

Abrasion and Reciprocating Wear of Hardmetals and Ceramics

M G Gee, A Gant, W P Byrne and B Roebuck
Centre for Materials Measurement and Technology
National Physical Laboratory
Teddington
Middlesex, UK, TW11 0LW

SUMMARY

This report describes the results of three different wear tests that were performed on a range of hardmetal and ceramic materials. Two abrasion tests and one sliding (reciprocating) test were employed.

The ASTM B611 steel wheel test gave a singular relationship between wear volume and hardness for the hardmetal samples. This relationship held for hardmetals with differing binder phase compositions and volume fractions. Using silica abrasive instead of the normal alumina abrasive gave wear volumes about an order of magnitude lower, but with a very similar relationship. Ceramics gave higher wear rates than hardmetals with the same hardness.

Modified ASTM G65 tests with silica abrasive also showed a reduction in wear with an increase in hardmetal hardness. Tests were carried out with a wet rubber wheel, a dry rubber wheel and a wet steel wheel. Wear increased in the order wet rubber>dry rubber>wet steel. Ceramics again gave higher wear rates than hardmetals.

In the reciprocating tests there was only a small amount of wear. The friction coefficient for the tests at 40 N was about 0.25, and decreased slightly with increase in hardness for the hardmetals.

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National Physical Laboratory
Teddington, Middlesex TW11 0LW, UK

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Approved on behalf of Managing Director, NPL, by Dr C Lea,
Head, Centre for Materials Measurement and Technology

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1. INTRODUCTION

Ceramics and hardmetals are used in many wear resistant applications. Project CAM 9, *Performance Related Wear Testing of Ceramics and Hardmetals*, is concerned with the development of wear testing procedures which are relevant to the industrial application of hardmetals and ceramics.

Wear by abrasion is the largest cause of wear problems in industry [1]. For this reason the emphasis of the testing reported here is on abrasive wear.

The different conditions that are encountered in abrasive applications have been modelled by modifying the conditions of the abrasion tests. Thus the ASTM G65 test [2] normally employs a rubber rimmed wheel to press the abrasive against the test-piece, providing a compliant bed for the abrasive. By contrast the ASTM B611 [3] test uses a steel wheel. Although the compliant rubber bed allows for stress relaxation and load sharing between the different abrasive particles, with the steel wheel, most of the applied load is carried by the small number of the largest particles. The degree of load sharing has a major effect on the severity of abrasion.

Another factor that is likely to be critically important is the chemical environment of the test. Thus if there is any corrosion or tribochemical reaction taking place which is enhancing wear, then this will be affected by the pH of the media that carries the abrasive, and also by the specific details of the chemical reaction that occurs. For this reason, some abrasion tests were performed in simulated sea-water as well as in distilled water.

Ceramics and hardmetals are also used in sliding contact applications; work has been carried out previously at NPL on the sliding wear of ceramics using pin-on-disc testing [4]. To complement this work, reciprocating sliding wear tests have been carried out on both ceramics and hardmetals.

The test methods and the rationale behind their choice are listed in Table 1 and a summary of the overall test conditions that have been used is given in Table 2. A summary of the test procedures that were used is given in an earlier report [5].

A companion report [6] describes the results of scratch tests and fine abrasion tests which had the aim of providing more information on the details of wear mechanisms that occur in abrasion.

2 MATERIALS

Hardmetals with a wide range of grain sizes, % wt fraction binder phase, and different binder phase composition (cobalt and nickel) were tested (Table 3). A selection of different ceramics was also tested and is listed in Table 4.

The sample size was 40 mm x 20 mm x 5 mm. This accommodated all the tests described in this report.

For the reciprocating tests, in addition to the flat samples, ceramic pins 30 mm long x 6 mm diameter were prepared with a spherical cap 10 mm in diameter at one end for the ceramics while hardmetal balls 10 mm in diameter from WC/7% Co were obtained for the hardmetal reciprocating tests.

3. TESTS PERFORMED AND RESULTS OBTAINED

3.1 ISO 12962/ASTM B611 Test

3. Test Description

In the ASTM B611 test (Figure 1), intended for hardmetal mining grades, a rotating steel wheel is used as the bed for the abrasive that is carried up out of a bath of slurry surrounding the lower part of the wheel and test-piece into the wear interface. The volume of wear is calculated from mass loss and density measurements after a given number of wheel revolutions. The abrasive specified in the test standard is alumina about 600 µm in size. This is industrially unrealistic since the alumina abrasive is very hard (about 2300 HV) and rarely encountered in practice. A better choice of abrasive from this respect would be silica (quartz sand) which is much more commonly encountered in practice and has a hardness of 1100 HV. The other test conditions are given in Table 2.

Test-pieces were prepared by diamond grinding with a resin bonded grinding wheel with 165 µm diamond grit. This surface preparation was chosen as it is a standard developed by the hardmetal industry.

3.2 Results

Figure 2 shows the volume of wear observed for the hardmetals with alumina and silica abrasive (Table 5). Very similar trends in results are observed for both abrasives, with the results for the alumina abrasive about an order of magnitude higher than for the silica. The nearly linear relationship observed between the logarithm of wear volume and hardness implies that the wear volume can be described quite well by

$$V = A \exp^{BH}$$

where V is the wear volume, H is the hardness and A and B are constants. At low hardness values the wear volumes are lower than predicted from this relationship.

Figure 3 shows the comparison between wear volumes obtained for tests performed using distilled water and those performed using simulated seawater. No discernible difference can be seen (Table 5).

Wear of ceramics also follows a decreasing trend of decreasing wear volume with hardness (Figure 4, Table 6) in a similar way to the hardmetal results, but the results are not as clear cut with more scatter. Again, the ceramics wore about an order of magnitude less with silica abrasive than with alumina abrasive.

The apparent wear volume of ceramics is much higher than for hardmetals of equivalent hardness. However, it should be noted that the hardness scales used for the two different types of material are different due to the need to use a lighter load for indentation of the ceramics to avoid fracture damage. It is possible that some of the difference in results between the ceramics and hardmetals is due to the difference in indentation load. (It is well known that the values obtained for hardness measurements increase markedly as the indentation load is reduced.)

However, it is extremely unlikely that this can account completely for the difference in results. It is probable that the lower fracture toughness of ceramics in comparison with hardmetals also contribute.

Examination Of Worn Surfaces

A typical wear scar on a hardmetal sample is shown in Figure 5. The direction of wear is left to right, and it is always true that the leading edge of the wear scar is clearly defined by comparison with the trailing edge which is less well defined and has a rougher appearance.

Examination of the worn samples of the hardmetals in the Scanning Electron Microscope (SEM) showed several different features:

Considerable fracture was evident on the worn surfaces (Figures 6-8).

WC grains had fragmented and re-embedded (or cobalt had extruded around the fragments of carbide [7,8]). The size of the fragments was very small (100 nm or less) in some cases (Figure 7).

- Areas where fragments or material had broken away from the surface were evident (Figure 8).
- Damage aligned with crystallographic directions in the grains was evident for some large WC grains (Figure 9).

Some samples were sectioned and polished perpendicular to the wear track and examined in the correct orientation so that a good image could be obtained simultaneously from the wear surface and the polished section. Figure 10 shows one of these samples. It is clear that the fragmented and compacted material does not form a continuous layer over the surface but is localised with a depth of several micrometres. A delamination crack is also clear a few micrometres below the surface.

Delamination cracks of this type were observed for many different hardmetals with different compositions and hardness. However, insufficient samples were examined to determine a quantitative relationship between crack size and depth and the composition and structure of the hardmetals.

3.2 *Modified ASTM G65 Test*

3.2.1 Test Description

Figure 11 shows a schematic diagram of the modified test system. The test-piece is pressed against the test wheel by dead-weight loading.

The test wheel can either be rubber rimmed, or can be a steel wheel. An inclined channel feeds the silica abrasive to the surface of the test wheel about 2 cm in front of the test-piece. The feed route is adjusted by altering the speed of a slotted drum pressed against the nozzle of the abrasive hopper. This mechanism gives very good control of the abrasive feed rate.

For testing under wet conditions, a fluid feed is located about 2 cm in front of the abrasive feed. The nozzle is placed close to the test wheel so that the fluid is transferred directly to the test wheel without the formation of drops of fluid. This gives a wet wheel without the build up of deposits of abrasive around the test-piece which would clog the feed chute. A peristaltic pump is used to pump the fluid

from a reservoir.

The test pieces were prepared by the same procedure as for the ASTM B611 tests and the wear volume calculated from mass loss and density. The test conditions are given in Table 2.

Results

Figure 12 shows the results of modified ASTM G65 tests on hardmetals under three conditions (Table 7). The three conditions use:

- dry rubber test wheel
- wet rubber test wheel
- wet steel test wheel

There is a decreasing trend in wear with increasing hardness in all three conditions, and the wear volume always increases in the order wet rubber → dry rubber → wet steel. By comparison with the ASTM B611 tests there is more scatter in results, but it should be noted that for the rubber wheel tests the volume of wear is much lower, so the increased scatter may be due simply to increased errors of measurement.

The ceramic results (Table 8) are shown in Figure 13 and again show a trend for decreasing wear with increasing hardness. With the exception of RBSN, there is less difference in results between the dry and wet rubber conditions than is the case for the hardmetals. It is interesting that the same trends in results are observed in all three test conditions.

When the ceramic results are compared with the hardmetal results (Figure 14) there is a marked apparent increase in wear for the ceramics compared with the hardmetals. However, in a similar way to the ASTM B611 tests it should be noted that the hardness scales for the hardmetals and ceramics are different and this apparent increase in wear may be due to the known effect of increased hardness as indentation loads are decreased.

Examination of worn surfaces

Figure 15 shows a typical wear scar produced on a hardmetal sample with a wet rubber wheel. The wear scar is quite shallow and is relatively smooth. Wear scars for tests performed with the dry rubber wheel are quite similar, but have a duller appearance.

Figures 16-18 show higher magnification micrographs of hardmetal samples tested with wet rubber, dry rubber and wet steel test wheels respectively. There is an increase in the degree of fracture and damage to WC grains as the WC grain size of the hardmetal increases, and an increase in the degree of damage as the severity of wear increases with changes in test condition from wet rubber wheel → dry rubber wheel → wet steel wheel.

The appearance of the worn ceramic surfaces varied considerably from one material to another. Two examples are given in Figures 19 and Figures 20.

The wear surface for the high purity alumina (Vitox) sample tested with a wet rubber wheel (Figure 19) showed a mix of features with about half the area polished with very faint marking in the direction of wear. Fragments of material had broken away from the remainder of the surface leaving characteristic appearance (grain facets) of intergranular fracture.

With the dry rubber wheel the worn surface was rougher, and there was some particulate debris present on the worn surface. There was still evidence for intergranular fracture.

The worn surface of the Vitox sample tested with a wet steel wheel was also rough with most of the surface showing evidence for intergranular fracture.

The sintered silicon nitride sample tested with the wet rubber wheel (Figure 20) was relatively flat and polished over most of the area, but with breakaway of material at some points. In the flat areas the microstructure of the ceramics is partially revealed.

When tested with the dry rubber wheel the surface is rougher and there are larger areas where material has broken away. With the wet steel wheel the surface is even more disrupted with layers of material covering most of the surface.

3.3 *Reciprocating Sliding Wear*

Description of Reciprocating Test

The reciprocating test system has been used very widely [9]. A stationary ball is pressed against a flat test-piece which undergoes reciprocating motion.

Friction is measured by measuring the force needed to restrain the pin or ball against the direction of travel. Wear displacement (the movement of the test-pieces into one another due to wear of one or other test-piece) is measured by use of a linear displacement transducer. It should be noted that although similar couples were used where possible, the relative wear that occurs to the ball or flat test-piece is a function of the material as well as the contact geometry, and different ratios of ball to flat test-piece wear may occur for different samples.

Where possible similar couples are tested, ie for the ceramics, a ball or rounded pin of the same material as the flat are tested. For the hardmetals, a single WC/Co composition is used for the ball test-pieces.

The test system used in CAM9 uses a reciprocating flat test-piece which is pressed against a stationary ball (or rounded end pin) (Figure 21).

Results

A typical plot of friction coefficient against horizontal displacement is shown in Figure 22. In this plot a friction coefficient has been calculated from the friction load divided by the normal applied load. However, to show the form of the friction loop the friction coefficient has been left negative for the return stroke of the reciprocating system.

The values of mean friction coefficient and wear displacement are given in Table 9.

Figure 23 shows the friction results for tests at 3N and 40N. The friction coefficient values for the hardmetals were about 0.3 with an indication of a slight fall in friction coefficient as the hardness of

the material increased. The scatter in friction coefficient was lower for the tests performed at 40N than for tests performed at 3N. Some tests were carried out with ground surfaces, but they showed no systematic difference in friction coefficient from the polished samples.

The values of friction coefficient for the ceramics were often higher than those for hardmetals of a similar hardness, particularly at loads of 40N. The scatter in friction for the ceramics at 40N was higher than at 3N.

There was no consistent pattern in the variation of final wear displacement with hardness (Table 4). The test on RBSN at 40N showed the largest amount of wear of any material tested.

The plots of friction coefficient and wear displacement with time¹ showed differences in the details of behaviour in almost every case. For this reason only a few examples of these plots are shown.

The test on N15 hardmetal at 40N showed a wear displacement that increased steadily as the test proceeded (Figure 24). Nevertheless, the total amount of wear was only 4 μm . There was a rapid variation in the friction coefficient with time, but the average value also varied as the test proceeded.

By contrast with the results for N15, the wear displacement for the CW8N hardmetal at 40N (Figure 25) shows high amplitude fluctuations in wear displacement which continue throughout the test. In the corresponding friction coefficient plot there are initially fluctuations, but then a relatively steady friction coefficient is observed.

An initial rapid increase in wear in the Vitox test at 40N (Figure 26) is followed by a slower increase in wear for the remainder of the test. However, there are several regions evident where fluctuations in the wear displacement occur as the test proceeds. The corresponding friction coefficient shows an initial rapid rise which continues as the test proceeds.

The wear displacement for the Sintox sample at 40N (Figure 27) showed an initial sharp decrease in wear displacement followed by an increase for the remainder of the test. There some rapid variations in the signal that also varied in amplitude as the test proceeded. The corresponding friction plot shows many sudden alterations in friction coefficient, and is also notable for the observed very large spread in friction coefficient.

Figure 28 shows the plots for the α -SiC test at 40N and shows sudden sharp increases in wear displacement as the test proceeds. These are associated with sudden brief peaks in the friction coefficient which is at very high values for short periods of time.

3.3.3 Surface Examination

Figure 29 shows the wear surface of polished hardmetal samples subjected to reciprocating tests at 3N. There is only a small amount of damage visible with some grooving and a small amount of breakaway of material from the sample.

¹ All the friction and wear displacement graphs show plots of mean friction coefficient (μ) and friction coefficient $\pm$ the standard deviation in values calculated instantaneously for each cycle of reciprocating data. In the friction coefficient plots the μ , $\mu + \sigma$ and $\mu - \sigma$ lines are calculated by an averaging algorithm. In addition, an integrated friction value is shown which is always lower than the averaged values.

The surface of a polished sintered silicon nitride test-piece tested at 3N is shown in Figure 30. At the centre of the wear track the surface is polished revealing the microstructure of the ceramic. There is some debris present in the form of rolls². At the end of the wear track the surface is partially obscured by layers of debris.

