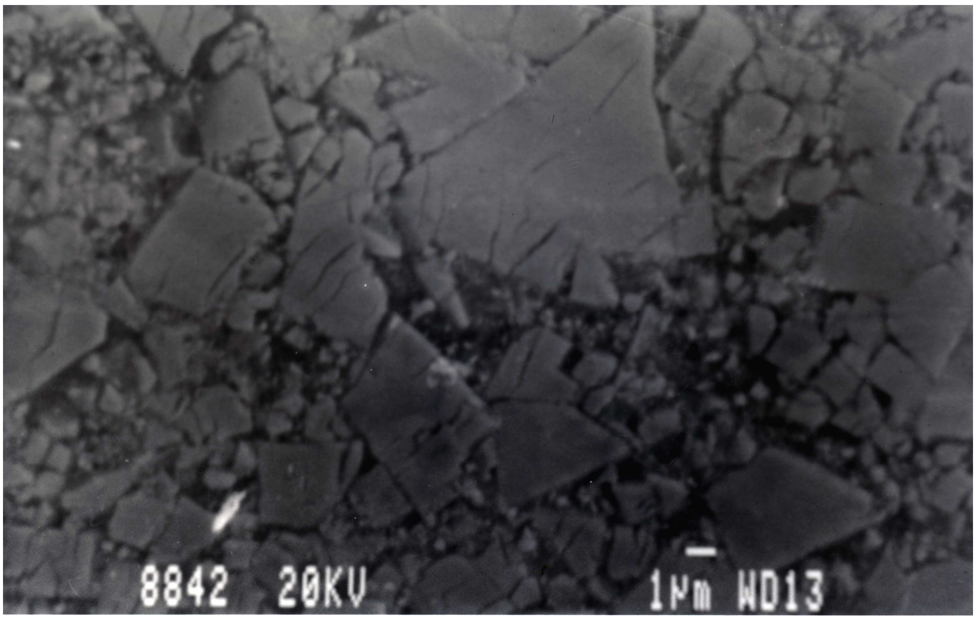


Figure 4.39: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "With debris" wear condition showing severely cracked WC grains and fragmented WC grains. The micrograph was taken along the edge of a groove.

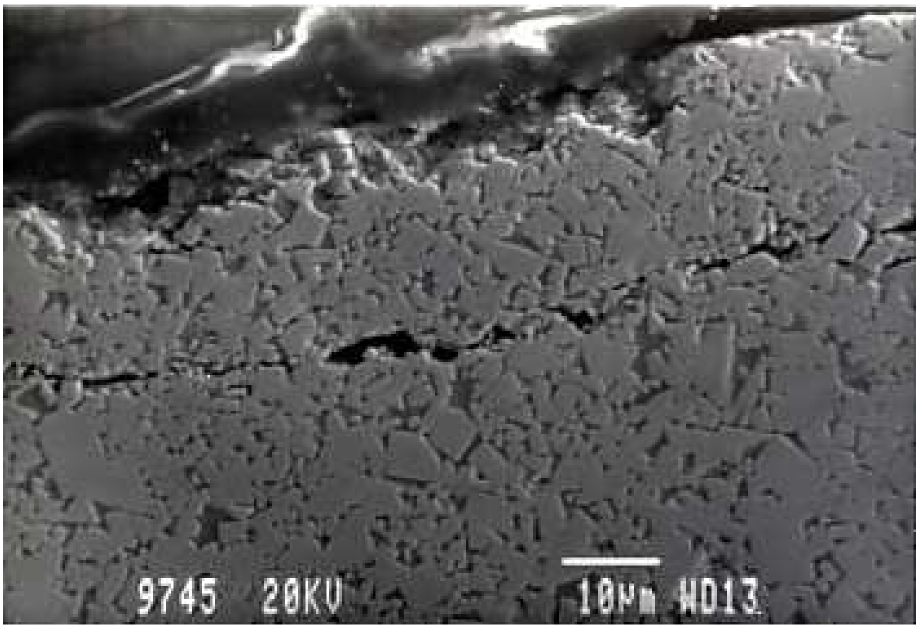


Figure 4.40: SEM micrograph of a WC-12wt%Co specimen worn for approximately 120 seconds under 2.84N load in the "With debris" wear condition showing a large subsurface crack similar to that formed at low load for the same wear condition.

