

CRATER

Interlaboratory Exercise Description, Procedure and Results

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CRATER: Interlaboratory Exercise Description and Procedure

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SUMMARY

This report describes an interlaboratory exercise that was being carried out within the EU funded CRATER project that has the aim of standardising the micro-scale abrasion test for wear testing of coatings.

The interlaboratory exercise was carried out to validate the test procedure that has been used to form the revision to ENV 1071-6, Micro-scale abrasion of coatings.

The interlaboratory exercise had 14 participants. It was found that the micro-scale abrasion technique has reasonable reproducibility and repeatability when compared with other wear tests.

Annexes to the report give the procedure for the interlaboratory exercise, and list the participants in the exercise, and define the analysis method that was used.

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1. BACKGROUND

The use of coatings and surface engineered components is now growing strongly. This is being driven by the need for high value added products with enhanced durability, efficiency and lower environmental impact. These coatings and surface engineered components are used in all sectors of engineering including, for example, aerospace engines and components, prosthetic implants, paint films on cars, internal combustion engines and textile machinery.

Information on the wear resistant properties of coatings is urgently required by suppliers and users to provide confidence in the performance of engineering coatings.

Ball cratering (otherwise known as micro-scale abrasion testing) is a promising new technique that has the potential to fulfil this need. It is used to assess the wear resistance of coated and surface engineered components. The test method can be used to evaluate all types of coating including polymeric films, thin hard ceramic coatings, metallic coatings and thick thermally sprayed coatings.

This project has the objective of assisting European industry to acquire access to validated and robust measurement methods for the evaluation of coatings wear and friction performance. This will be accomplished by validating a draft European Standard for the ball cratering method that has been published by CEN. In addition to the development of an agreed test method, the project has been carrying out further development of the test system and analysis methods.

In the test the sample and rotating steel ball are loaded together by dead weight loading. A slurry of abrasive is fed into the wear interface. The wear is determined through measurement of the size of the craters after the test is complete.

A review of the state of the art (encompassing both literature and input from relevant EU centres of expertise) has been carried out [1,2], and is being used as input to the rest of the project. Tool steel and titanium alloy samples have been coated with DLC, TiN and aluminium. These samples were used in an experimental investigation of the parameters that control the test so that the effect of changing test parameters and the robustness of different systems could be examined. The different methods of analysing the test results were examined thoroughly [3].

The reproducibility of the test has now been evaluated by performing an interlaboratory exercise. This report describes the tests that will be carried out in the interlaboratory exercise and describes the results of the exercise. Annexes detail the procedure that was followed by the participants, and give the contact details of the participants that took part in the exercise.

By participating in this interlaboratory exercise participants recognize that any specific results obtained on the supplied test samples cannot be used for commercial purposes. The results of the exercise have been reported anonymously.

2. MATERIALS

The test samples were ASP23 powder metallurgy steel 6 mm thick x 32 mm in diameter coated with TiN. The substrates were polished before coating. A comprehensive characterisation of the coated samples was been carried out [4].

Two abrasives were supplied. The alumina abrasive, which has a nominal particle size of 1 μm was for the non-perforating tests, and the SiC abrasive, which has a nominal particle size of 4 μm was for the perforating tests.

Bearing steel balls 25.4 mm in diameter were also supplied.

3. TESTING REQUIRED

3.1 General Points

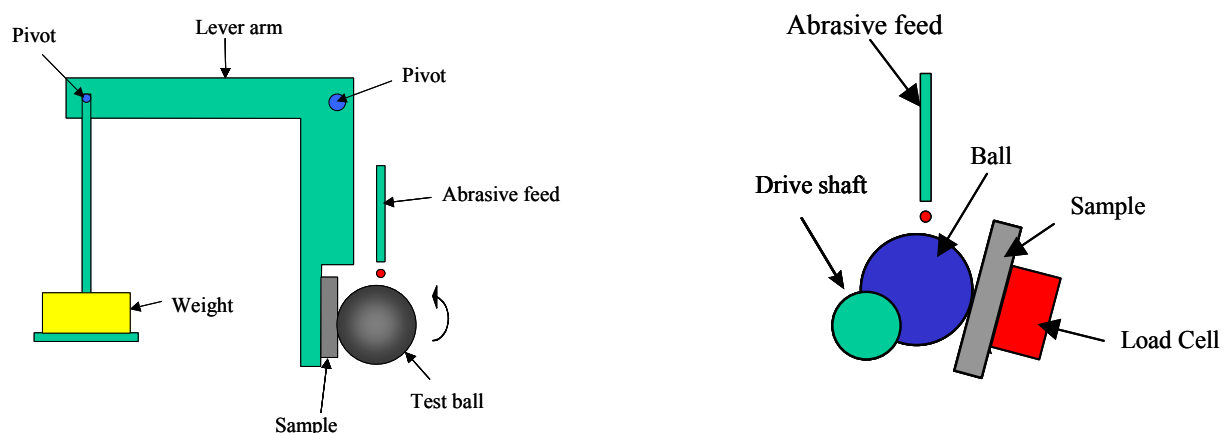
Two different types of testing were required. These are perforating tests, where a sequence of craters is produced on the sample of different test durations, the size of the resultant craters measured, and the results analysed to yield wear rates for the steel substrate and the TiN coating. In these tests the TiN coating is intentionally perforated following the basic method first suggested by Rutherford and Hutchings [5], since updated [3]. These tests were carried out using the SiC abrasive, although in three cases some additional non-perforating testing was carried out by three partners using alumina abrasive.