Wear surfaces of polished hardmetal samples tested at 40N are shown in Figure 31. For the ultrafine (Figure 31a) and medium grain sized (Figure 31c) materials there is some breakaway of material from areas of the surface. For the coarse grain 20% Co WC hardmetal (Figure 31b) some damage to WC grains has occurred, but there is some cracking evident in the binder phase which often runs close to the boundary between the binder phase and the WC grains. There are also some fragments of carbide which seem to be embedded into the binder phase.

The wear surfaces for the ceramic samples tested at 40N all showed different features (Figure 32):

- The RBSN was covered with masses of layered debris which is likely to be amorphous silica.
- The Sintox alumina was covered with a powder of debris
- The sintered silicon nitride was covered by a compacted layer of debris. Debris rolls were visible on the surface.
- The α -SiC was covered with a thin layer of material.
- The microstructure was revealed at the wear surface of the reaction bonded silicon carbide.
- The Vitox alumina surface showed some fracture damage, some evidence for the formation of interfacial layers, and the formation of rolls.

4. DISCUSSION

4.1 Abrasion

The results of the ASTM B611 tests on the hardmetal materials all fall within a remarkably narrow band which extends over nearly three orders of magnitude in wear volume. This close band of results for the hardmetals means that it is likely that only a single set of common mechanisms is determining the rate of abrasive wear for the hardmetals. It should be noted that this narrow band of results includes tests for hardmetals with different cobalt binder volume fractions, different compositions (Ni and Ni/Co binders as well as Co binders) and different grain sizes.

The narrow band is also evident in the results of tests performed with silica abrasive. It might be expected that the mechanisms and relationships in relative wear would change when the hardness of the abrasive was less than the test material. (The hardness of alumina abrasive is approximately 2300 kg mm^{-2} , and the hardness of silica about 1100 kg mm^{-2}). This does not appear to be the case for either the ASTM B611 or the ASTM G65 tests.

When the results of the ASTM B611 and ASTM G65 steel wheel tests using silica abrasive are compared, it can be seen that very similar trends in results are obtained (Figure 33). Of course there is a difference in grit size for the abrasive used in the two tests, so complete agreement cannot be

² Debris rolls have been observed frequently in the wear of ceramics [10]. They are formed from soft material generally provided by tribochemical reaction at the wear interface. Rolls are thought to act to reduce friction coefficients.

expected.

It is noticeable that in the modified ASTM G65 tests the scatter in results is higher for the tests performed with the wet rubber wheel than for tests performed with the dry rubber wheel or the wet steel wheel. One reason for this may simply be the increase in experimental error that is experienced in these tests due to the low values of mass loss that were observed in these experiments.

It has often been postulated that wear is inversely proportional to the hardness of the sample. This relationship has been derived for abrasive wear as well as for sliding wear [11,12]. To see if this relationship holds for the ASTM B611 tests, the wear volume was plotted against the reciprocal of hardness in Figure 34. It is clear that a linear relationship is not obtained, particularly at high values of hardness (low $1/H$). However, over an appreciable range of hardness the wear volume is approximately proportional to $1/H$.

The alternative empirical relationship that has already been mentioned is an exponential fit of the form $V = A \exp^{-BH}$. This relationship has been fitted to the abrasion results for hardmetals and the parameters A and B are given in Table 5.

It can be seen that the three steel wheel sets of data (B611 alumina and silica, and G65 silica) steel wheel gave similar slope (B) parameters. Both wet and dry rubber wheel tests also gave similar slope (B) parameters, but they were significantly different to the steel wheel tests.

In the ASTM B611 abrasion testing of hardmetals several different wear mechanisms were observed that may be dependent on one another;

- Fracture and fragmentation of WC grains under the high stresses applied to the sample locally.
- Incorporation of fragments of WC back into the binder phase either by re-embedding or by extrusion of binder phase around the fragments of material.
- Delamination cracking a few micrometres below the surface of the sample with breakaway of some relatively large fragments of material.
- Scratching and grooving of the surface leading to plastic deformation and fracture of the WC grains.

As the hardness of the hardmetal increases and the grain size decreases there is a reduction in the apparent contribution of fracture processes to wear. However, this perception may not be correct; fracture may be more obvious in the large grained materials than the small grained materials where features such as intergranular fracture and transgranular fracture are more difficult to identify and distinguish from one another.

Although several wear mechanisms have been observed, it is not clear which mechanism is the rate controlling process. Further work is clearly needed before a full understanding of the wear processes and their interaction can be developed. Some progress has been made in this respect in multiple scratch test experiments where the build up of damage under the action of repeated scratching along the same scratch path has been examined [6], and also in the examination of the early stages of abrasive wear in short duration ASTM B611 tests [13].

There was no discernible difference in wear rate between the ASTM B611 tests performed in distilled water from those performed in simulated sea-water. There are two potential reasons for this. These are that the simulated sea-water had a pH of 8.2 compared with the pH of the distilled

water of 6. This is a relatively small difference in pH and may not, of itself, be sufficiently different to cause major changes in corrosion processes and hence in mass loss. The wear rates are also quite large in the ASTM B611 tests so that the surface in contact with the corrosive media is removed by abrasive processes before significant corrosion can occur.

4.2 *Reciprocating Results*

It is clear that the scatter in friction results for the tests at 3N were quite high, but it is likely that this is due largely to experimental errors in the measurement of friction with the reciprocating rig used for the tests. This is supported by the fact that there is much less scatter in the results for the tests carried out at 40N.

The mechanisms of wear observed for the hardmetals were some abrasion damage from contact with the opposing surface, and some breakaway of material from local areas on the sample surfaces. The exception to this is the coarse grained, high Co volume fraction material where cracking was observed in the binder phase, often close to the boundary between the binder phase and the WC grains.

In the reciprocating wear of the ceramics it is likely that tribochemical reaction at the wear interface to form layers of material has a major effect on the appearance of the wear surface. This will markedly affect the wear mechanisms that occur.

5. CONCLUSIONS AND RECOMMENDATIONS FOR USE OF TESTS

A series of abrasive and reciprocating sliding wear tests have been performed on a range of hardmetals and ceramics.

For the hardmetals a singular relationship between wear volume and hardness was found in ASTM B611 tests.

When silica was used in the ASTM B611 tests instead of alumina a similar trend in results was found with a reduction in wear of about an order of magnitude.

Performing ASTM B611 tests in simulated sea-water rather than distilled water did not affect the wear volume obtained. This is likely to be due either to the small difference in pH between the simulated sea-water and the de-ionised water, or to the high rate of abrasion in the tests leaving insufficient contact time for a significant contribution from erosion.

- In modified ASTM G65 tests using three different test conditions wear increased in the order wet rubber wheel → dry rubber wheel → steel wheel.

All the abrasion results could be described quite well by an empirical exponential relationship between wear volume and hardness.

In reciprocating tests on hardmetals the friction coefficient was found to be about 0.25 for all the hardmetals examined.

- Higher friction coefficients were found for the ceramics than for the hardmetals in the reciprocating tests.

The worn surfaces of the ceramics in reciprocating wear showed an appearance that was characteristic of tribochemical reactions; this is likely to have a major effect on the friction and wear.

The ASTM B611 test has a simple design, and gives very effective results in the testing of hardmetals and ceramics. It is suitable for use to simulate abrasion where high stresses are applied, and where grit has a size of about 0.4–0.6 mm. A major potential drawback is that the test recirculates abrasive, inevitably with damage to the abrasive under the high stress conditions operating in the test. For this reason, care should be used in the interpretation of results when this test is being used to simulate conditions where a continual renewal of abrasive occurs.

The modified ASTM G65 test has a slightly more complex design, but has several advantages over the ASTM B611 test system:

- Wheels of different compliance can be used to simulate abrasion under conditions of different counterbody compliance.
- The test has a well controlled abrasive feed.
- The test system can cope with a wide range of abrasive sizes.
- The abrasive is not recycled, but is continuously renewed during the test.
- Test conditions such as relative speed and applied load can be widely varied.
- Tests can be carried out dry as well as wet.

The two tests give similar results under similar conditions. The modified ASTM G65 test is suitable for the simulation of a wide range of abrasion conditions; it gives the flexibility in control that enables the conditions that apply in the application to be simulated quite closely in many cases.

The use of either test should be combined with microscopy of the wear surfaces to determine the mechanisms of how abrasion damage is built up. This has several functions. Firstly, comparison of the worn surface on the test sample with the original worn component is an important check that the same mechanisms of wear are operating in both cases. Secondly, it can provide information that can be used to improve the selection of materials for a particular application or to suggest how changes in operating conditions might ameliorate abrasion.

Reciprocating tests should be used where sliding where with an oscillating motion takes place. The results of the tests reported here show reasonable trends in friction, but there is no consistency in the measurements of wear. It is thought that tests of a longer duration should be used if the measurement of wear is an important consideration.

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7. ACKNOWLEDGEMENT

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8. TABLES

Table 1, Test methods

Test Method	Rationale
ASTM B611	Test relevant to high stress abrasion where there is little load sharing between abrasive particles.
Modified ASTM G65	Test relevant to low stress abrasion where there is load sharing between abrasive particles.
Reciprocating wear	Test relevant to sliding contacts.

Table 2, Summary of test conditions

Test	Load, N	Duration	Abrasive Type & Size	Relative Speed	Other
ASTM B611	20	518 m	600 μm alumina, 600 μm silica	0.86 m s^{-1}	Distilled water and simulated sea-water. Steel wheel.
Modified ASTM G65	130	942 m	200 μm silica	0.78 m s^{-1}	Rubber rimmed wheel and steel wheel; tests dry and in distilled water
Reciprocating	3, 10	36 m	5 mm radius ball of like material	2 Hz, 5 mm stroke	

Table 3, Hardmetal Materials

Material	Source	Nominal Binder content wt%	WC Arithmetic Mean Linear Intercept μm	Hardness, HV30	Composition, wt %
A2a	#	6	1.15	1576	
B4	#	6	1.33	1513	
D1	#	6	1.15	1468	
D4	#	6	2.22	1242	
F3	#	6	0.24	1717	
K4	#	6	0.51	1722	
K5	#	6	1.31	1487	
L1	#	6	0.94	1576	
M4	#	6	2.94	1948	
M6	#	6	0.28	1585	
MA6	Marshalls	6	1.56	1265	
MA10	Marshalls	10	1.83	1230	
MA15	Marshalls	15	1.09	1080	
MA20	Marshalls	20	1.22	991	
MA24	Marshalls	24	1.14	860	
MAN6	Marshalls	6*	0.64	1535	5.43 Ni, 0.44 Mo
MAN10	Marshalls	10*	0.80	1280	9.83 Ni
CW15F	CW Carbides	15	1.03	1192	
CW15C	CW Carbides	15	1.94	1043	
CW20C	CW Carbides	20	2.17	890	
CW25C	CW Carbides	25	2.14	804	
CWN8	CW Carbides	8*	0.83	1391	7.38 Ni, 0.33 Ta
T	Hydra	10	2.03	1218	
UC9	Hydra	9	4.90	982	
M15	Hydra	15	2.04	1028	
T6	Boart Longyear	6	1.24	1494	
G10	Boart Longyear	10	1.76	1238	

Material	Source	Nominal Binder content wt%	WC Arithmetic Mean Linear Intercept μm	Hardness, HV30	Composition, wt %
G15	Boart Longyear	15	1.93	1100	
N6	Neepsend	6	0.78	1565	
N10	Neepsend	10	0.40	1630	
N15	Neepsend	15	0.56	1255	
TC6	Teco	6	0.86	1589	
T16D	Teco	16	0.94	1227	
T20D	Teco	20	1.02	976	
T25D	Teco	25	1.11	879	
SHM5CN	Sandvik HM	5**	0.35	1971	3.35 Co, 1.1 Ni
SHMUF	Sandvik HM	6	0.15	2146	
D10	Dymet	10	1.14	1311	
D15	Dymet	15	0.88	1204	
DN6	Dymet	6*	0.67	1591	5.51 Ni
DN10	Dymet	10*	0.84	1311	9.59 Ni
TC222	Kennametal	6	3.59	1156	
K3560	Kennametal	10	2.75	1156	

Supplied by members of the British Hardmetals Association

* Ni bonded

** Ni/Co bonded

Table 4, Ceramic materials

Material	Source	Grain Size, μm	Hardness, HV0.1	Density	Composition
RBSN	Tenmat	1-2	750	2.53	Si_3N_4
RBSC	Tenmat	10-30	2000	2.96	SiC, 10 % Si
SSN	Tenmat	3	1600	3.11	
α -SiC	Carborundum	10	2300	2.87	SiC
Vitox	Morgan Matroc	1-2	1900	3.96	99.99 % alumina
Sintox	Morgan Matroc	3-8	1600	3.72	95 % alumina

Table 5, Results of ASTM B611 abrasion tests on hardmetals

Material	Abrasion Volume Loss, cm³ Al₂O₃	Abrasion Volume Loss, cm³ SiO₂	Abrasion Volume Loss, cm³ Simulated Sea- water, Al₂O₃
A2a	0.038		
B4	0.063		
D1	0.068		
D1	0.068		
D4	0.048		
F3	0.018		
K4	0.12		
K5	0.056		
L1	0.06		
M4	0.161		
M4	0.12		
M6	0.0073		
M6	0.0075		
MA6	0.112		
MA10	0.182		0.189
MA15	0.313		
MA20	0.439		
MA24	0.504		
MAN6	0.054		0.054
MAN10	0.160		
CW15F	0.235	0.028	
CW15C	0.308	0.048	0.353
CW20C	0.445	0.068	
CW25C	0.528	0.097	
CWN8	0.088	0.015	

Material	Abrasion Volume Loss, cm³ Al₂O₃	Abrasion Volume Loss, cm³ SiO₂	Abrasion Volume Loss, cm³ Simulated Sea- water, Al₂O₃
T	0.164		
UC9	0.292		
M15	0.330		
T6	0.068	0.0067	0.0724
G10	0.190	0.027	0.206
G15	0.300	0.048	
N6	0.034		0.034
N10	0.034		0.032
N15	0.14		0.18
TC6	0.036	0.0054	
T16D	0.253	0.028	
T20D	0.393	0.067	
T25D	0.532	0.098	
SHM5CN	0.0072	0.0072	
SHMUF	0.0024	0.0024	
D10	0.111	0.016	0.132
D15	0.193	0.017	0.188
DN6	0.047	0.0096	
DN10	0.122	0.019	
TC222	0.222	0.029	
K3560	0.2389	0.032	

Table 6, Results of ASTM B611 Abrasion Tests on Ceramics

Material	Abrasion Volume Loss, cm ³	Abrasion Volume Loss, cm ³
	Al ₂ O ₃	SiO ₂
RBSC	0.288	0.009
SSN	0.082	0.020
SINTOX	1.296	0.145
VITOX	0.423	0.072
RBSN		0.148
α-SiC	0.088	0.006

Table 7, Results of modified ASTM G65 tests on hardmetals given as volume of wear.