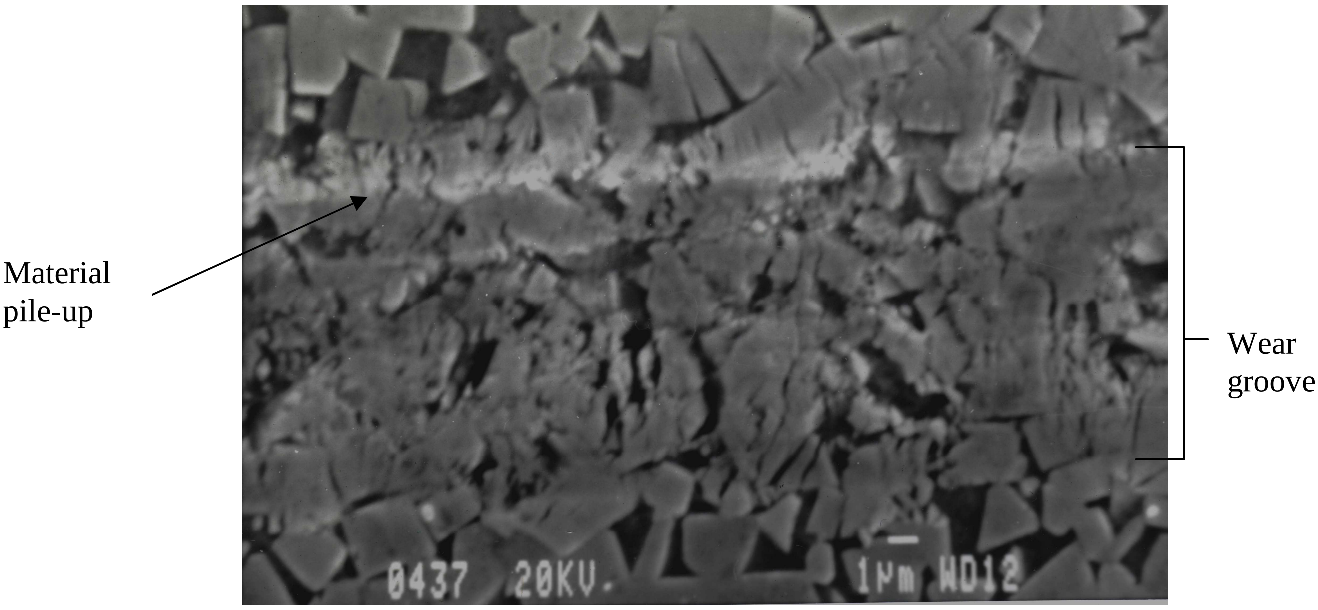


Figure 4.41: SEM micrograph of a WC-12wt%Co specimen worn for approximately 10 seconds under 2.84N load in the "With debris" wear condition showing a wear groove, severely cracked WC grains and material pile-up.

4.5 Analysis of SiC abrasive paper

The SiC abrasive paper used during the “No debris” wear conditions was analysed before and after wear using different microscopes.

4.5.1 SiC abrasive paper before wear

The average SiC abrasive grit size was measured (section 4.2.1) as being 251±112µm with a hardness of 2400kg/mm^2. The WC-12wt%Co wear rate is affected by the shape of the SiC grits as this influences the depth and width of the grooves formed [10]. Figure 4.42 shows micrographs of unworn SiC abrasive grit paper. The shape of the grits is irregular and angular.