The other type of test was carried out using the alumina abrasive. Here the test conditions were carefully controlled to ensure that perforation of the coating did not occur. The diameter of the crater was measured and the wear rate of the coating alone calculated.

The procedure given in Annex A also required a few subsidiary experiments to be carried out with diamond paste to measure the thickness of the coating.

3.2 Test Systems

The procedures outlined in section 4 were designed so that they can be carried out with either the fixed ball type of test system, for example as shown in Figure 1a, or the free ball test system (Figure 1b).



a) b)
Figure 1, Main different types of ball cratering systems, a) fixed ball, b) free ball

There were some requirements concerning the test equipment.

3.2.1 Fixed Ball Test System

The fixed ball test system needed to include a mechanism to ensure that the number of ball rotations is recorded accurately. The load needs to be adjusted so that the correct load is applied to the test sample.

3.2.2 Free Ball Test System

Free ball test system had to incorporate a load cell to give a direct measure of the load applied to the test sample by the ball. There were also restrictions on the dimensions of the drive shaft. Thus if a rectangular groove on a drive shaft of about 12.5 mm diameter was employed, the shaft preferably needed to have a width of between 10 mm and 12 mm for a ball with a diameter of 25 mm. The angle of inclination of the test sample to the horizontal preferably needed to be between 60 and 75 degrees. Adjustment of load is carried out by adjusting the distance of the sample table to the drive shaft.

3.2.3 Test Systems Used

Both commercially manufactured and “home-built” equipment was used by participants in the interlaboratory exercise (Table 1). Some pictures of test systems used are given in Figure 2.

Table 1, Test systems used by participants.

Machine	Participant
Plint TE66 (fixed ball)	NPL, CU, Nottingham University, LSGS, Sheffield Hallam University, VITO, TNO, Tohoku University, Southampton University
CSEM Instruments Calowear (free ball)	Ion Bond
Other Free Ball	IST, NPL
Other Fixed Ball	Coimbra, Teer Coating Limited
Genco Free Ball	HEF

4 RESULTS

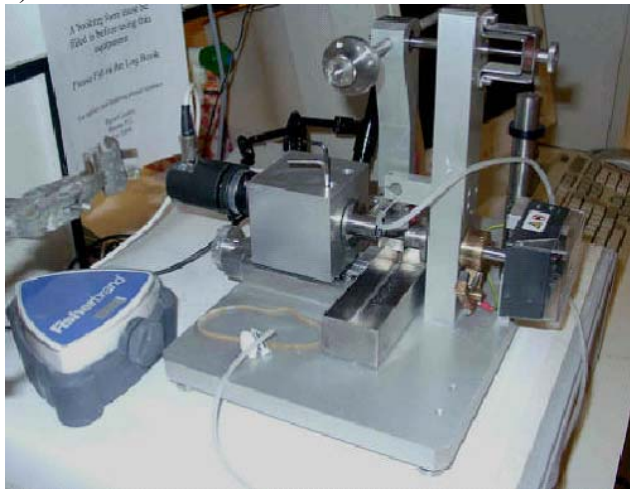
Initially 19 organisations agreed to take part in the interlaboratory exercise. In the event 14 finally returned results. These are listed in Annex B. It should be noted that the order of participants in this Annex is alphabetical and specifically does not correlate with the list of laboratories given in the Figures. On request, the identification of their own results will be released to individual laboratories.



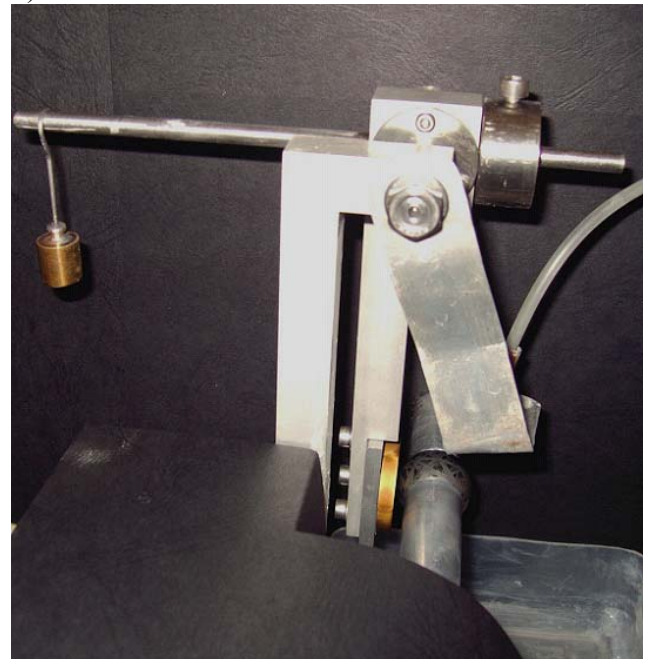
a)



b)



c)