Materials	Dry Rubber, mm³	Wet Rubber, mm³	Wet Rubber, Repeat, mm³	Wet Steel, mm³
MA6	1.49	0.46	0.26	42.49
MA10	3.40	0.59		57.10
MA20	8.09	1.29	0.35	124.58
MAN6	2.93	0.59		14.76
MAN10	3.94	0.47		32.07
CWC15F	5.99	0.31		50.32
CWC15C	3.76	1.72		136.34
CWC20C	7.12	2.76	0.41	196.54
CWC25C	10.77	2.39		221.42
CWN8	3.32	0.30		26.24
T	3.63	0.76		75.37
UC9	1.98	0.69		217.31
M15	5.42	1.22		123.88
T6	2.89	0.24		19.51
G10	11.26	0.44		72.01
G15	6.38	0.74		121.63
N6	0.61	0.27		9.67
N10	0.58	0.07		2.23
N15	2.91	0.25		12.89
SHMUF		0.06		0.21
D10	2.78	0.73		29.84
D15	3.01	0.55		25.62
K3560	2.14	0.14	0.45	153.62
TC222	1.79	0.24	0.43	134.18
B1	0.81	0.30		0.75

Table 8, Results of modified ASTM G65 tests on ceramic samples. Results given as wear volumes.

Materials	Dry Rubber, mm³	Wet Rubber, mm³	Wet Steel, mm³
Vitox	10.48	8.43	282.16
RBSC	1.39	1.45	83.82
RBSN	17.43	86.81	2224.54
SSN	9.25	7.44	71.35
α -SiC	0.80	1.01	28.18

Table 9, Results of reciprocating tests

Material	Hardness' HV30 for hardmetals, HV0.1 for ceramics	3 N load		40 N load	
		Mean Friction Coefficient	Wear Displacement, μm	Mean Friction Coefficient	Wear Displacement, μm
CWC25C	804	0.46	2.2	0.33	26.3
CWC20C	890	0.22	0.3		
UC9*	982	0.22	1.4		
MA20	991	0.74	1.7	0.3	4.0
MA20	991	0.33	0.1		
CWC15C	1043	0.15	1.0		
G15*	1100	0.24	2.2		
TC222	1156	0.26	0.2	0.28	1.7
K3560	1156	0.40	0.4	0.26	1.5
CWC15F	1192	0.42	0.5		
D15	1204	0.41	3.1	0.18	4.7
T*	1218	0.27	0.3		
MA10	1230	0.33	1.2	0.27	1.0
G10*	1238	0.27	0.3		
G10	1238	0.54	0.8		
N15	1255	0.41	3.5	0.26	2.7
MA6	1265	0.31	0.5	0.25	5.2
MAN10	1280	0.36	0.2	0.20	0.4
D10	1311	0.32	1.1	0.26	9.3
CW8N	1391	0.25	0.5	0.23	2.0
T6*	1494	0.35	1.5		
T6	1494	0.32	0.7		
MAN6	1535	0.28	2.4	0.23	1.1
N6	1565	0.53	2.4	0.25	16.9
N10	1630	0.25	0.1	0.24	0.8
SHMUF	2146	0.22	1.8		
SHMUF	2146	0.24	1.9	0.23	1.5
RBSN	750	0.57	3.6	0.36	15.0
RBSC	2000	0.13	1.3	0.54	39.0
VITOX	1900	0.25	0.2	0.48	6.6
SINTOX	1600	0.25	0.9	0.45	537.2
α -SIC	2300	0.17	0.4	0.30	13.9
SSN	1600	0.63	2.7	0.61	32.6

* Tests on sample with ground finish.

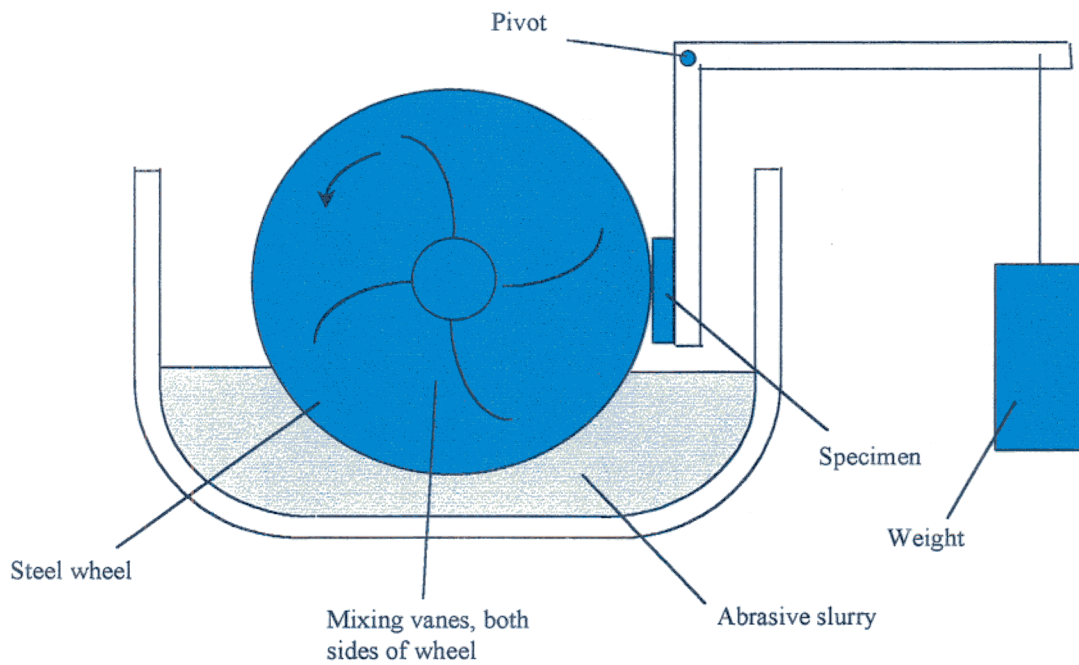


Figure 1, Schematic diagram of ISO 12962/ASTM B611 abrasion testing system [3]

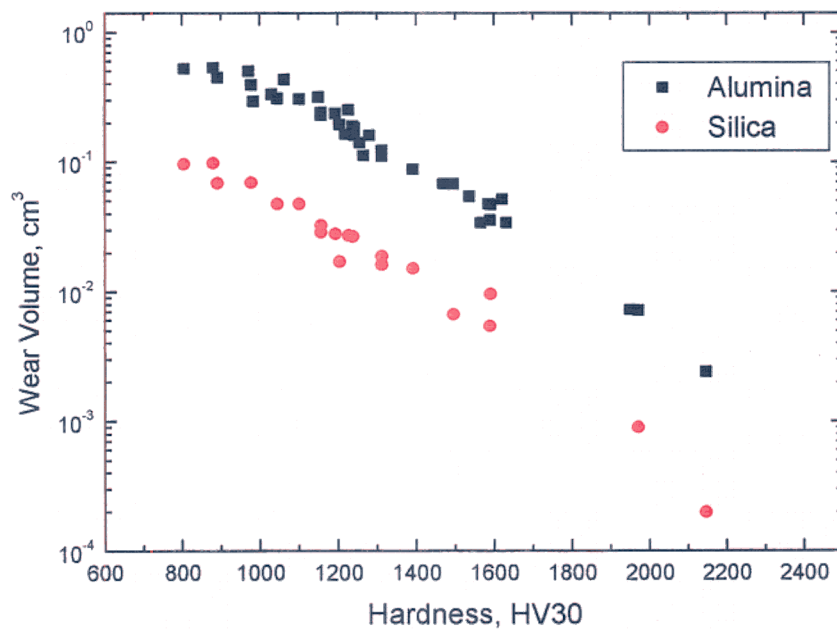


Figure 2, Comparison of wear volumes in ASTM B611 tests for hardmetals tested in distilled water with alumina and silica abrasive

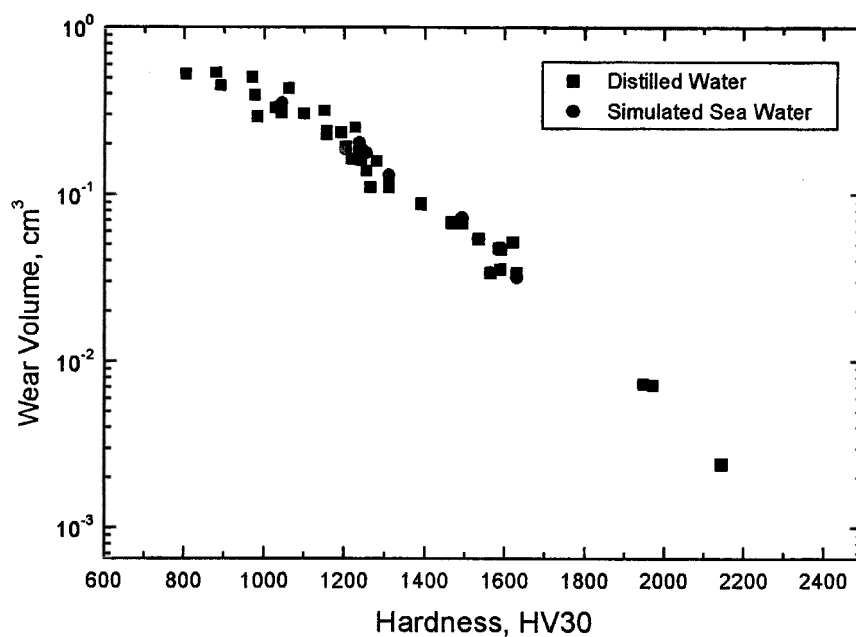


Figure 3, Comparison of wear volumes in ASTM B611 test for hardmetals tested in distilled water with alumina and silica abrasive

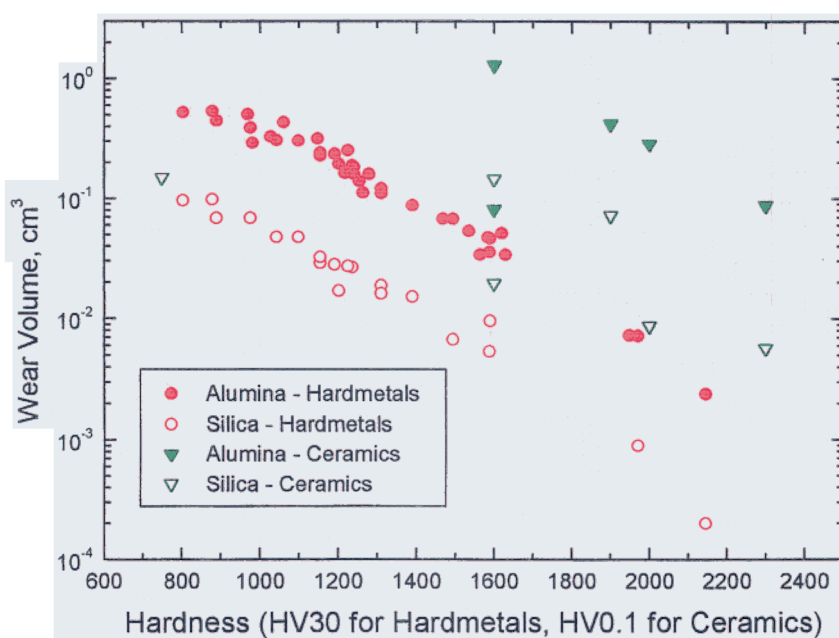


Figure 4, Comparison of wear volumes in ASTM tests for ceramics and hardmetals. Note that the hardness scales are different.

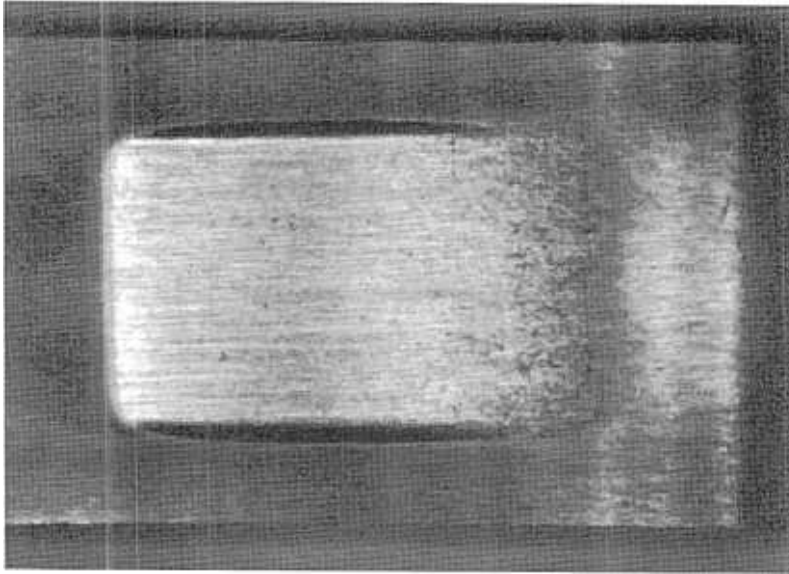


Figure 5, Typical wear scar on hardmetal sample



Figure 6, Fragmentation of WC grains on hardmetal surface worn in an ASTM B611 test.



Figure 7, Worn surface of hardmetal tested in ASTM B611 test showing fragmentation of WC grains.



Figure 8, Breakaway of grains from worn hardmetal surface



Figure 9, Single large WC grain damaged in ASTM B611 test on hardmetal sample.

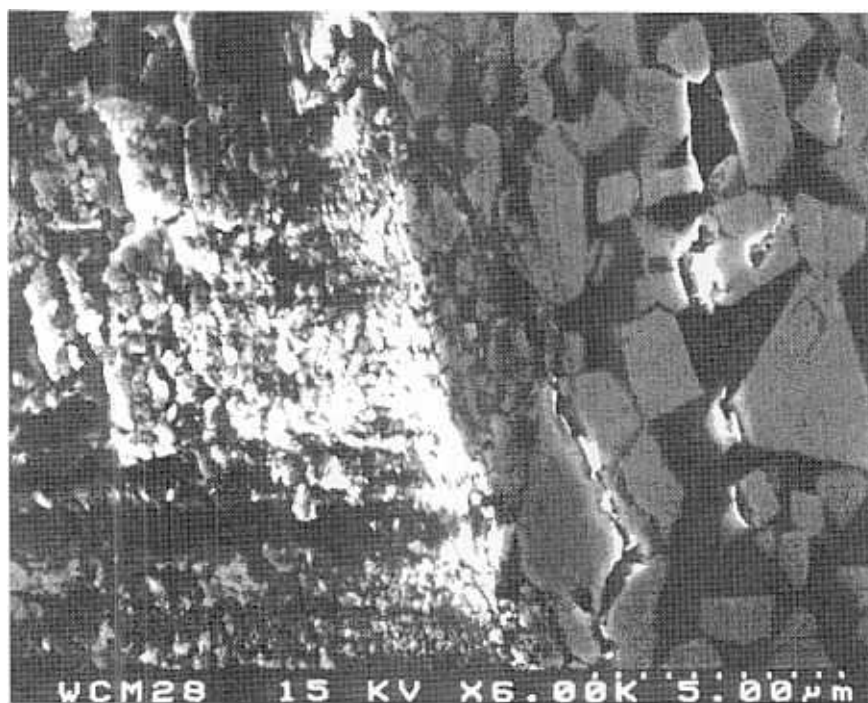


Figure 10, Cross section through surface of ASTM B611 hardmetal sample.