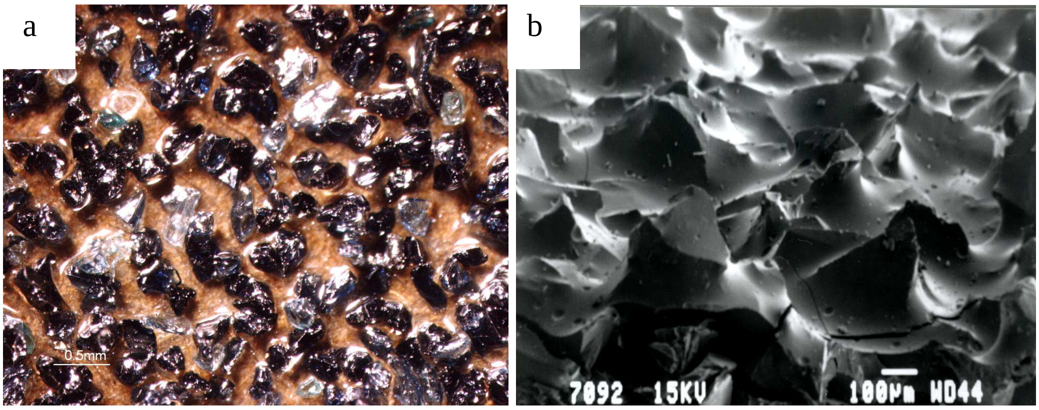


Figure 4.42: (a) Plan view of an unworn SiC abrasive paper taken with a stereo microscope and (b) SEM micrograph of a tilted side view.

4.5.2 SiC abrasive paper after wear

Figure 4.43 shows a SiC paper before and after wear for approximately 70 seconds at 2.16N load. Figure 4.44 shows a SiC paper worn for approximately 24 seconds at 2.84N load.

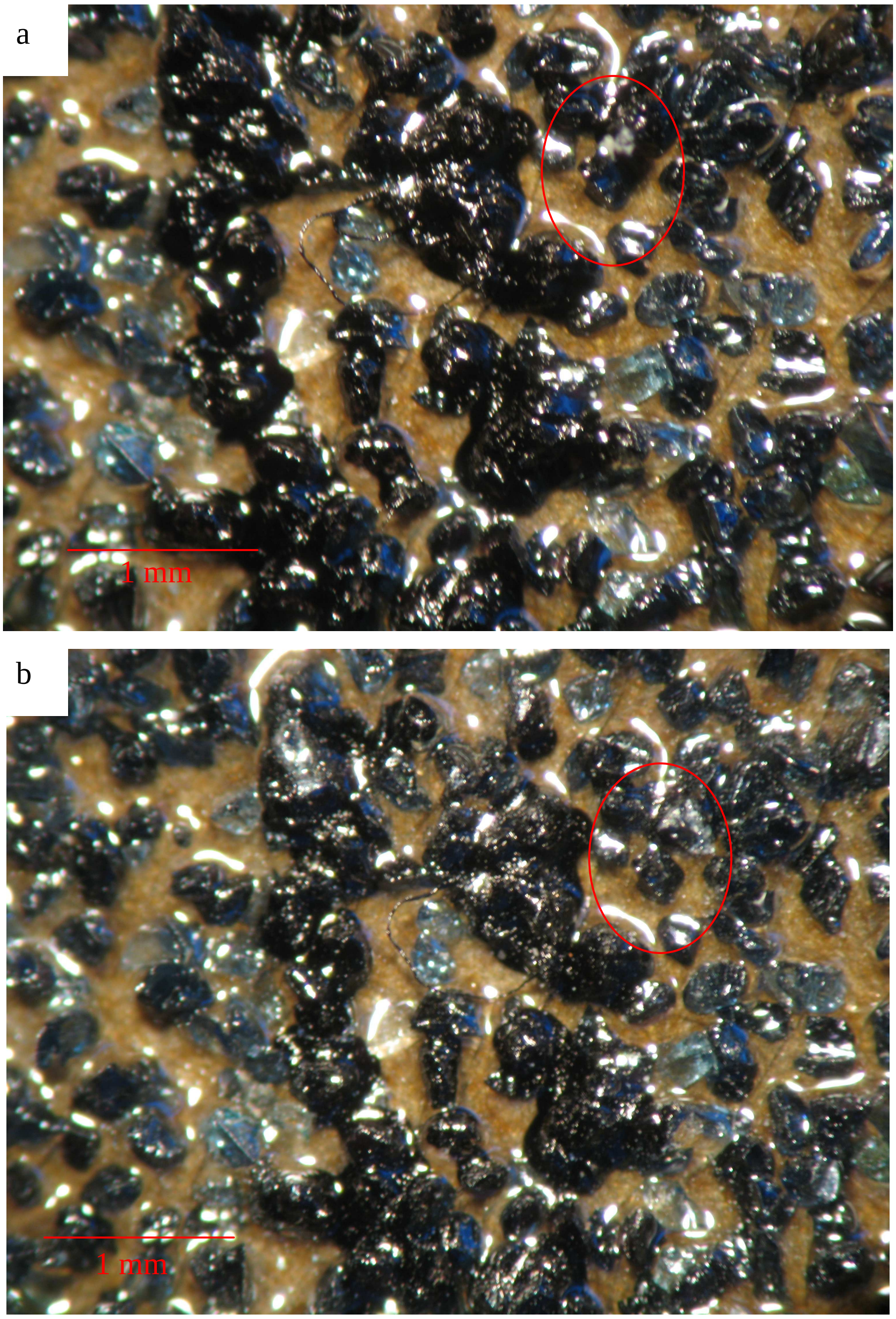


Figure 4.43: (a) Unworn SiC abrasive paper and (b) after approximately 70 seconds of wear. Highlighted region depicts worn grit.