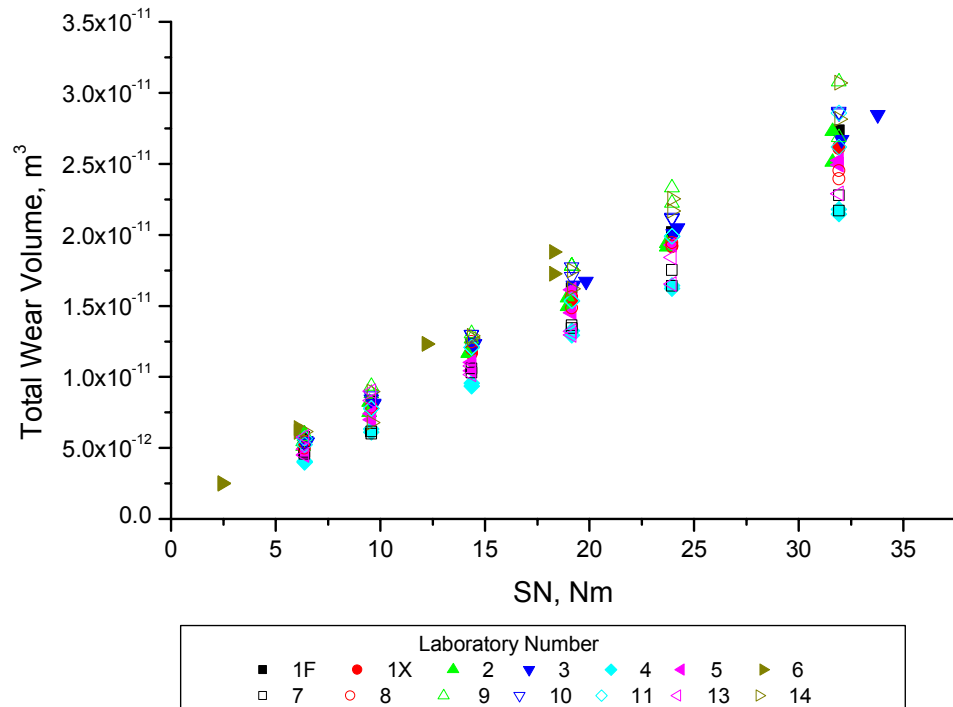
d)

Figure 2, Photographs of different test systems, a) IST test system, b) CSEM Instruments Calowear, c) Plint TE66, d) Coimbra test system

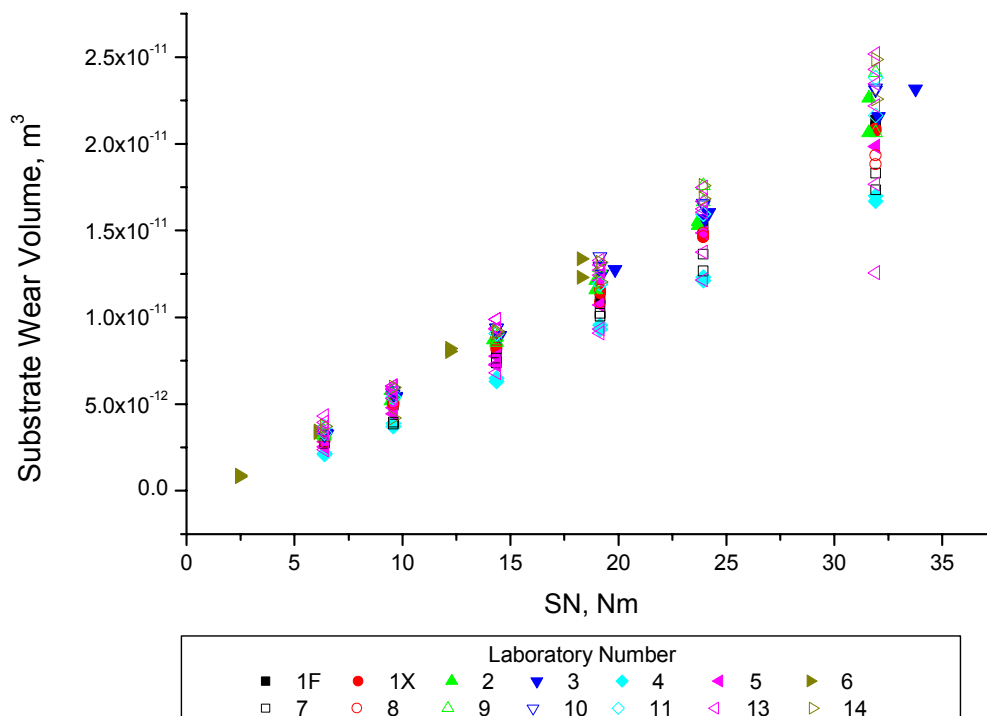
4.1 Perforating Tests

Thirteen laboratories returned results for the perforating tests using SiC abrasive. The results are shown in Figure 3. Figure 3a shows the agreement for different laboratories in terms of total volume of the craters, Figure 3b in terms of the inner crater diameter, and Figure 3c in terms of the thickness calculated from the crater measurements. There is some scatter in the results, but it should be noted that every laboratory had a different sample so that some of the scatter in results may be due to variation in sample thickness from one sample to another. The graph of calculated thickness shows that the thickness calculated from the outer crater diameter is always much larger than that found for the diamond abrasive. This is likely to be due to the observed difficulty in measuring the true diameter of craters made with the relatively large SiC abrasive due to rounding of the edge of the crater and scuffing around the