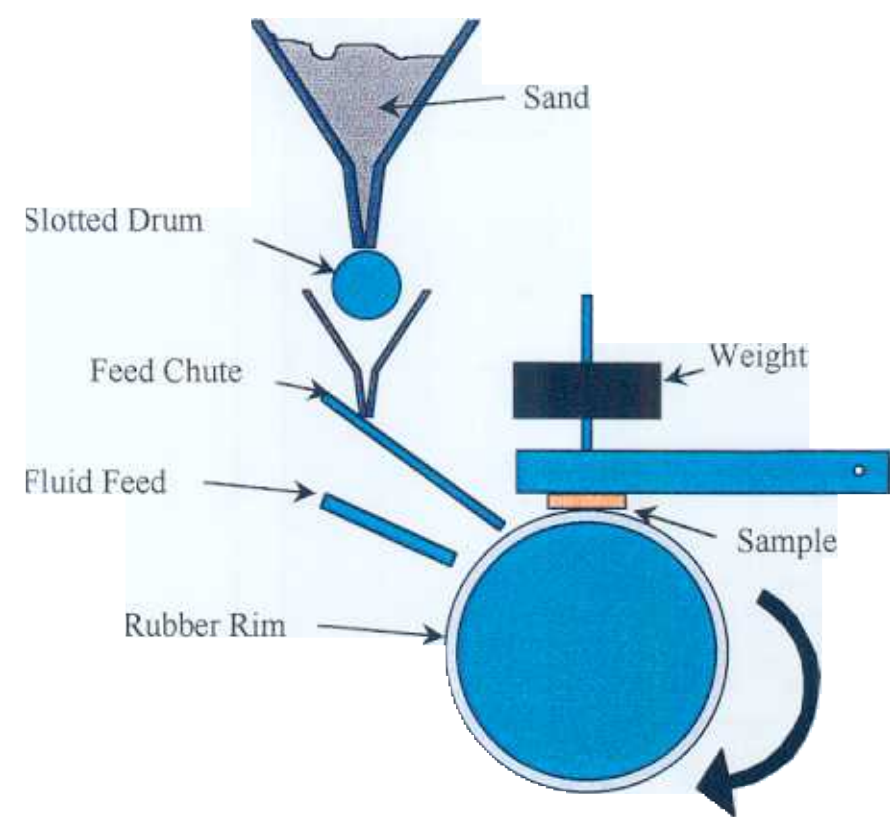


Figure 11, Modified ASTM G65 abrasive test system

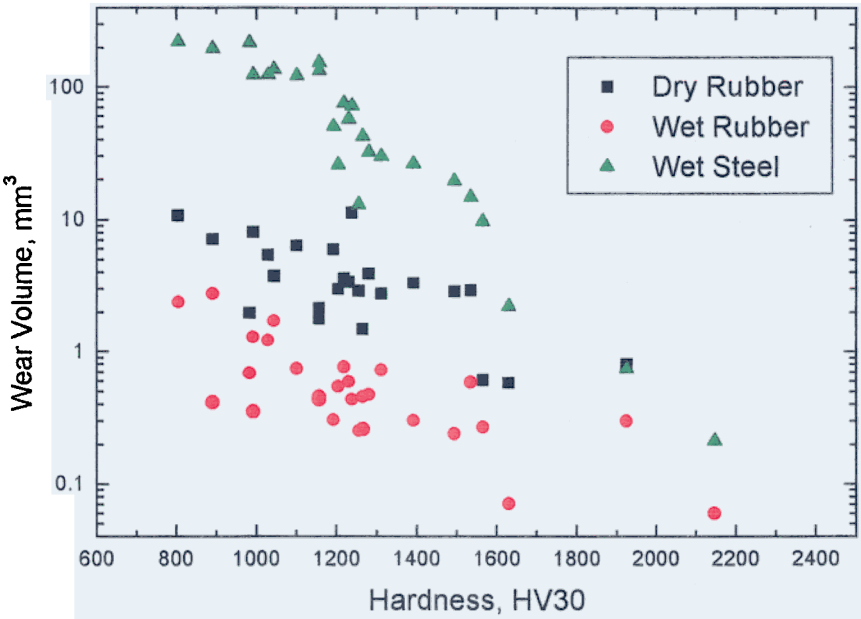


Figure12, Modified ASTM G65 Wear Results

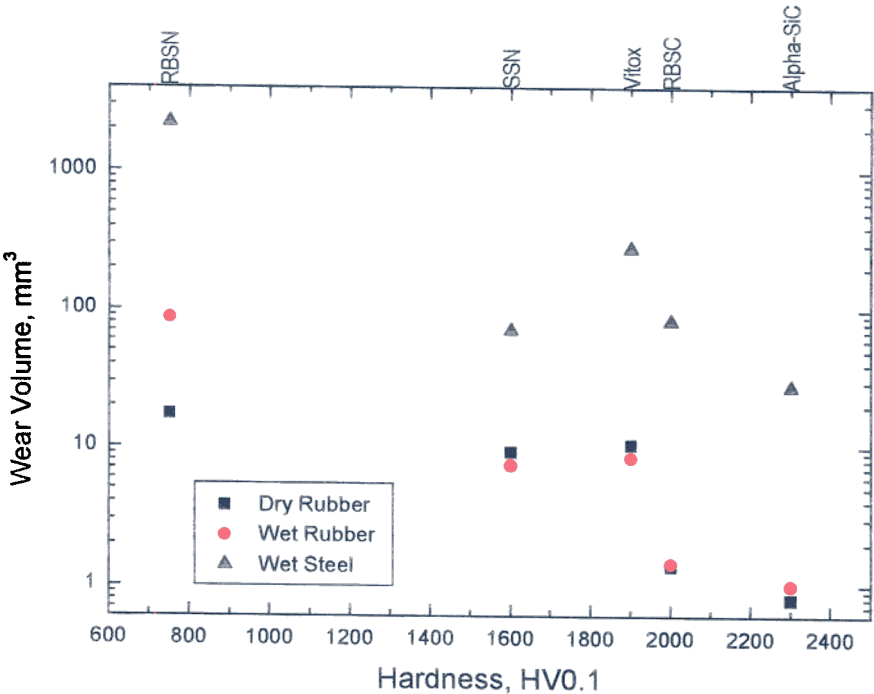


Figure 13, Modified ASTM G65 Ceramics

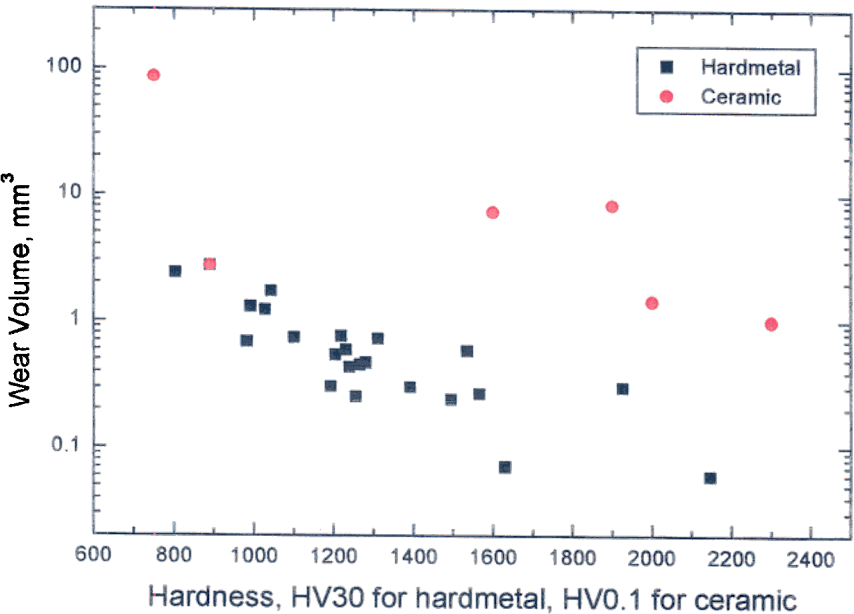


Figure 14, Comparison between modified ASTM G65 results for ceramics and hardmetals

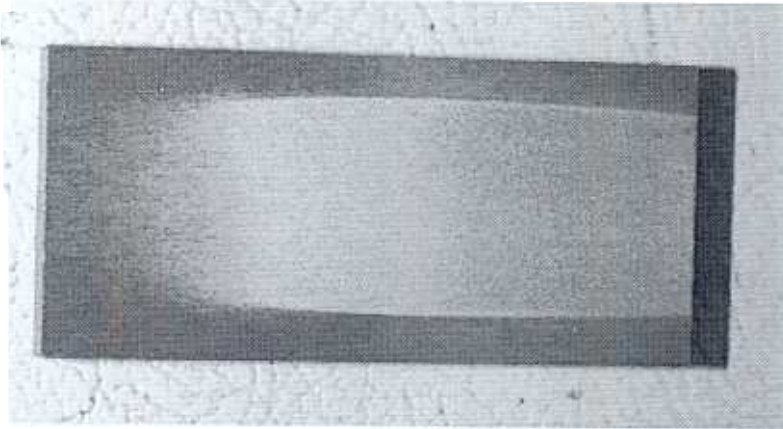
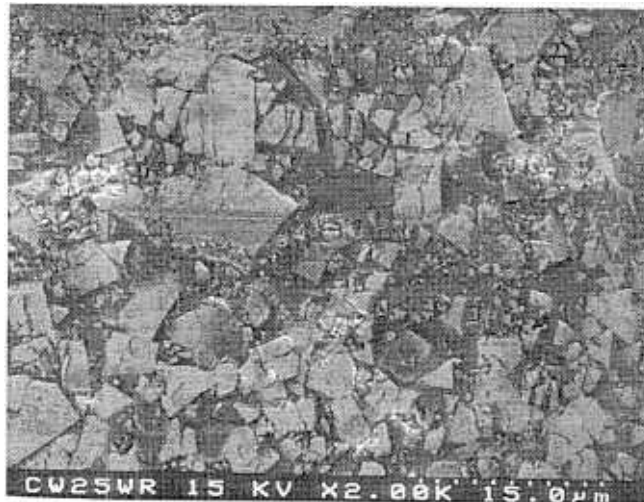


Figure 15, Typical rubber wheel wear scar on hard metal sample.



a)

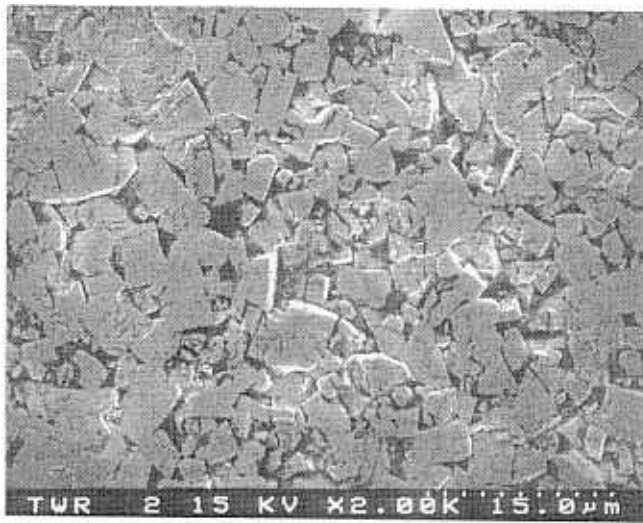


b)

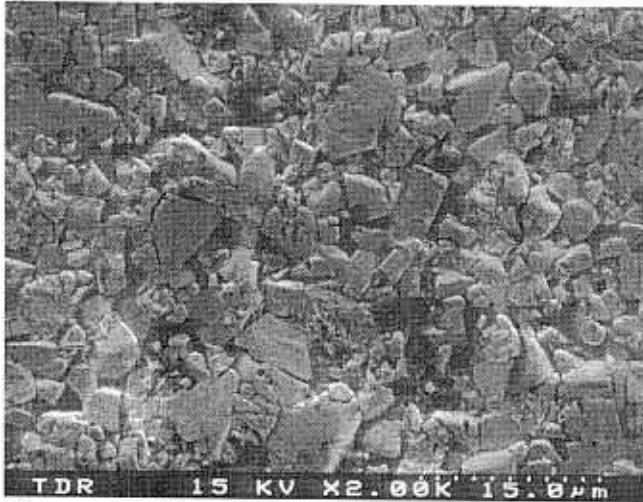


c)

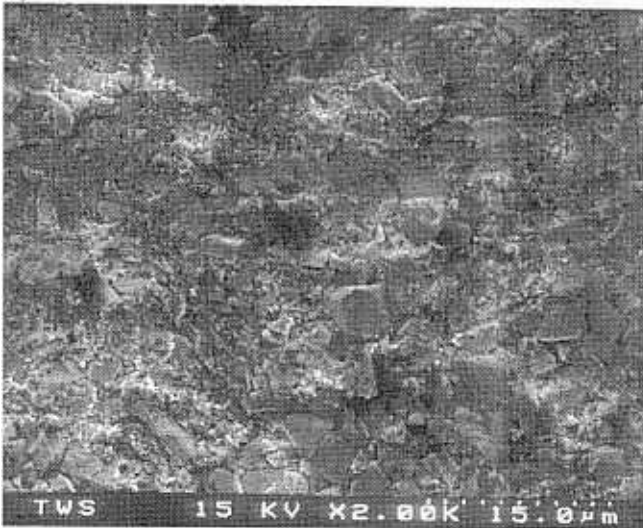
Figure 16, Worn surface of CWC25C hardmetal sample tested in modified ASTM G65 test system, a) rubber wheel, wet, b) rubber wheel, dry, c) steel wheel, wet



a)

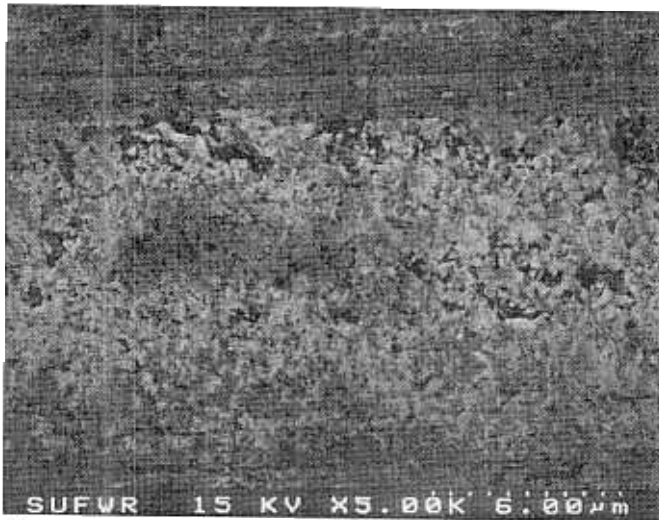


b)

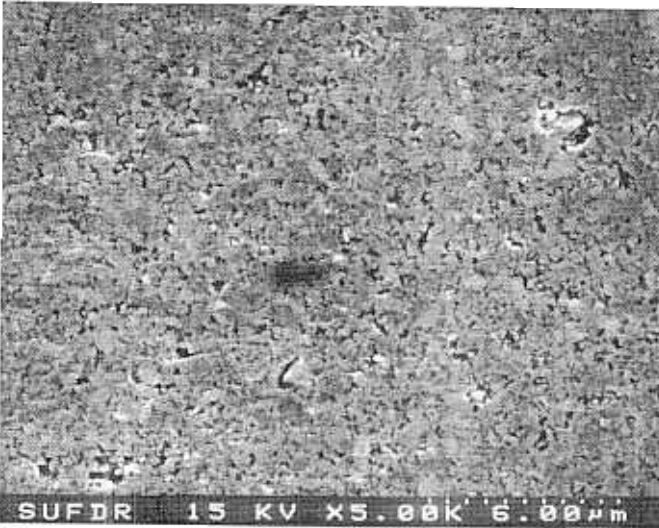


c)