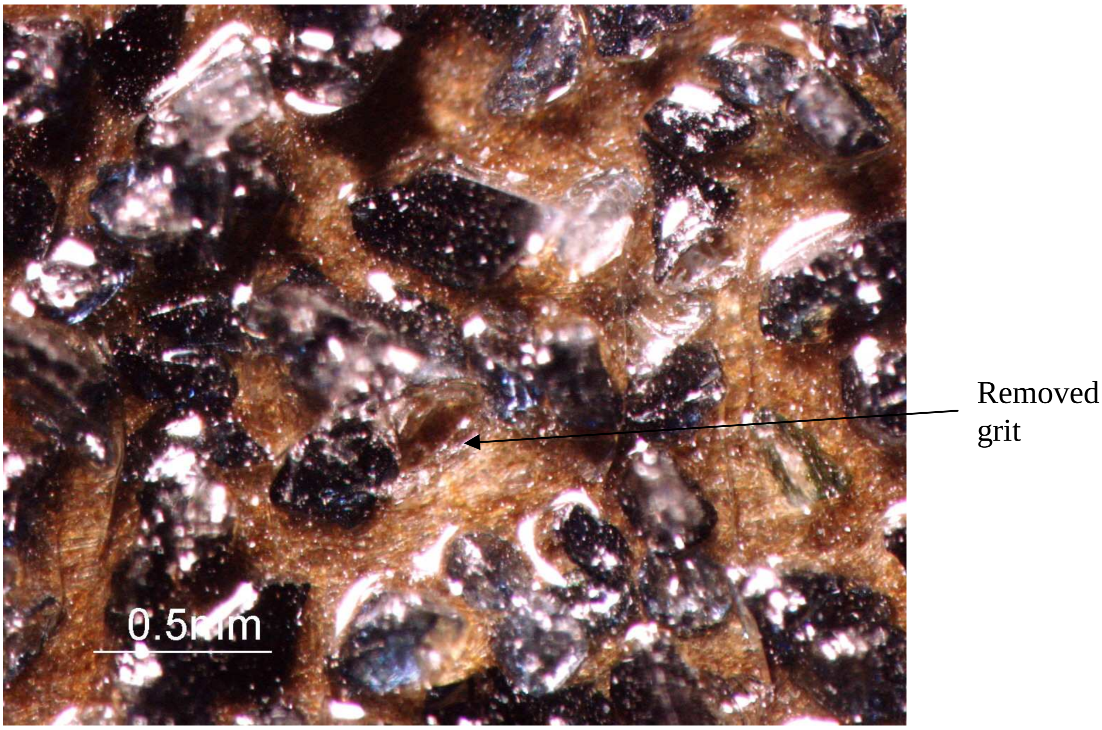


Figure 4.44: SiC abrasive paper worn for approximately 24 seconds. The grit was removed near the center of the SiC abrasive paper.

From the microscopic investigations it was observed that the SiC grits were worn as the wear test progressed. However quantitative analysis on the worn grits was not possible as cracks had been detected on grits of the new and unused abrasive paper. In addition the difficulty in locating the same grit before and after wear also limited this analysis.

4.6 Analysis of the wear debris

The wear debris was collected and analysed every 2.4 seconds under the “No debris” wear conditions at 2.16N and 2.84N loads. This was done by inverting and gently tapping the SiC abrasive paper after a test.

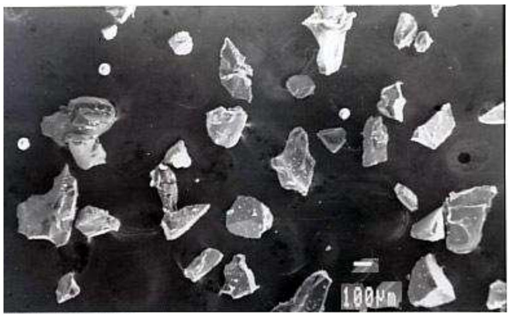
4.6.1 Low load (2.16N)

Wear debris shown in figure 4.45 was collected after approximately 2.4, 12, 36, 49 and 51 seconds, analysed by SEM and the particle size calculated using an image analyzer.