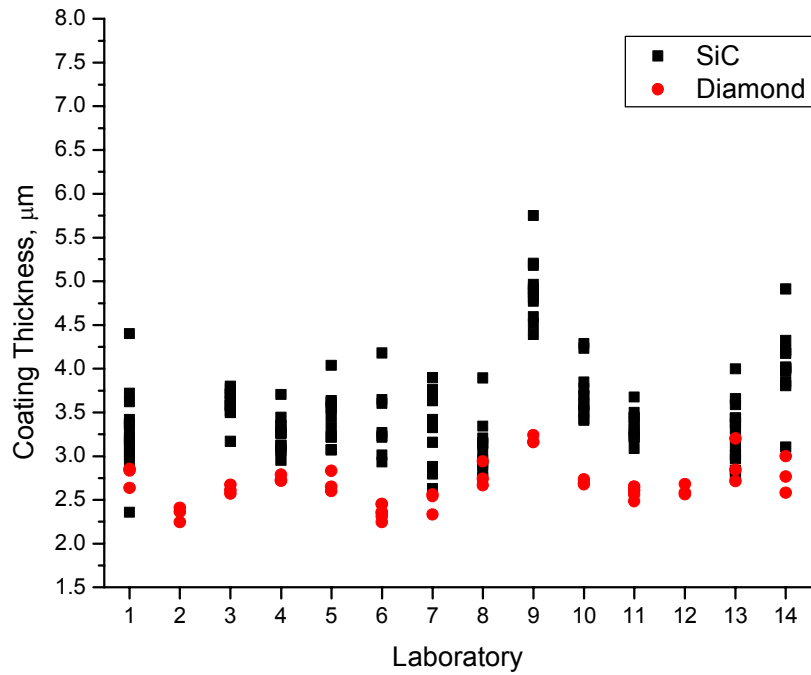
periphery of the crater. Figure 3c is also suggestive of a systematic variation in the thickness of the samples from laboratory to laboratory, but this may equally be due to systematic variations in measurement method from one laboratory to another.



a)



b)



c)

Figure 3, Interlaboratory exercise results for perorating tests with SiC abrasive, a) total crater volume, b) substrate crater volume, c) thickness caculated from crater dimensions for SiC and diamond abrasive.

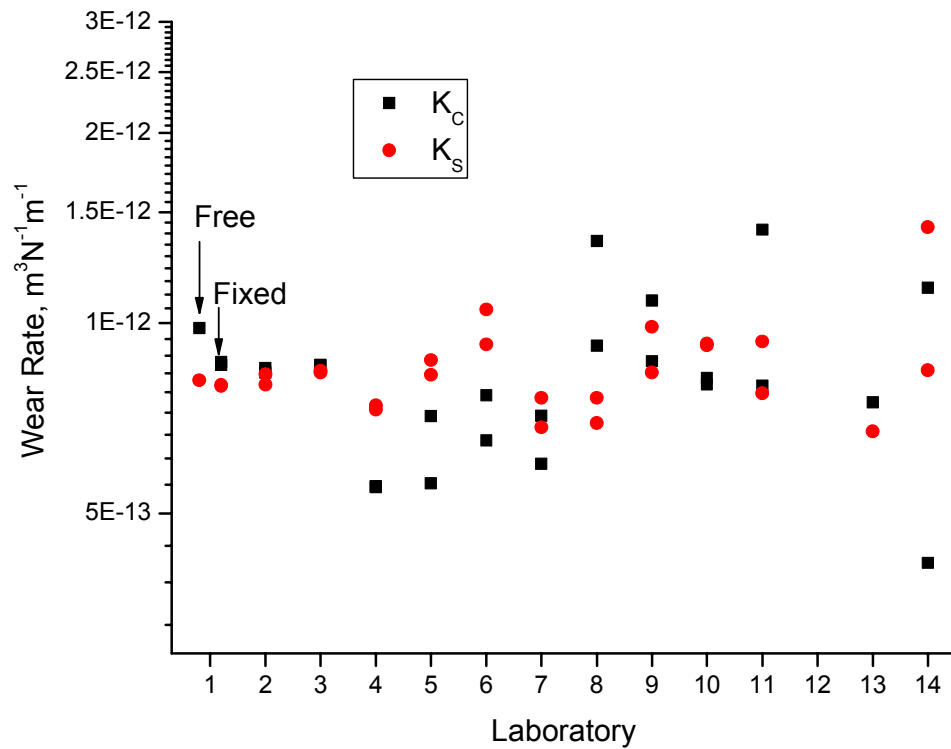
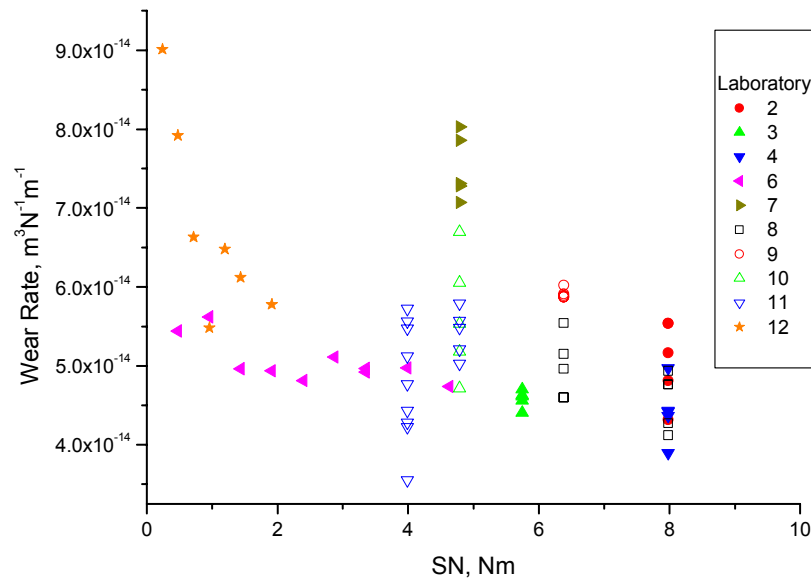