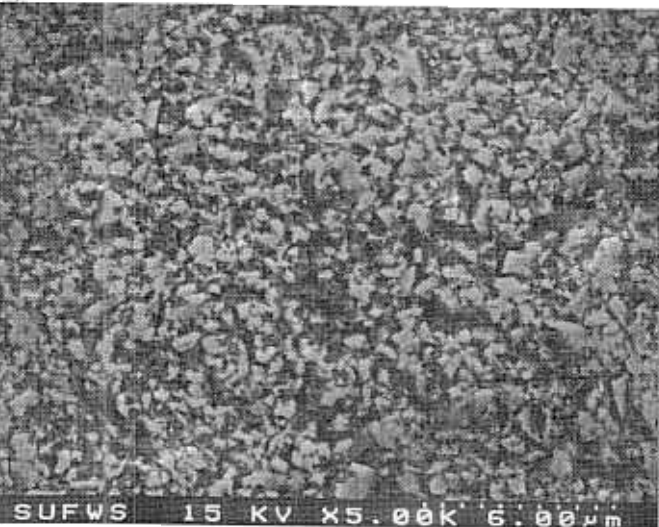
Figure 17, Worn surface of T hardmetal sample tested in modified ASTM G65 test system, a) rubber wheel, wet, b) rubber wheel, dry, c) steel wheel, wet



a)

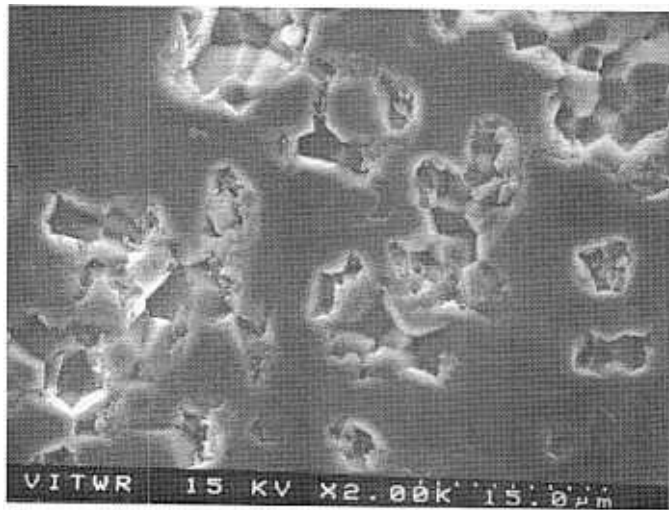


b)

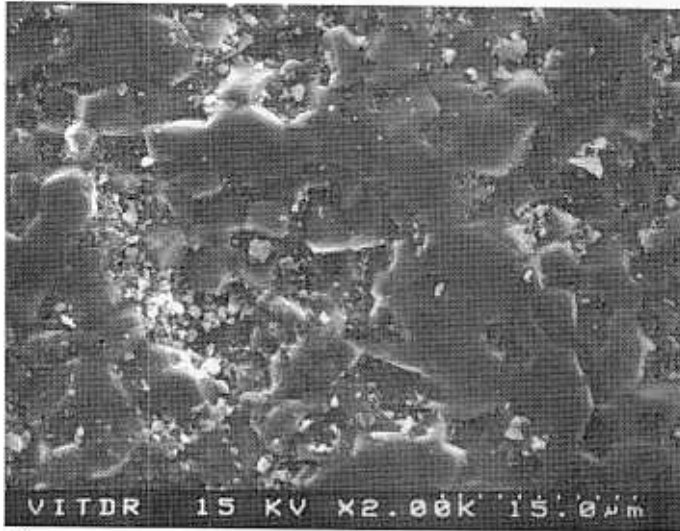


c)

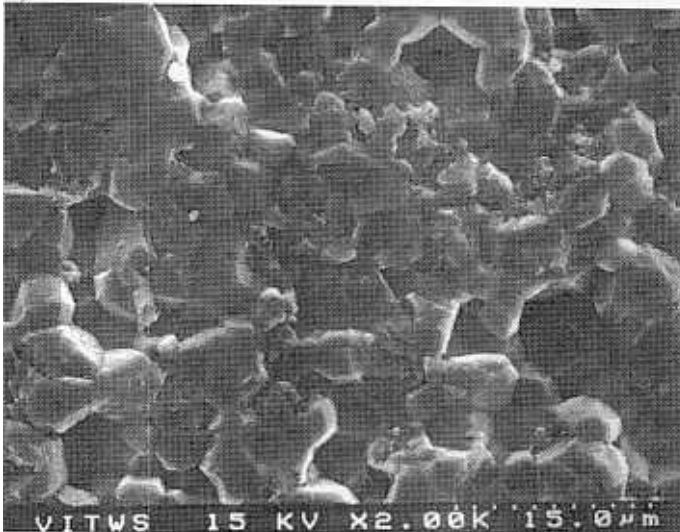
Figure 18, Worn surface of SHMUF hardmetal sample tested in modified ASTM G65 test system, a) rubber wheel, wet, b) rubber wheel, dry, c) steel wheel, wet



a)

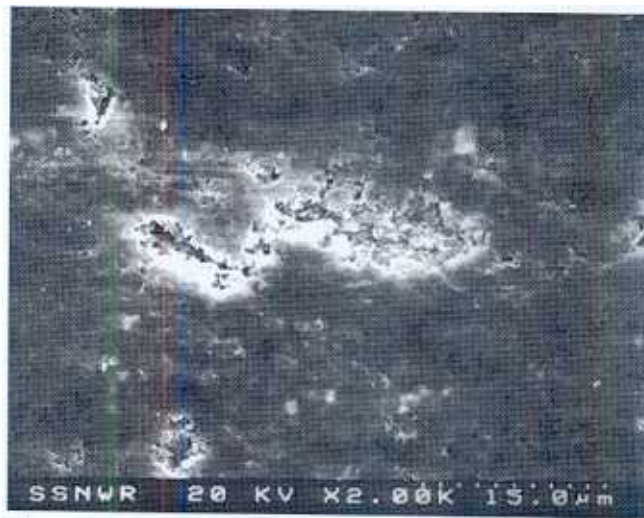


b)

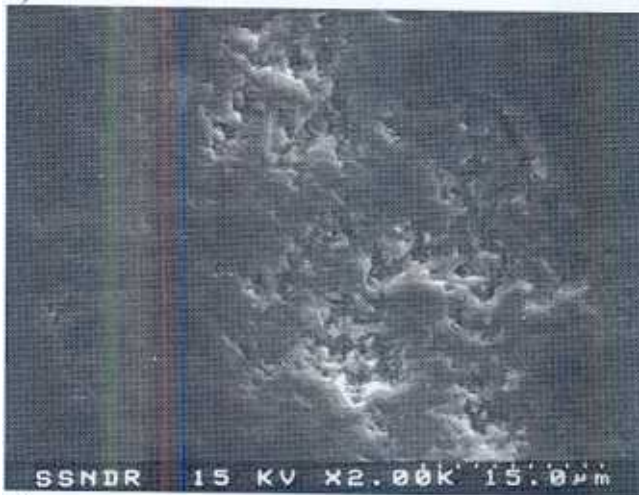


c)

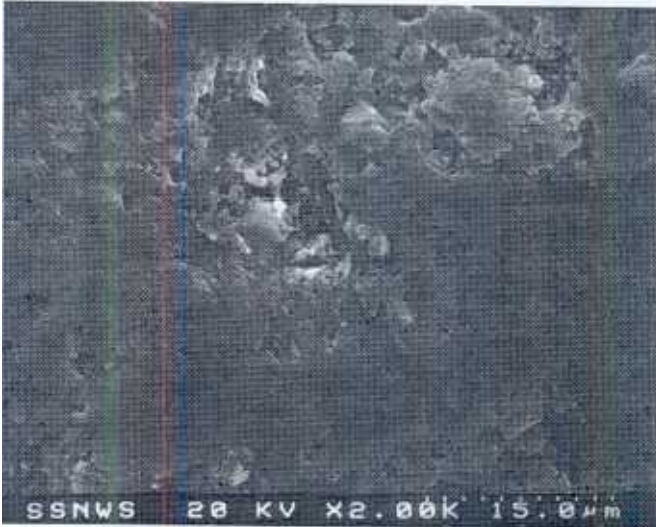
Figure 19, Worn surface of Vitox ceramic sample tested in modified ASTM G65 test system, a) rubber wheel, wet, b) rubber wheel, dry, c) steel wheel, wet



a)



b)



c)

Figure 20, Worn surface of SSN ceramic sample tested in modified ASTM G65 test system, a) rubber wheel, wet, b) rubber wheel, dry, c) steel wheel, wet

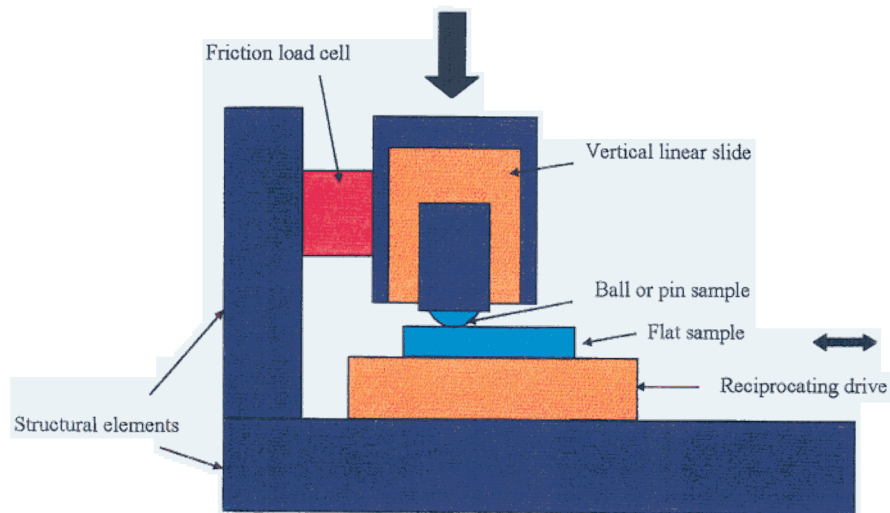


Figure 21, Schematic diagram for reciprocating test system

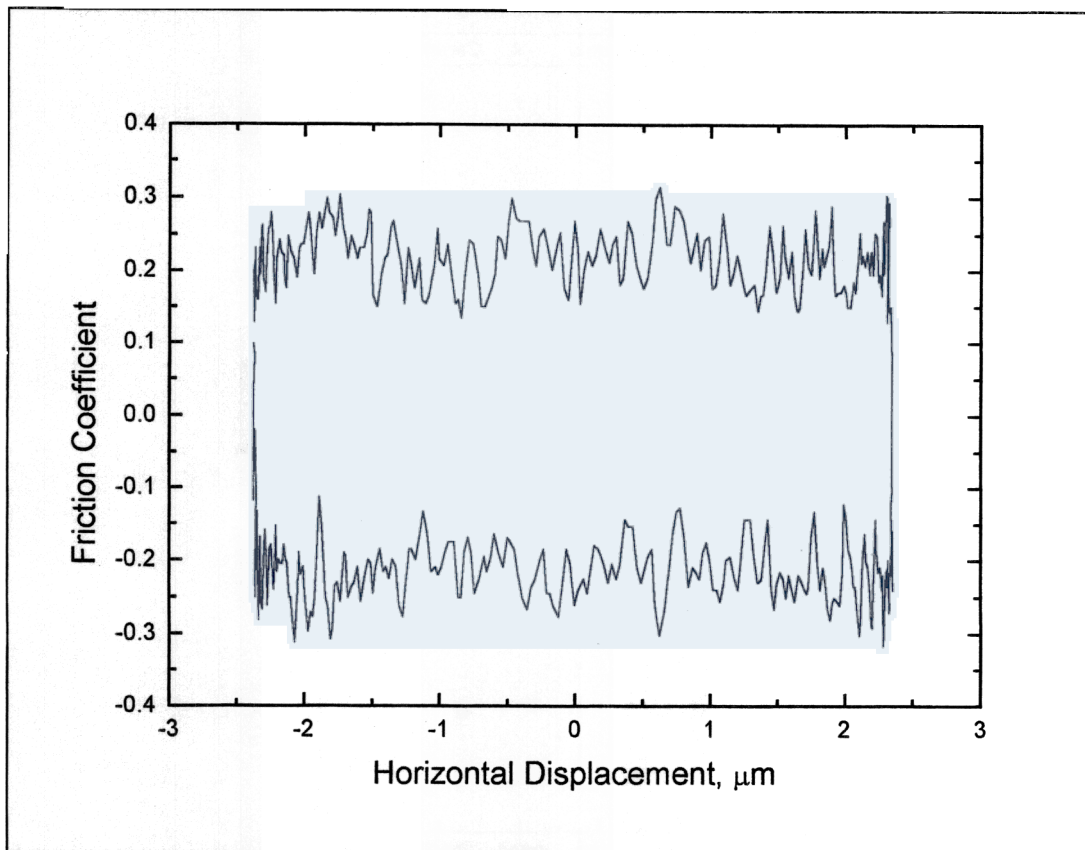
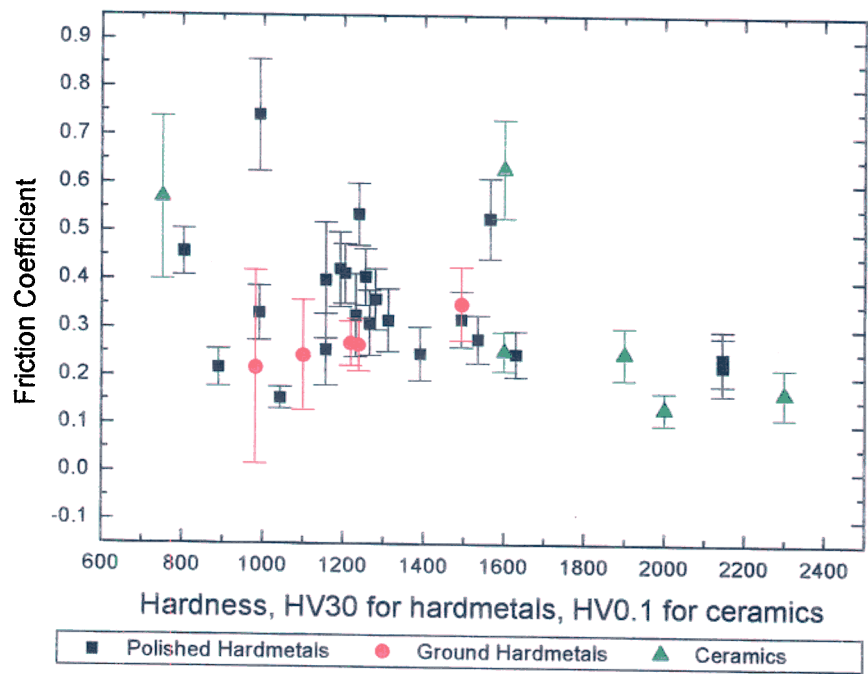
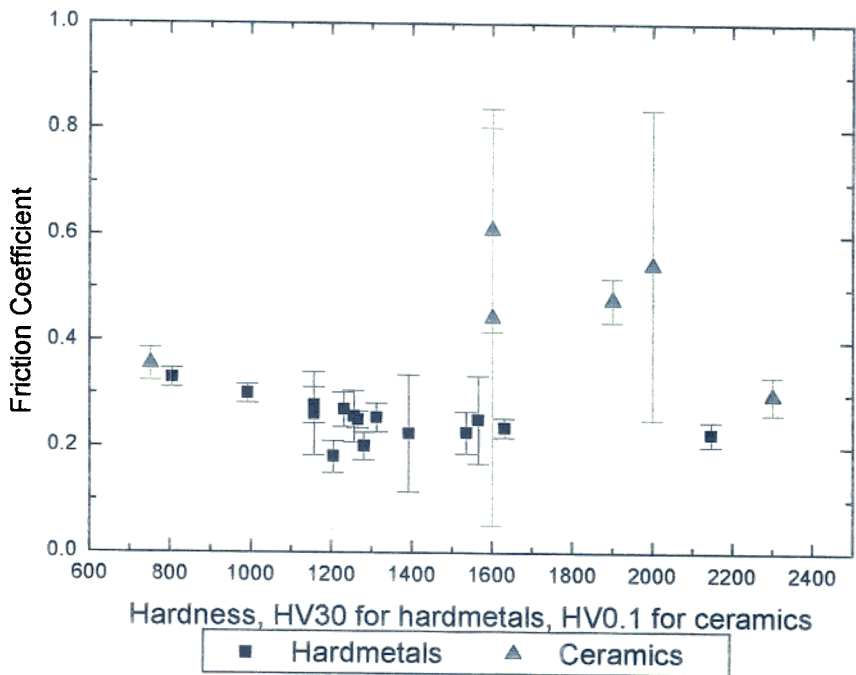


Figure 22, Typical plot of friction coefficient against horizontal displacement.