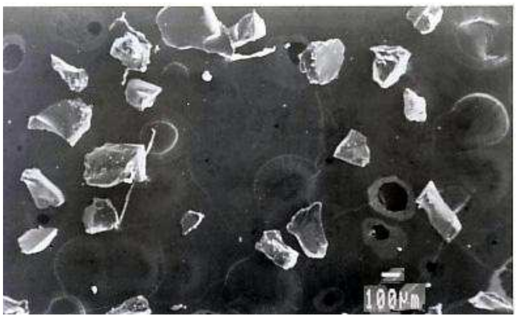
t = 2.4 seconds

t = 12 seconds

t = 36 seconds



t = 49 seconds



t = 51 seconds

Figure 4.45: Samples of wear debris collected at different time intervals during a wear test showing a difference in debris particle size and amount for 2.16N load.

The amount of debris decreased as the time progressed thereby limiting analysis at longer time periods. The decrease occurs due to rounding off of the SiC grits after the angular asperities of the fresh grit have been removed during the initial wear stages. This blunting of the SiC grits limits grit wear by the hardmetal specimen.

The size of the debris is tabulated in table 4.5. The average SiC grit size of the fresh abrasive paper as calculated in section 4.2 is 251 ± 112μm.

Table 4.5: Size of the wear debris collected during wear under 2.16N load.

Time	2.4 seconds	12 seconds	36 seconds	49 seconds	51 seconds
Median	209 μm	153 μm	149 μm	125 μm	127 μm
Mean	231±117μm	166±78μm	160±81μm	143±75μm	141±69μm

Table 4.5 shows that the mean size of the wear debris removed decreased as wear progressed. After approximately 2.4 seconds (i.e. one wear cycle), the mean size of the debris removed was close to an average SiC grit size. From figure 4.46, the mean of the debris size (at 2.4 seconds) is greater than the median implying that there are more debris particles larger than the average compared to debris particles smaller than the average. This was true for all time periods. Most of the wear debris collected at approximately 51 seconds (figure 4.46) was less than the average SiC grit size.

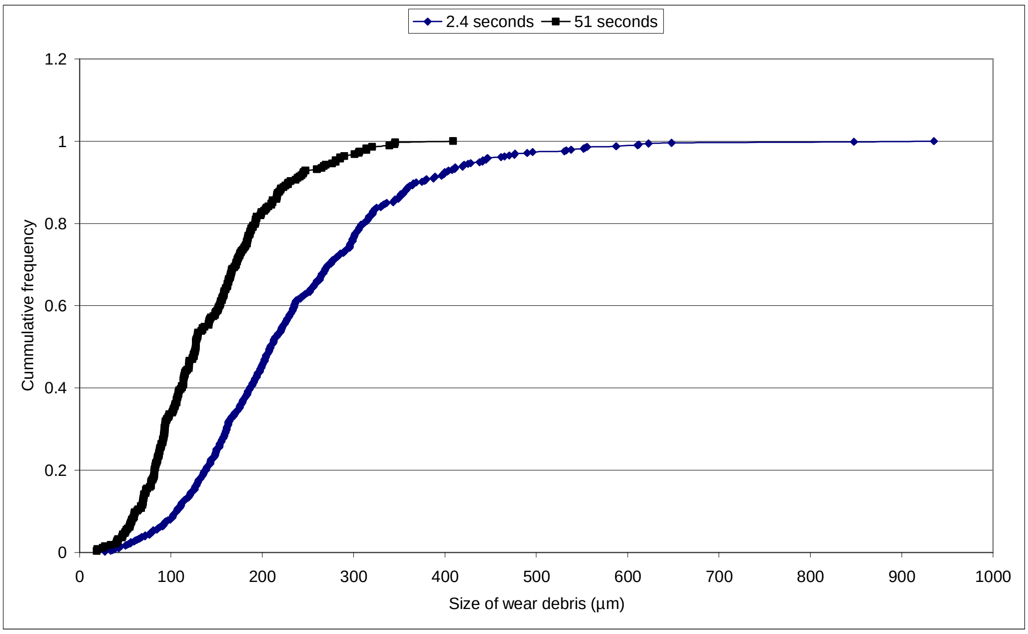
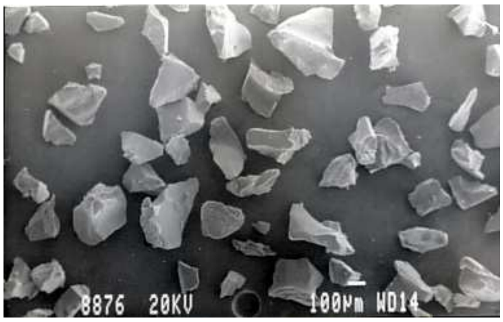