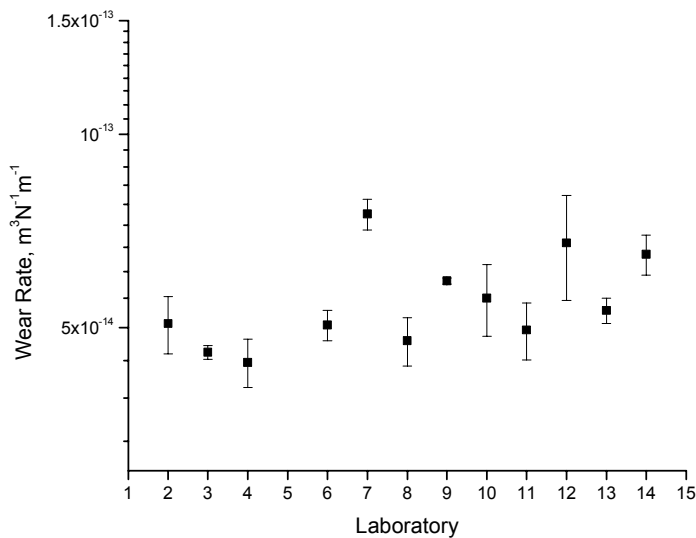
Figure 4, Wear rates calculated for perforating tests with SiC abrasive.

Figure 4 gives a comparison between the wear rates calculated by the analysis procedure given in Annex D. It can be seen that there is some variation in wear rate for the different laboratories, and that with this abrasive the wear rate for the steel substrate is the same as the wear rate for the TiN coating. It should also be noted that the fixed ball and free ball results for laboratory 1 are very similar.

4.2 Non-Perforating Tests



a)



b)

Figure 5, Variation of coating wear rate in non-perforated alumina tests a) with SN, b) comparison of mean and spreads for different laboratories.

Figure 5 gives the results of the non-perforating tests. There seems to be a systematic reduction in wear rate with increasing SN, particularly for the two laboratories that carried out tests at low values of SN where the crater size is small. At higher values of SN, this systematic variation is obscured by the variation in measurement from one laboratory to another.

4.3 Comparison of Results from Perforating and Non-perforating Tests

Two laboratories carried out tests with 10% alumina abrasive using both the perforating and the non-perforating test procedures. Good agreement was found between the coating wear rate K_c results for the non-perforating and perforating tests. However, a considerable difference was found between the different laboratories for the substrate wear rate K_s .

Laboratory	Non-perforating K_c , $10^{-14} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1}$	Perforating K_c , $10^{-14} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1}$	Perforating K_s , $10^{-14} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1}$
A	5.5	5	17.80
B	6.5	5.7	288.50

4 ANALYSIS OF REPRODUCIBILITY AND REPEATABILITY

The reproducibility and repeatability of the results were analysed following the procedure laid down in ISO 5725 Part 2 [6]. The results of this analysis are given in Table 2.

Table 2, Results of analysis of reproducibility and repeatability to ISO 5725 (Figures in brackets are percentage of means).

	Perforating Tests		Non-Perforating Tests	
Number of participants	13	13	12	4
	K_c , $10^{-13} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1}$	K_s , $10^{-13} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1}$	K_c , $10^{-13} \text{ m}^3 \text{ N}^{-1} \text{ m}^{-1}$	b , mm
Mean	8.00	8.34	5.35	0.561
sr	1.94 (24)	0.57 (7)	0.41 (8)	0.011 (2)
sR	2.09 (26)	0.92 (11)	0.94 (17)	0.016 (3)

For the non-perforating tests for the coating wear rate K_c the repeatability (within labs) standard deviation sr is 24% and the reproducibility (between labs) standard deviation sR is 26%. Again in the perforating tests, for the substrate wear rate K_s sr is 7% and sR is 11%. For the non-perforating test coating wear rate sr is 8% and sR is 17%. For the measurement of crater diameter sr is 2% and sR is 3%.

These values of reproducibility and repeatability are considered to be acceptable for a wear test.

5 CONCLUSIONS

An interlaboratory exercise was carried out to validate the test procedure that has been used to form the revision to ENV 1071-6, Micro-scale abrasion of coatings. The procedure has been revised through the EU project CRATER that finished recently.

The interlaboratory exercise had 14 participants. It was found that the micro-scale abrasion technique has reasonable reproducibility and repeatability when compared with other wear tests.

6 REFERENCES

- 1) M G Gee, A Gant, I Hutchings, R Bethke, K Schiffman, K Van Acker, S Poulat, Y Gachon, and J von Stebut, Review of Ball Cratering or Micro-Abrasion Testing of Coatings, NPL Report MATC(A)62
- 2) M G Gee, A Gant, I Hutchings, R Bethke, K Schiffman, K Van Acker, S Poulat, Y Gachon, and J von Stebut, Progress Towards Standardisation of Ball Cratering, Wear, 255(2003)1-13
- 3) Y Kusano, K Van Acker and I M Hutchings, Methods of data analysis for the micro-scale abrasion test on coated substrates, to be published in Surface and Coatings Technology
- 4) M G Gee, K Schiffman, C Leroy, J von Stebut, K van Acker, P Hatto, S Poulat, Y Gachon, R Versmeersch, Crater: Characterisation of Coatings, NPL Report MATC(D)153, May 2003
- 5) K L Rutherford, I M Hutchings, Theory and application of a micro-scale abrasive wear test, Journal of Testing and Evaluation, 25(1997)250-260
- 6) ISO5725- Part 2: 1994 Accuracy (trueness and precision) of measurement methods and results

ANNEX A PROCEDURE FOR MICRO-SCALE ABRASION TESTING

A1 Scope

This procedure describes the method for performing wear tests on coated samples by a perforation test, producing a series of craters at increasing time intervals/number of rotations, or by performing a non-perforation test on coated samples.

A2 Measurement of Temperature

A2.1 Measure the temperature of the room and record it on the data sheet.