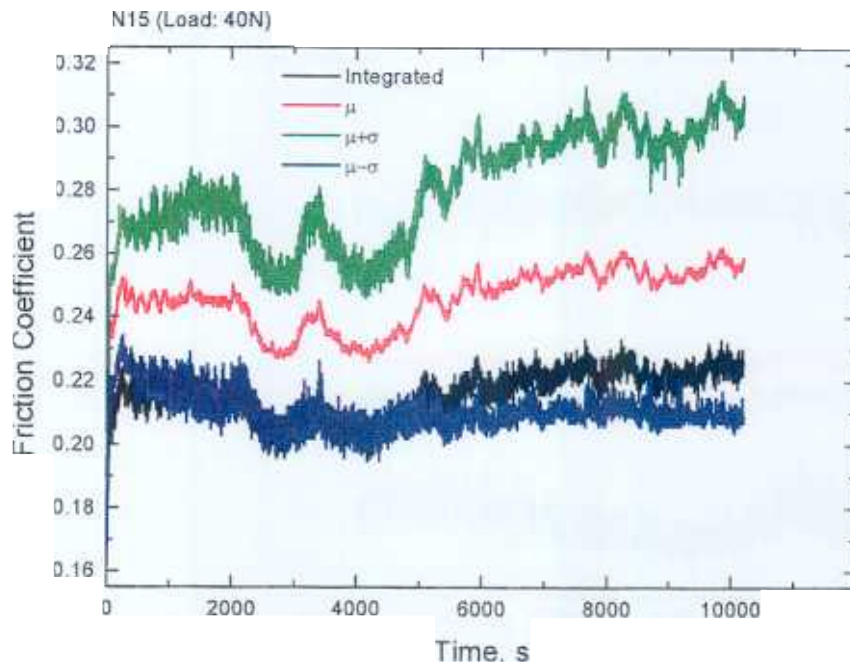


a)

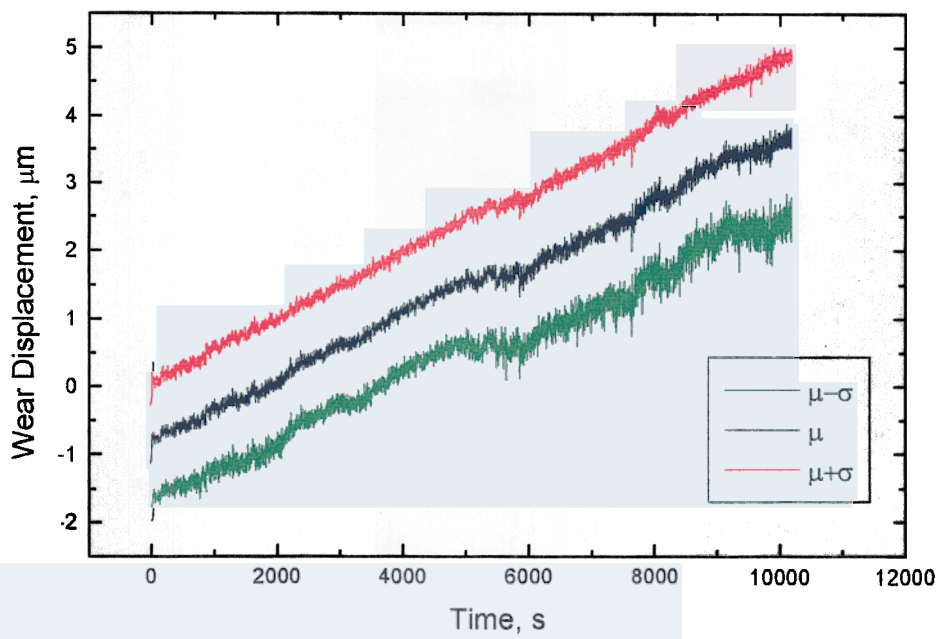


b)

Figure 23, Variation in friction coefficient with hardness in reciprocating tests at a) 3N, b) 40 N.

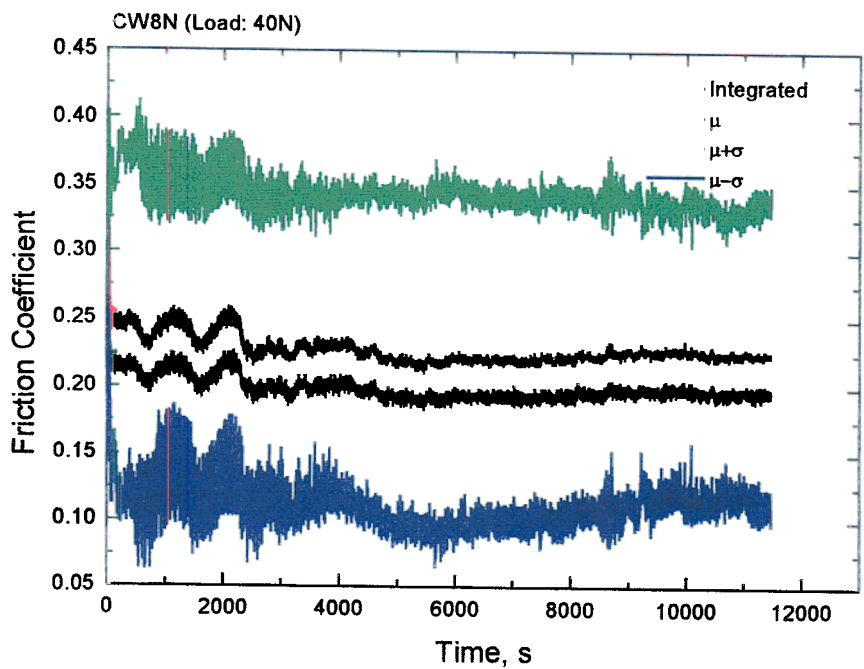


a)

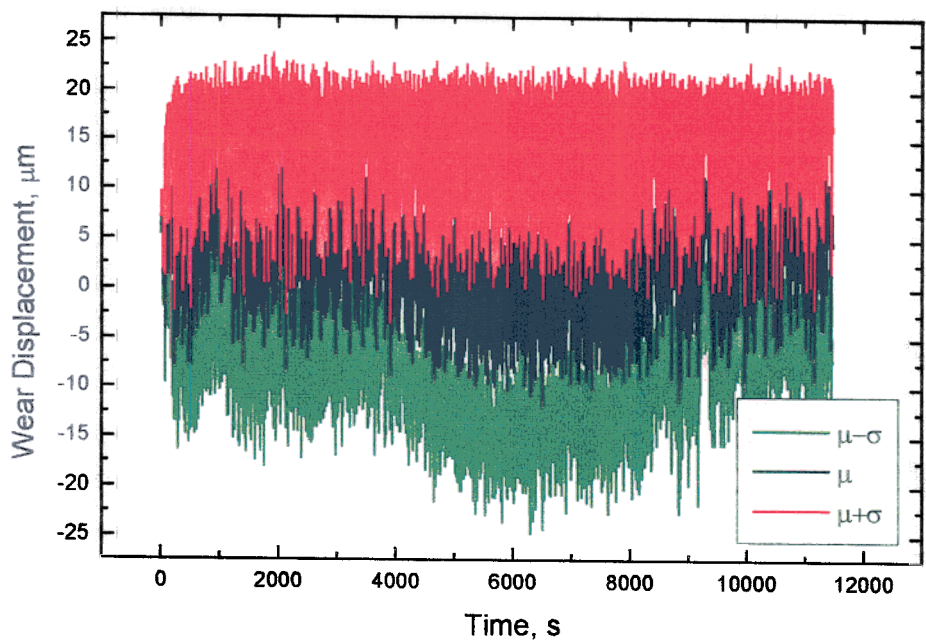


b)

Figure 24, Reciprocating results for test at 40 N for polished N15 hardmetal, a) friction coefficient, b) wear displacement.

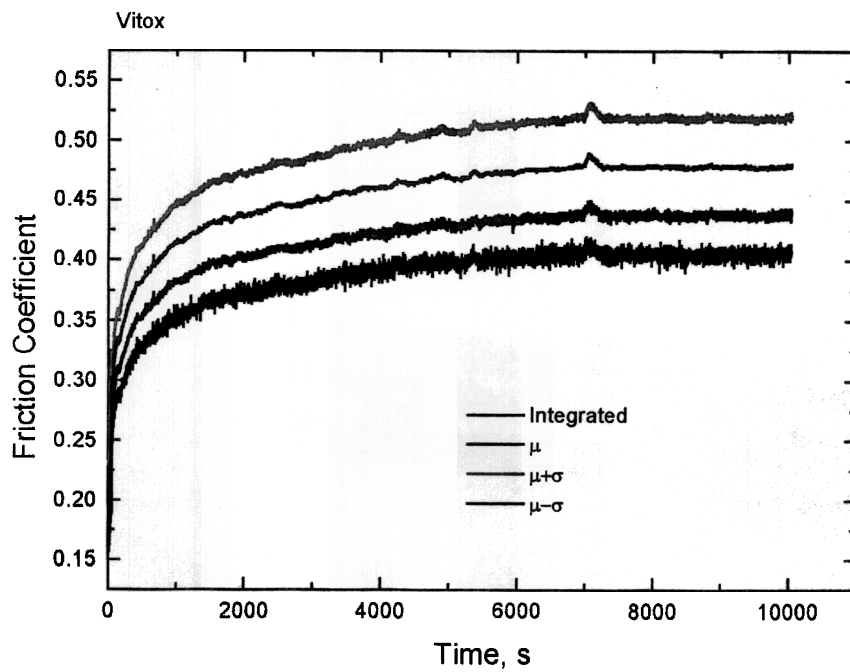


a)

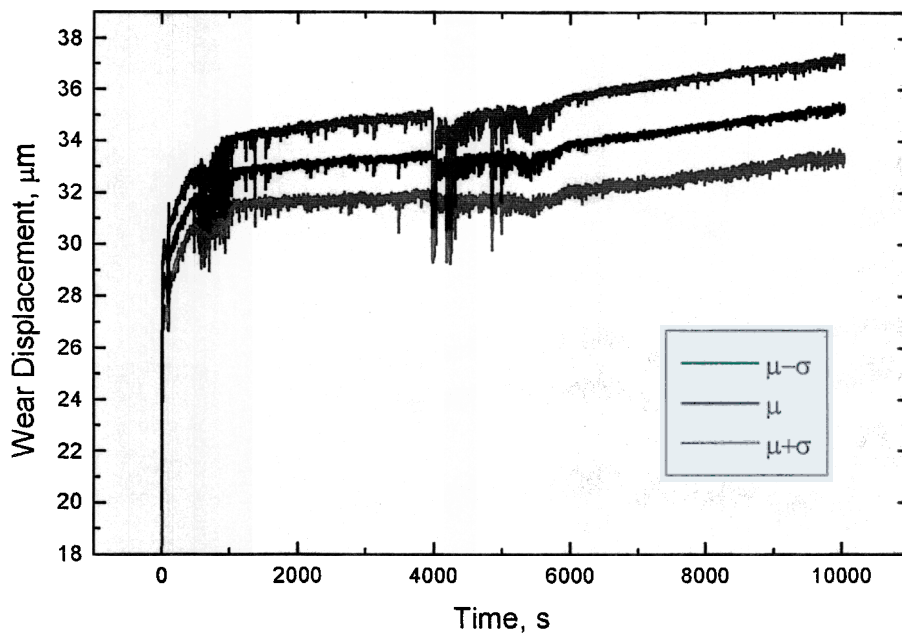


b)

Figure 25, Reciprocating results for test at 40 N for polished N15 hardmetal, a) friction coefficient, b) wear displacement.