Figure 4.46: Graph of cumulative frequency versus size of wear debris collected for the "No debris" condition under 2.16N load after 2.4 and 51 seconds.

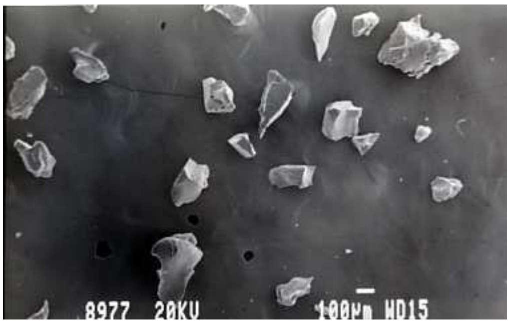
4.5.2 High load (2.84N)

Wear debris was collected after approximately 2.4, 12, 24, 49 and 51 seconds, analysed in the SEM (figure 4.47) and the particle size determined.



time = 2.4 seconds *time = 12 seconds*

time = 24 seconds *time = 49 seconds*



time = 51 seconds

Figure 4.47: Samples of wear debris collected during a wear test at different time intervals showing a difference in debris size for 2.84N load.

From figure 4.47, there is a reduction in the size and amount of the wear debris collected from the abrasive paper as wear progressed. This is probably due to the rounding off of the SiC grits after asperities of fresh grit have been removed during the initial wear stages. This lead to a reduction in the WC-12wt%Co wear rate. Table 4.6 shows the wear debris particle size at different time intervals.

Table 4.6: Size of the wear debris collected during wear under 2.84N load.

Time	2.4 seconds	12 seconds	24 seconds	49 seconds	51 seconds
Median	186 µm	160 µm	152 µm	138 µm	130 µm
Mean	203±99µm	170±81µm	163±80µm	158±84µm	139±74µm

The average debris sizes were close (within experimental error) to those observed at the low load (2.16N) (compare tables 4.5 and 4.6). Figure 4.48 shows the cumulative frequency versus size of the wear debris curves for debris collected after 2.4 and 51 seconds. The distribution of the debris is similar to that observed for debris collected at low load. There was more debris greater than the average SiC grit size at 2.4 seconds compared to 51 seconds.