A3 Calibration

A3.1 The crater measurement system will have been calibrated using the laboratory's normal method.

A4 Preparation of Samples

A4.1 Check the sample condition, scar position (see Figure 2), and direction of ball motion relative to the surface being tested.

A4.2 Wash sample to remove all traces of grease.

A4.3 A separate clean steel sample is required for ball surface preparation (running-in procedure). Any steel with hardness between 200 and 900 HV should be suitable.

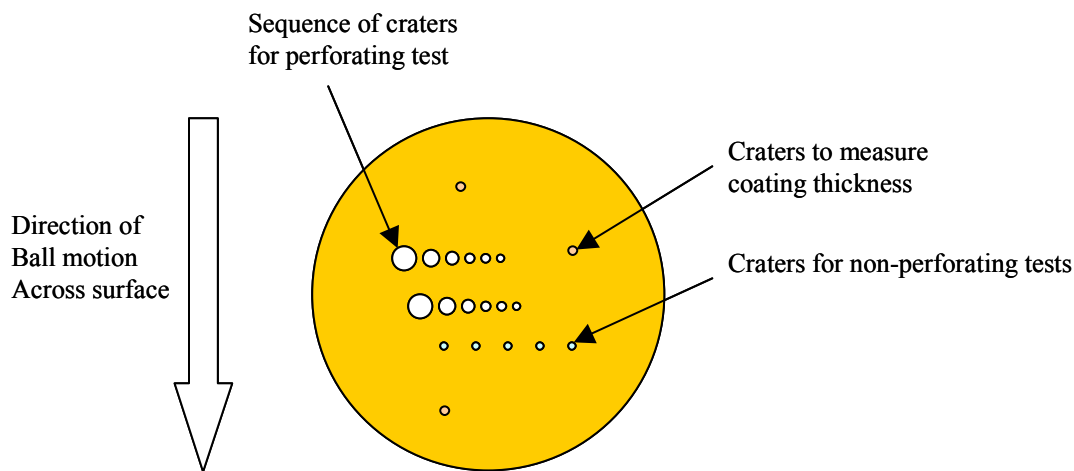


Figure A1, Example of position of wear scars on sample

A5 Preparation of Abrasive Slurry

A5.1 Leave deionized water in an open container in laboratory for at least 1 h (for CO₂ absorption).

A5.2 Add deionized water to the appropriate weighed quantity of abrasive powder (Table 1 lists the mass of abrasive for each 100 cm³ of water).

Table A1, Mass of abrasive required for 100 cm³ of water.

Abrasive	Size [μm]	Density [g cm^{-3}]	Concentration [vol. %]	Mass [g]
SiC	4	3.2	20	80.0
Al ₂ O ₃	1	4.0	10	44.4

A5.3 Mix thoroughly to produce a uniform suspension of particles with a concentration of 20 vol. % for the SiC slurry, and 10 vol. % for the alumina slurry.

A5.4 To prevent corrosion of the steel substrate in the perforated craters 1 g of sodium nitrite (NaNO₂) per 100 cm³ of water should preferably be added to the slurry.

A5.5 Ensure that the slurry is kept well mixed, e.g. by using a magnetic stirrer.

A6 Preparation of the Ball Surface (run-in procedure)

A6.1 Wash the ball to remove all traces of grease.

A6.2 Mount a steel sample (for the run-in procedure) in the apparatus.

A6.3 Adjust the motor speed to give the correct value for the rotational speed of the ball (in the range $0.1 \pm 0.01 \text{ m s}^{-1}$ sliding speed; or approximately 76 rpm for a 25 mm diameter ball).

A6.4 Adjust the system to give the correct normal loading between the ball and sample at the test point on the sample (the standard value is 0.2 N, but values between 0.18 and 0.22 N are acceptable).

A6.5 The method of feeding slurry to the contact point can vary between instruments. It may be via a pump or applied manually by the operator. Care must be taken to ensure that the slurry remains well mixed. The feed rate shall be sufficient that the contact between the ball and sample is always well wetted by the slurry. The slurry shall be used once only and not recirculated.

A6.6 Load the sample and ball together having ensured that the sample and ball are pre-wetted by the slurry, then start the motor and timer or counter. Typically 5 minutes running time, or between 300 and 400 revolutions should be used for the running in procedure.

A6.7 In a free ball test, count the number of revolutions of the ball in a fixed period of time T (T is typically 100 s). This stage should be repeated in subsequent tests until confidence is established in the repeatability of the value of the sliding speed.

A6.8 When the set time interval or number of revolutions is completed, switch off the motor, stop the slurry feed, and remove the ball or load.

A6.9 Clean the ball and the drive shaft (for free ball systems).

A6.10 Change the orientation of the ball, and repeat from stage 4.6.6 until more than 5 run-in tracks are produced randomly on the ball. The ball is now conditioned for further use. Typically such a ball can be used for at least 10 samples (> 60 tests).

A7 Test Method for Perforating Tests

A7.1 Mount the test sample in the apparatus so that the centre of the crater that will be formed will be at least 3.5 mm away from any previous crater.

A7.2 Confirm that the motor speed is the correct value to give the required rotational speed of the ball.

Table A2 Test conditions for perforating tests

Load [N]	0.2±0.02
Speed [m s^{-1}]	0.1±0.01
Ball material	As supplied
Ball diameter [mm]	25.4
Ball finish	Conditioned using run-in procedure
Abrasive material	SiC, as supplied
Fluid carrier	Water
Feed rate	Keep wet
Abrasive concentration [vol.%]	20
Test duration [Approximate number of ball revolutions]	400, 600, 900, 1200, 1500, 2000

A7.4 Confirm that the system gives the correct normal load between the ball and sample.