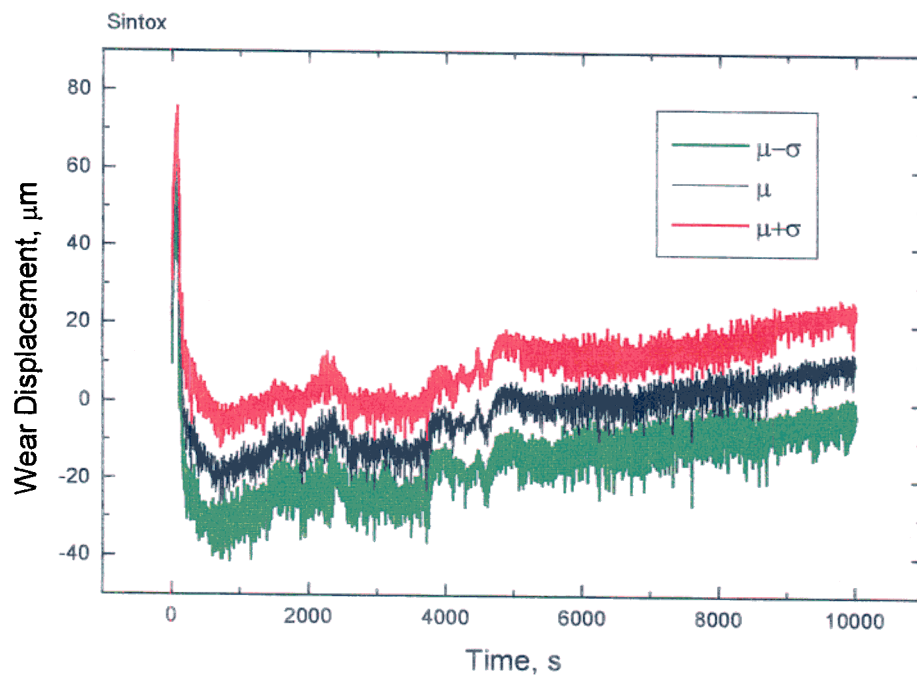


a)

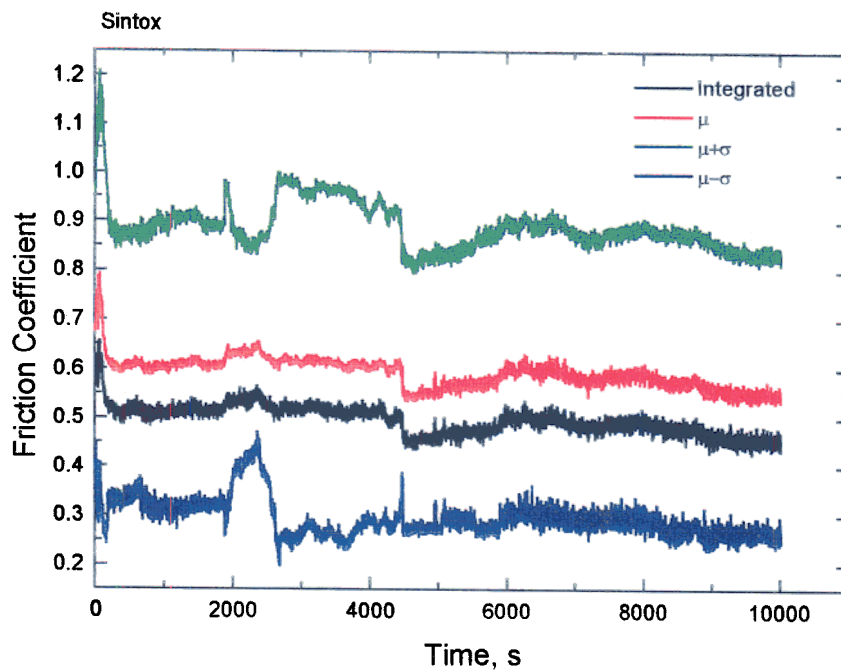


b)

Figure 26, Reciprocating results for test at 40 N for polished vitox ceramic, a) friction coefficient, b) wear displacement.

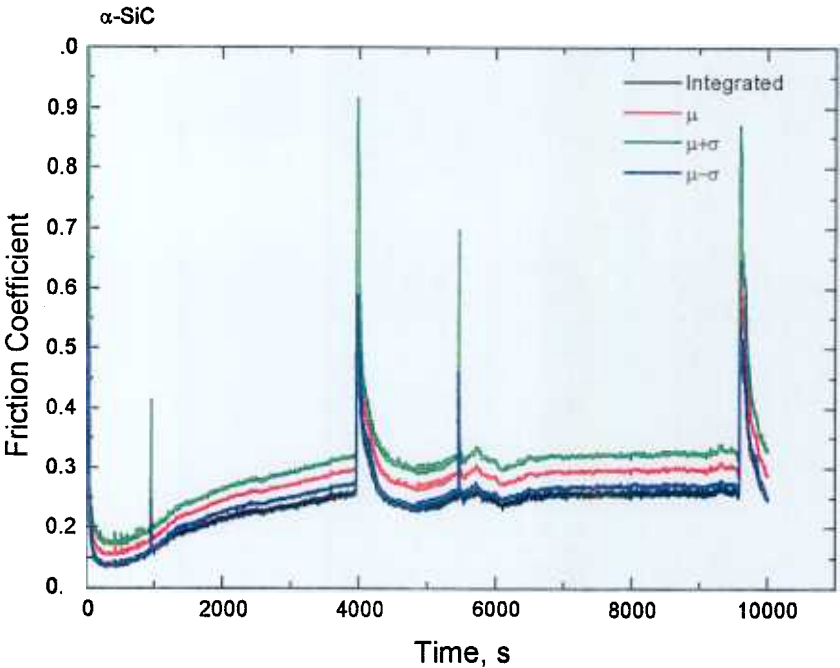


a)

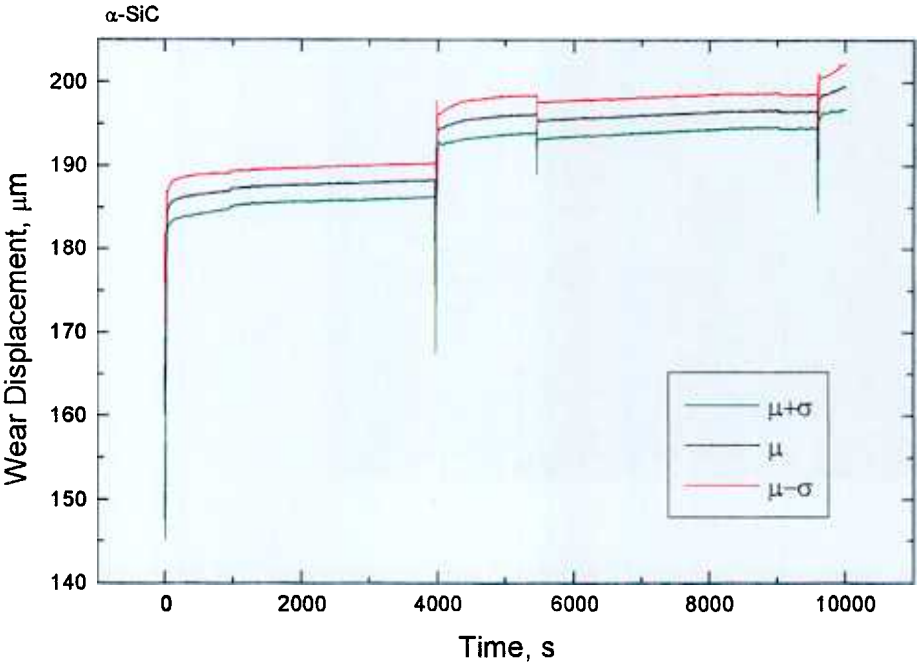


b)

Figure 27, Reciprocating results for test at 40 N for polished sintox ceramic, a) friction coefficient, b) wear displacement.

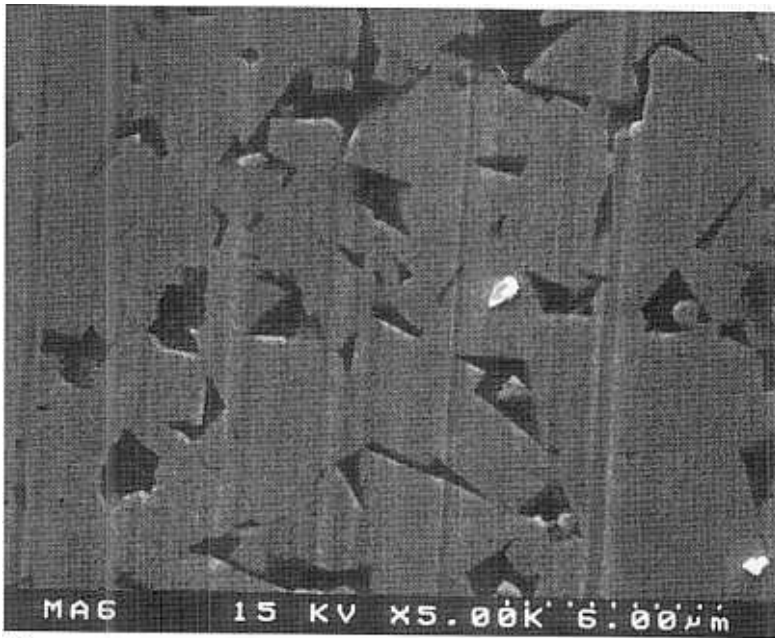


a)

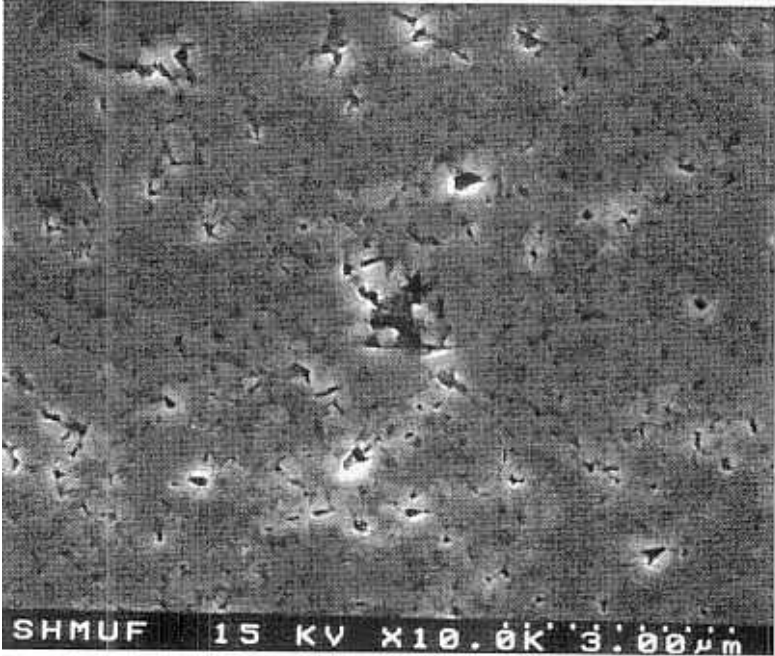


b)

Figure 28, Reciprocating results for test at 40 N for polished α -SiC, a) friction coefficient, b) wear displacement.

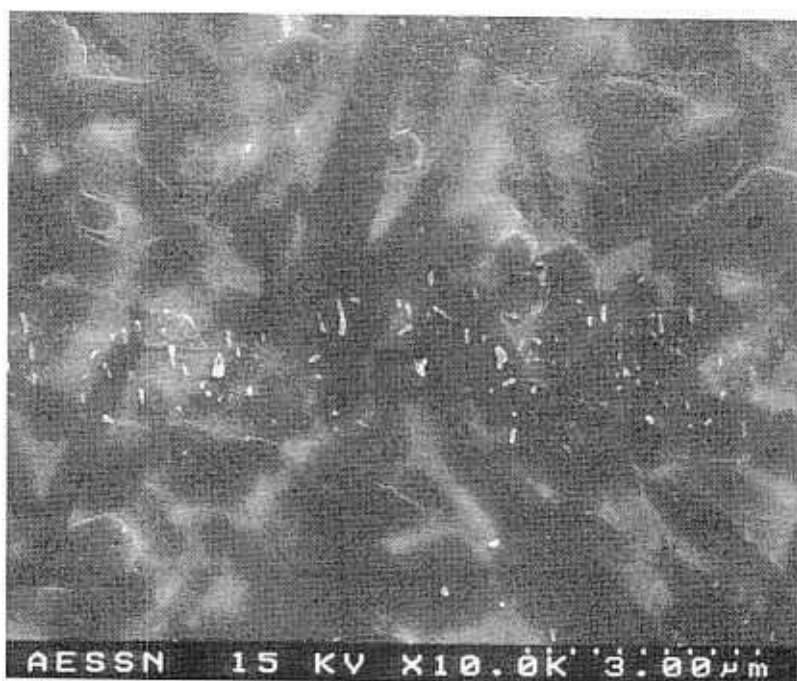


a)

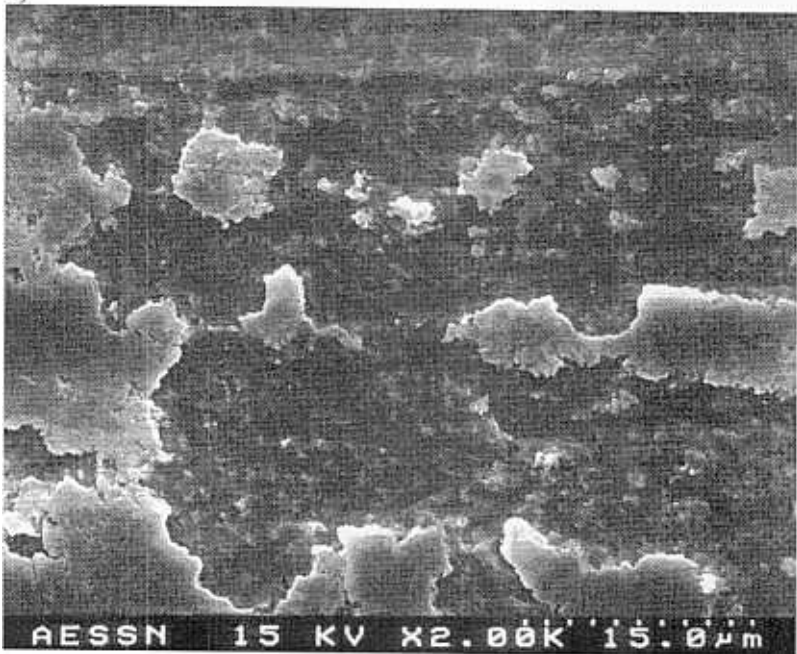


b)

Figure 24, Worn surfaces of polished hardmetal samples tested at 3 N in reciprocating tests, a) MA6, b) SHMUF.

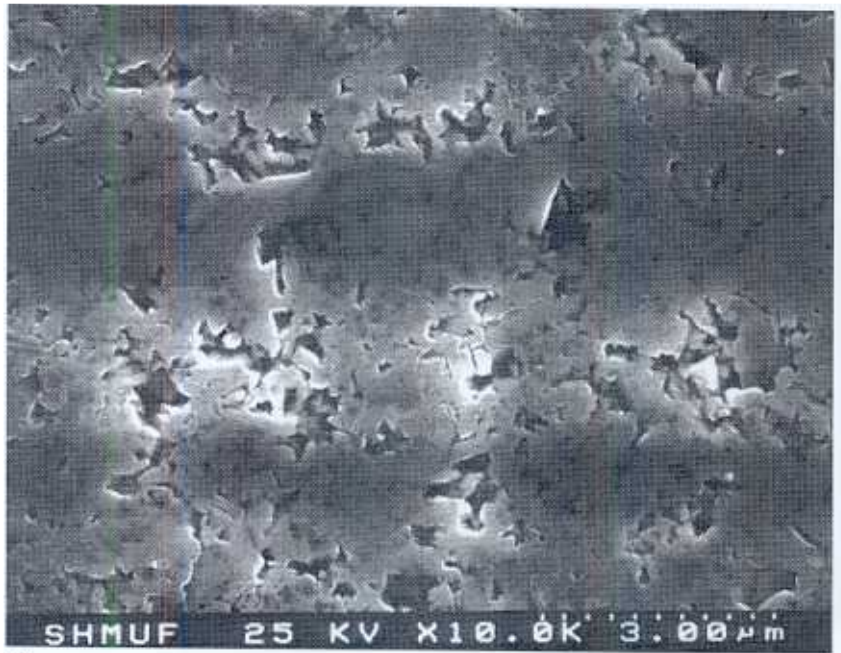


a)

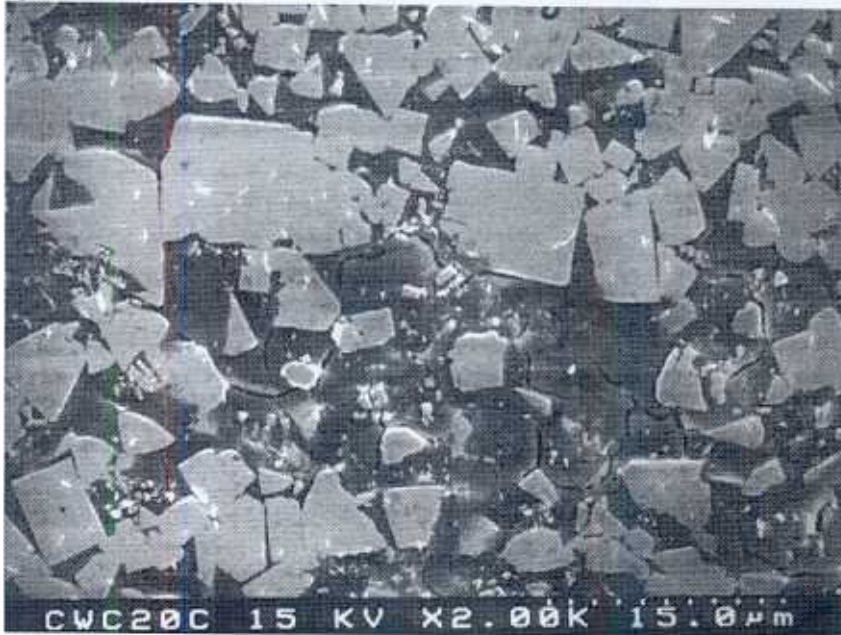


b)

Figure 30, Worn surface of polished SSN sample tested at 3N, a) polished surface with roll debris, layers of debris at end of wear track.