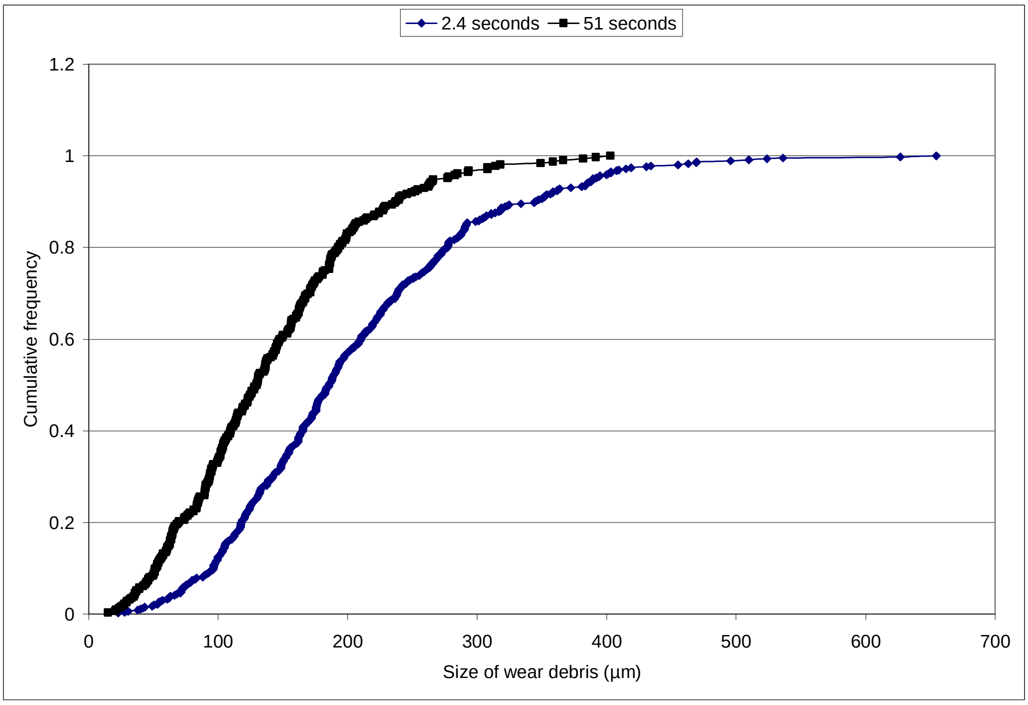


Figure 4.48: Graph of cumulative frequency versus the size of the wear debris collected for the "No debris" condition under 2.84N load after approximately 2.4 and 51 seconds.

The graph of WC-12wt%Co wear rate versus time for both loads is plotted in figure 4.49. Initially the wear rate at 2.84N load is higher than the wear rate at 2.16N load. This is expected since it is well documented that increasing the load causes an increase in wear rate [10]. After approximately 17 seconds, the wear rates are similar within error. After approximately 50 seconds, the wear rate starts to be higher at lower load than at higher load. The size of the wear debris removed is similar at this time periods for both loads but the amount of debris removed was slightly less for 2.84N load compared to 2.16N load.

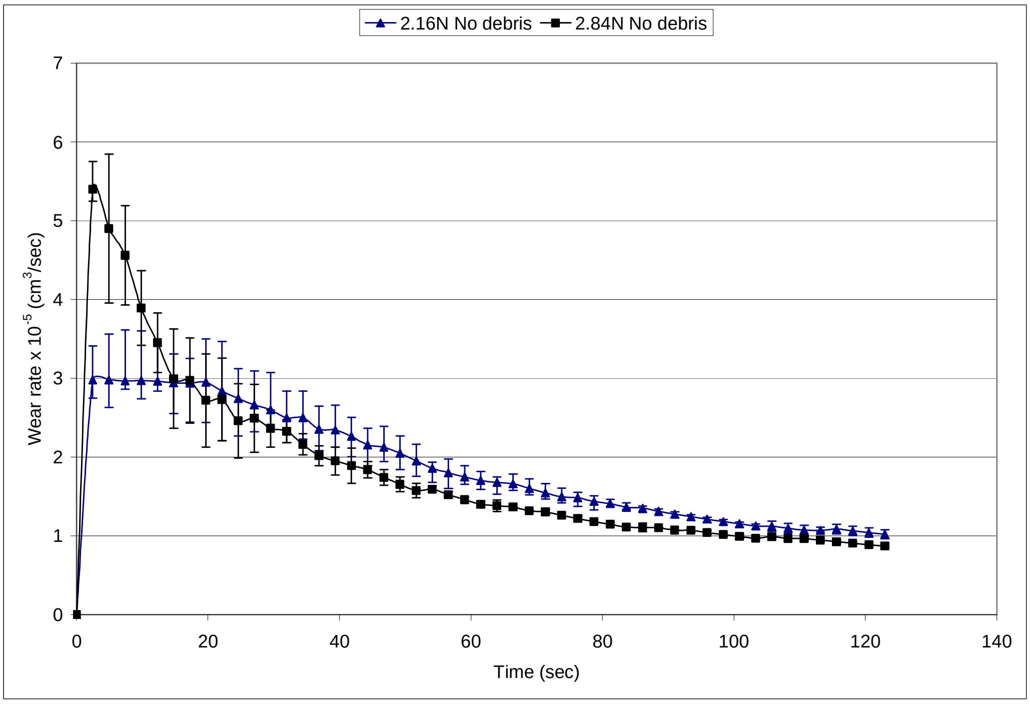


Figure 4.49: Graph of WC-12wt%Co wear rate versus time under 2.16N and 2.84N for the "No debris" conditions.