A7.5 Use 20 % SiC slurry prepared according to paragraph A5

A7.6 Start the slurry drip feed according to stage A6.5. The feed rate shall be sufficient that the contact between the ball and sample is always well wetted by the slurry. The slurry shall not be re-circulated.

A7.7 Load the sample and ball together having ensured that the sample and ball are pre-wetted by the slurry, then start the motor and timer or counter.

A7.8 When the set time interval or number of revolutions is completed, switch off the motor, stop the slurry feed, and remove the ball or load.

A7.9 Clean the ball and the drive shaft using a fine jet of water and paper tissue (for free ball test, particular care must be taken to clean the edges of the groove in the drive shaft).

A7.10 Carefully wash the test sample using a fine jet of water and dry the sample with tissue.

A7.11 Repeat from stage A7.1 for a new position of the sample with different time interval or number of revolutions until the series of tests for the same condition is completed. For the standard condition, six tests with different durations should be performed. The test

durations given in Table 2 are recommended. For each test, use a new orientation of ball relative to the sample.

A7.12 Two complete series of six tests should be carried out.

A7.13 When tests are completed, clean the sample and dry with hot air. Store the sample in dry conditions.

A7.14 Ensure that the position of all craters can be identified (eg by drawing a sketch of the sample) and correlated with the relevant measurements.

A8 Test Method for Non-perforating Tests

A8.1 Mount the test sample in the apparatus so that the centre of the crater that will be formed will be at least 3.5 mm away from any previous crater.

A8.2 Confirm that the motor speed is the correct value for the rotational speed of the ball.

A8.3 Confirm that the system gives the correct normal load between the ball and sample.

A8.4 Use 10 % alumina slurry prepared according to paragraph 4.5

A8.5 Start the slurry drip feed according to stage A6.5. The feed rate shall be sufficient that the contact between the ball and sample is always well wetted by the slurry. The slurry shall not be re-circulated.

A8.6 Load the sample and ball together having ensured that the sample and ball are pre-wetted by the slurry, then start the motor and timer or counter.

A8.7 When the set time interval or number of revolutions is completed, switch off the motor, stop the slurry feed, and remove the ball or load. Some trial and error may be required, but preliminary tests have shown that the test duration given in Table A3 is appropriate.

Table A3, Test conditions for non-perforating tests

Load [N]	0.2±0.02
Speed [m s^{-1}]	0.1±0.01
Ball material	As supplied
Ball diameter [mm]	25.4
Ball finish	Conditioned using un-in procedure
Abrasive material	Al_2O_3 , as supplied
Fluid carrier	Water
Feed rate	Keep wet
Abrasive concentration [vol.%]	10
Test duration [Approximate number of revolutions]	500, but perforation must not occur

- A8.7 Clean the ball and the drive shaft using a fine jet of water and paper tissue (for free ball test, particular care must be taken to clean the edges of the groove in the drive shaft).
- A8.8 Carefully wash the test sample using a fine jet of water and dry the sample with tissue.
- A8.9 Five repeat tests should be made.
- A8.10 When tests are completed, clean the sample and dry with hot air.

A9 Measurement of Coating Thickness

- A9.1 A fine metallographic diamond paste or spray (1 μm abrasive size or less) should be used to create craters at three positions well spaced over the surface of the sample. The outer crater diameter should be about 0.7 mm.
- A9.2 The inner and outer crater diameters a and b measured from these craters (see Figure A3) are used to calculate a coating thickness at each position. The three values of coating thickness are used to calculate an average coating thickness for the sample. The formula for the coating thickness t is:

$$t = R(\alpha - \beta).$$

where R is the radius of the ball and

$$\alpha = \left(1 - \frac{a^2}{4R^2}\right)^{\frac{1}{2}} \text{ and } \beta = \left(1 - \frac{b^2}{4R^2}\right)^{\frac{1}{2}}.$$

A10 Measuring Method

- A10.1 Measure the dimensions of the wear craters in two directions (parallel $\parallel$ and perpendicular $\perp$ to the direction of ball motion) of both the inner a and outer b crater diameters (see Figure A3). For the non-perforation tests, measure the crater diameters b in the two directions parallel $\parallel$ and perpendicular $\perp$.