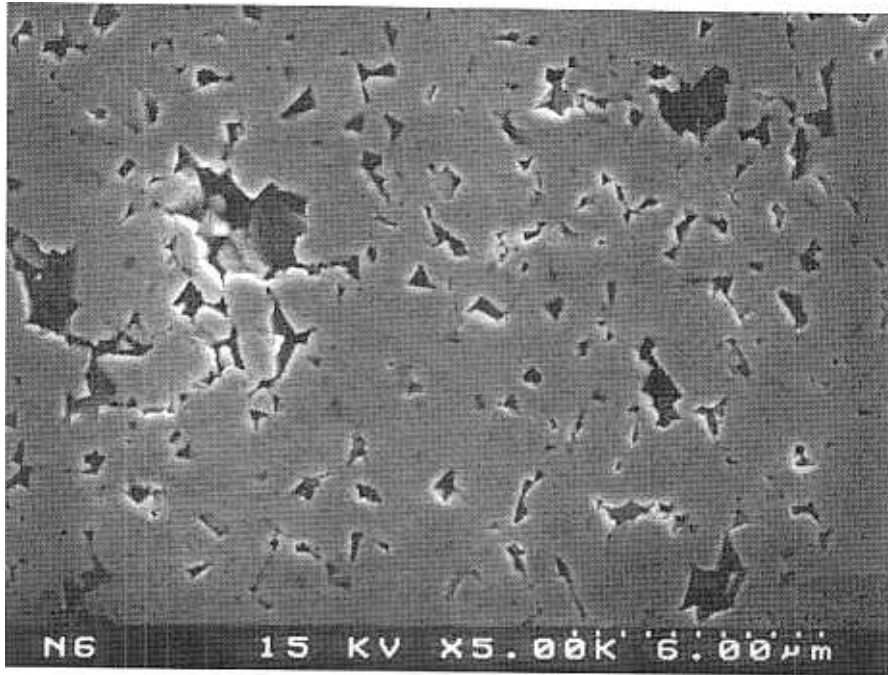


a)



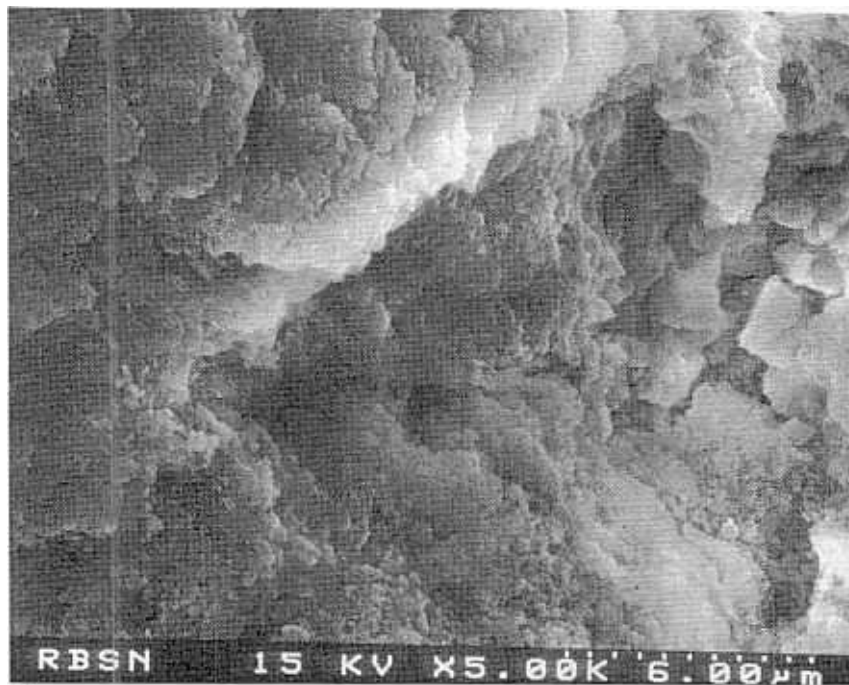
b)

Figure 31, Worn surfaces of polished hardmetal samples tested at 40 N in reciprocating tests, a) SHMUF, b) CWC20C, c) N6.

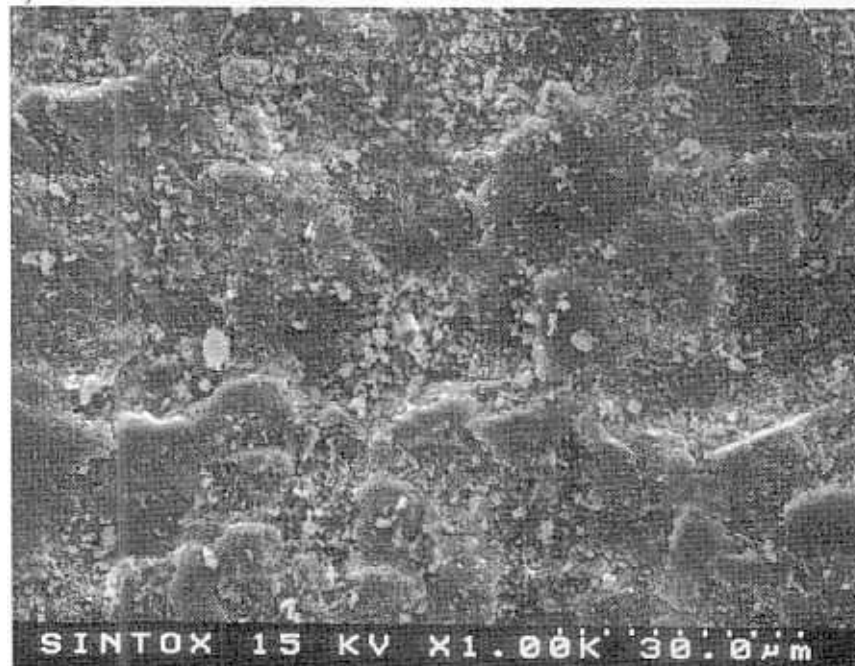


c)

Figure 31, Worn surfaces of polished hardmetal samples tested at 40 N in reciprocating tests, a) SHMUF, b) CWC20C, c) N6.



a)



b)

Figure 32, Worn surfaces of polished ceramic samples tested at 40 N in reciprocating tests, a) RBSN, b) Sintox, c) SSN, d) α -SiC, e) RBSC, f) Vitox.

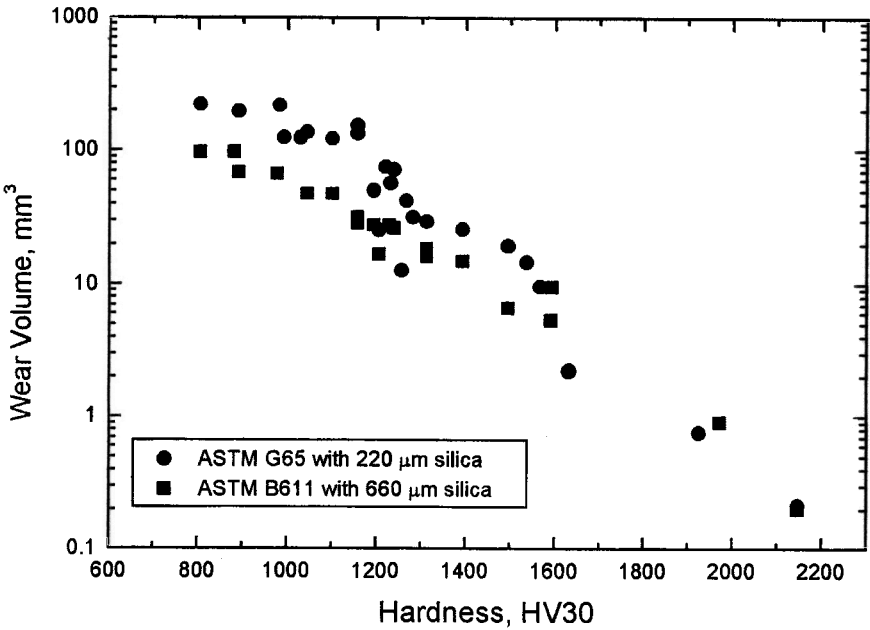


Figure 33, Comparison between ASTM G65 and ASTM B611 steel wheel results.

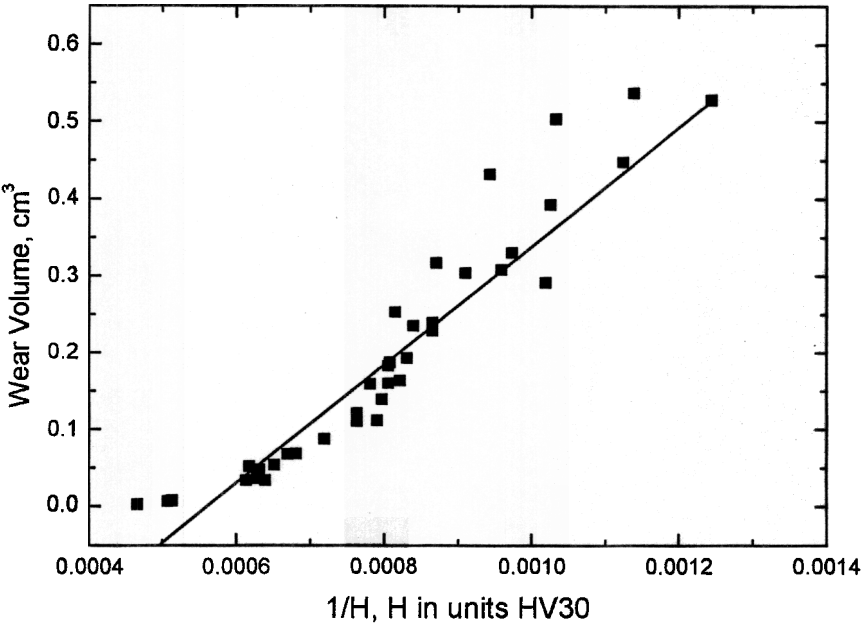


Figure 34, Variation of wear volume with inverse hardness in ASTM B611 tests.

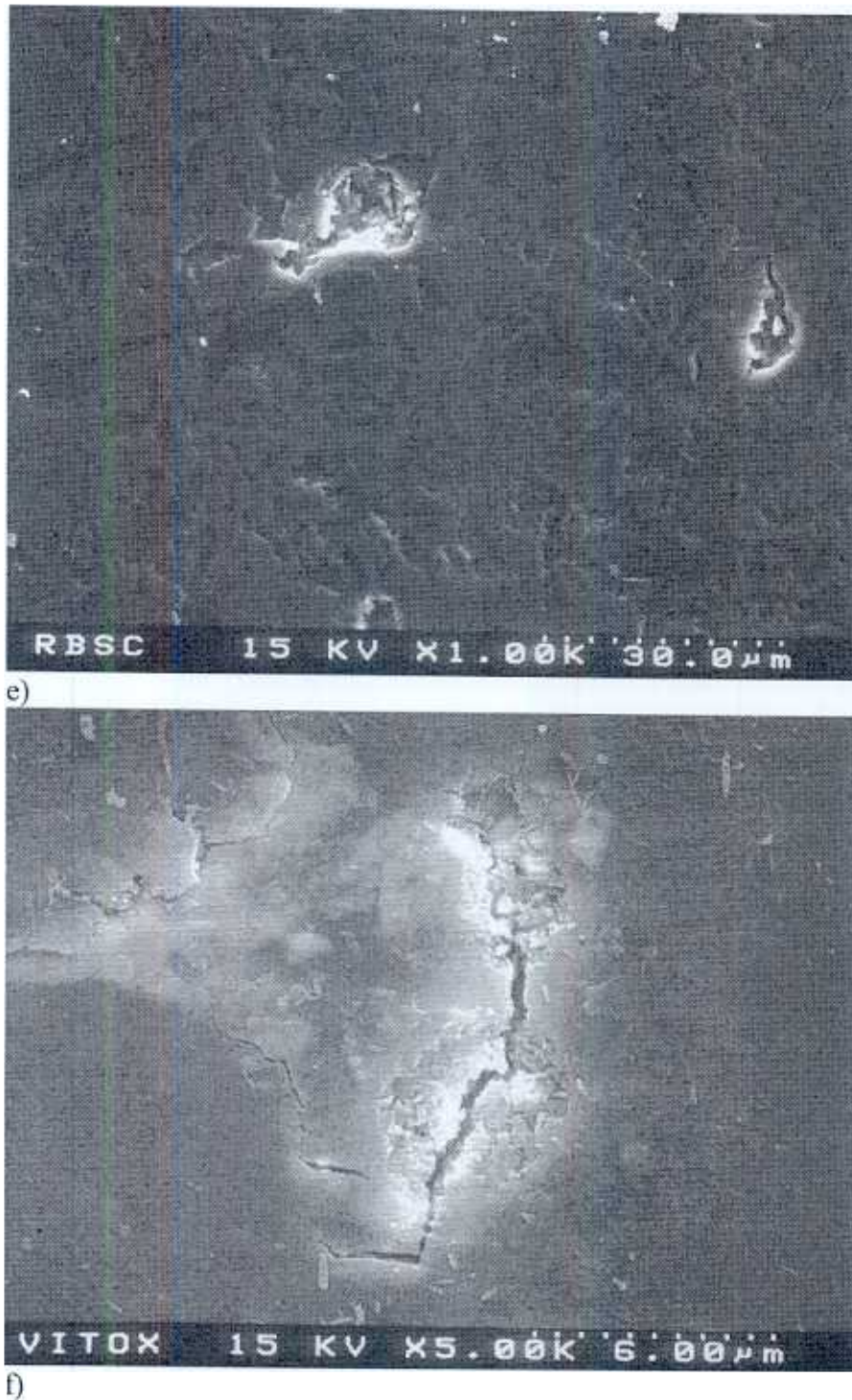


Figure 32, Worn surfaces of polished ceramic samples tested at 40 N in reciprocating tests, a) RBSN, b) Sintox, c) SSN, d) α -SiC, e) RBSC, f) Vitox.