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REPORT

SUMMARY OF WEAR TEST METHODS:

NOTES ON

**10TH INTERNATIONAL CONFERENCE ON
WEAR OF MATERIALS**

BOSTON, 1995

S Owen-Jones

December 1997

NPL 
National Physical Laboratory

Summary of Wear Test Methods

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WEAR OF MATERIALS**

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ABSTRACT

This summary gives a brief description of the different wear testing methods that were reported in the proceedings of the 10th International Conference on the Wear of Materials

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

Introduction

These notes have been written as part of project CAM 8, *The Production of a Guide to Wear Testing for Industry*, which has the overall aim of developing guidance for industry on the choice of different wear testing methods and its applicability to particular industrial wear problems. The project will also define procedures for carrying out these tests. Project CAM 8 is funded by the Department of Trade and Industry under its Characterisation and Performance of Advanced Materials Programme.

Information on the wear test methods that are currently available to industry is being gathered from a number of different sources. These include:

- a survey of industry
- the VAMAS report on standard wear test methods
- a search of the standards database
- wear and friction testing literature
- proceedings of recent conferences on wear testing

These notes are a summary of the information on wear testing that is contained in the proceedings of the 10th International Conference on Wear of Materials. This conference is a biennial event where a considerable amount of information is given on wear testing methods.

Summary

Brief notes on the individual papers are given in the following sections. The notes refer to the page numbers in the conference proceedings. However, it is useful to give an overall summary the test methods that are described in the proceedings, which is given in the Table below.

Test Method	Number Reported
Rolling/Sliding (Amsler)	2
Pin-on-disc	22
Pin-on-ring	11
Reciprocating	8
Other sliding tests	8
Gas blast erosion	4
Slurry erosion	3
Cavitation erosion	2
Fretting	5
Abrasion testing	3
Cutting	1
Microtribology	5
Engine testing	1

Notes

The conference is published as volumes 181-183 of the journal *Wear*.

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Part 1

pp1-10 *The implementation of tribological principles in an expert system ("PRECEPT") for the selection of metallic materials, surface treatments and coatings in engineering design.*
S.E. FRANKLIN & J.A. DIJKMAN

pp11-19 *Predicting the wear of rails on curves from laboratory data.*
P. CLAYTON

The Amsler wear testing machine was designed for research into wheel/rail wear in the late 1920s (Fink).

Similar test bench machines have been employed by Krause *et al* (1986-7), Heller *et al* (1982), Hodgson *et al* (1982), Ichonose *et al* (1982) and Masumoto *et al* (1978). In many cases a combination of relatively low pressures and low slide/rolls ratios were employed. Little consideration was given to the overall patterns of behaviour, or their wear mechanisms and their relevance.

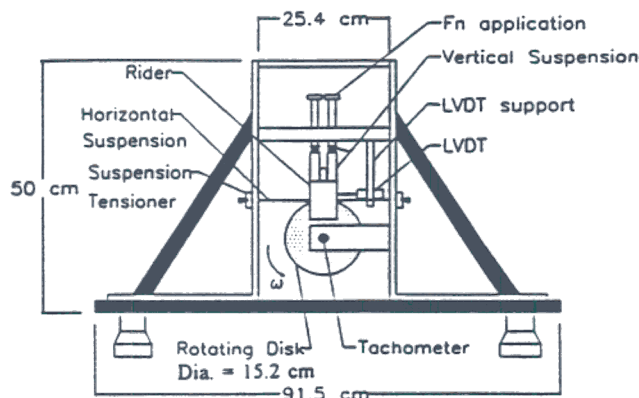
Beagley (1976) was the first to use the Amsler machine to determine patterns of wear.

20-31 *A mathematical model for sliding wear of metals at elevated temperatures.*
J. JIANG, F.H. STOTT & M.M. STACK

Sliding wear tests were performed on a pin-on-disc reciprocating wear rig in the like-on-like mode at an average speed of 83 mm s^{-1} . The pin specimen has a domed end with radius 12.5 mm. The environment was pure oxygen. The normal load was 15N. Temperature range 20-600 °C.