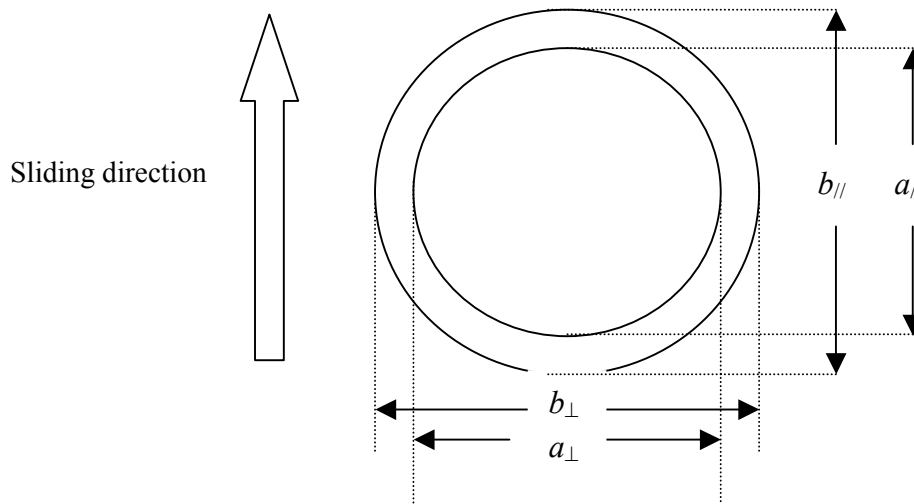


Figure A3 Measurement on wear scar

A11 Data report

- A11.1 Report details of the test system that was used in the experiment, including a digital picture of apparatus if possible. In the case of a commercial instrument, note the manufacturer, model number and instrument serial number, and any modifications that have been made. Note any specific test conditions that were used such as the sample inclination, shaft diameter, and groove dimensions in a free ball machine.
- A11.2 Report the results of the thickness measurements from section 4.7 by completing the worksheet in the Excel spreadsheet (Annex D) for the coating thickness measurement.
- A11.3 For the perforating tests complete the appropriate worksheets in the Excel spreadsheet separately for each set of measurements, giving sample number, scar position, test conditions (type of micro-abrasion test (fixed or free), ball diameter, abrasive material, fluid carrier, abrasive concentration, rotation speed, normal load, number of revolutions), and measured diameters $a_{||}$, $b_{||}$, $a_{\perp}$, and $b_{\perp}$ for each crater. Report any other comments where appropriate. The Excel spreadsheet incorporates the analysis method given in Annex C for completeness.
- A11.4 For the non-perforating tests report all test results using the appropriate worksheet from the Excel spreadsheet. This worksheet also calculates wear volumes.
- A11.5 Optionally, supply digital micrographs with a clear indication of scale of all craters.
- A11.6 All samples with sketches to identify craters should be returned with the data to NPL. Data (Excel spreadsheet) should also be sent electronically to NPL.

ANNEX B: LIST OF PARTICIPANTS

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ANNEX C: ANALYSIS METHOD

- C1 For each crater calculate the volume of wear in the coating, V_c and the volume of wear in the substrate, V_s from the values of a and t . The formulae below should be used; for practical purposes these approximate expressions are sufficiently accurate. The parameters a and b are calculated with the expressions given in para 4.7.

$$V_c \approx \frac{\pi t}{4} (a^2 + 4 R t)$$

$$V_s \approx \frac{\pi a^4}{64 R}$$

- C2 Plot a graph of SN/V_c against V_s/V_c for all the craters (S is the total distance of relative movement and N is the normal applied load).
- C3 The data points should lie close to a straight line. Any outlying points may be disregarded or repeat experiments performed before subsequent data analysis.
- C4 Apply linear regression (least squares method) to determine the line of best fit to the data points.
- C5 Obtain the coating wear coefficient κ_c from the intercept, and calculate the substrate wear rate coefficient κ_s from the slope, as indicated by the equation

$$\frac{SN}{V_c} = \frac{1}{\kappa_s} \frac{V_s}{V_c} + \frac{1}{\kappa_c}$$

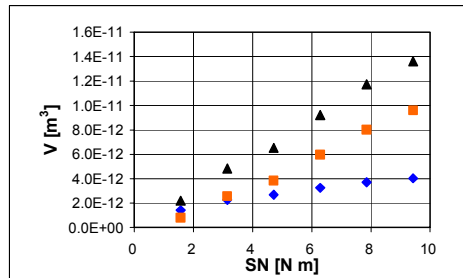
Crater Project Interlaboratory Exercise

First Series Perforating Tests

Laboratory	Lab 1	no. of	parallel		perpendicular		
date(dd/mm/yy)		revolutions	a [mm]	b [mm]	a [mm]	b [mm]	
instrument type	System 1	100	0.690	0.860	0.650	0.860	
abrasive slurry	SiC	200	0.910	1.030	0.890	1.060	
particle size [μm]	4	300	1.000	1.140	0.990	1.130	
abrasive conc. [vol.%]	20	400	1.100	1.230	1.120	1.250	
rotation speed [rpm]	76	500	1.200	1.310	1.190	1.320	
ball diameter [mm]	25	600	1.250	1.360	1.250	1.370	
substrate	ASP23						NV
surface finish	Polished						NV
coating	TiN						NV
sample ID	Test ID						NV
normal load [N]	0.20						NV
coating thickness [μm]	3.00						NV

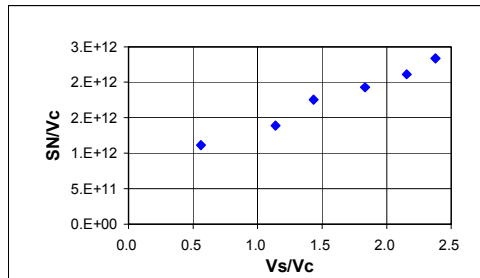
(input "coating thickness" or "b")

Kc [m ² N ⁻¹]	1.40E-12
Ks [m ² N ⁻¹]	1.50E-12



V:black, Vc:blue, Vs:red

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CRATER project

Figure D3, Worksheet for first series of perforating tests

Crater Project Interlaboratory Exercise

Non-Perforating Tests

Laboratory	Lab 1	no. of	parallel	perpendicular	Wear Volume	Wear Rate
date(dd/mm/yy)		revolutions	b [mm]	b [mm]	mm ³	m ² N ⁻¹
instrument type	System 1					
abrasive slurry	Alumina					
particle size [μm]	1					
abrasive conc. [vol.%]	20					
rotation speed [rpm]	76					
ball diameter [mm]	25					
substrate	ASP23					
surface finish	Polished					
coating	TiN					
sample ID	Test ID					
normal load [N]	0.20					

Figure D4, Worksheet for non-perforating tests