32-41 *Application of a two-dimensional model of continuous sliding friction to stick-slip.*
A.A. POLYCARPOU & A. SOOM

Friction apparatus:



Two subsystems: a rotational system driven by a DC servomotor and a nominally stationary rider assembly.

The rider assembly holds a cylindrical sample (insert). The flat side of the sample forms a line contact with the edge of a rotating disc mounted at the end of the drive system.

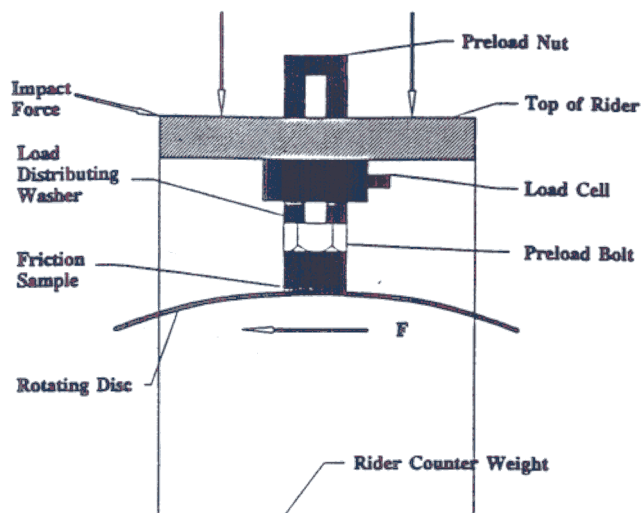


Fig. 5. Contact and rider details.

Friction force generated at contact is carried by horizontal suspension of the rider which consists of 4 horizontal strips constructed from a constrained-layer viscoelastic material. The strips are attached to the rider, in line with the contact. The normal load is applied through 2 adjustable vertical helical springs that are positioned symmetrically on top of the rider. These springs also provide the primary angular stiffness to the rider assembly. The time-varying velocity commands are applied to the disc independently, by a function generator.

42-49 *Development of an equation for the wear of polymers.*
N. VISWANATH & D.G. BELLOW

A horizontal pin-on-disc machine was used with polymer pin sliding against the rim of a vertical steel disc. Two types of steel discs: AISI 1018 steel and HTSR 4140 steel. Both discs were finished to specific surface roughnesses and tests were conducted at prescribed loads, speeds and test durations.

50-55 *Structure-based selection of wear-resistant materials.*
I.I. GARBAR

Reciprocating friction machine: average speed 0.05 ms^{-1} , pressures of 0.8, 1.6 and 3.3 MPa. Lubrication by the drip-feed method. Two types of specimen: copper foils for TEM studies, copper and steel cylindrical specimens 20 mm diameter, 7.5 mm height, for X-ray studies.

56-62 *Scaling laws for particle velocity in the gas-blast erosion test.*
A.N.J. STEVENSON & I.M. HUTCHINGS

Gas blast erosion rig, erodent particles fed at constant rate into air stream and accelerated along a parallel-sided cylindrical nozzle with 4.90 mm bore.

63-69 *Erosion-corrosion resistance of tungsten carbide hard metals with different binder compositions.*
E.J. WENTZEL & C. ALLEN

Slurry jet erosion rig based on that of Zu (1990).

Rig permits variations in impact angle, impact velocity, erodent size, erodent concentration and carrier fluid.

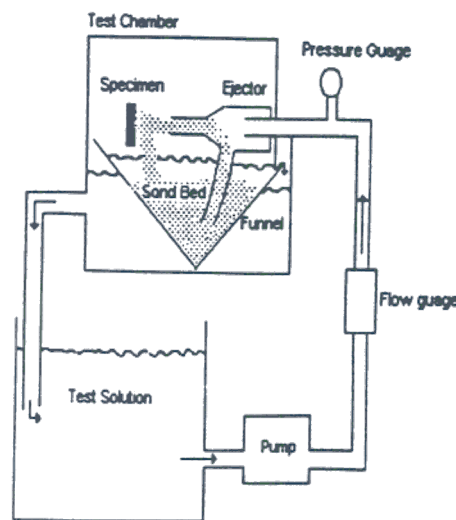


Fig. 1. The slurry jet erosion test rig.

The carrier fluid is circulated by a centrifugal pump from holding tank via rotameter to ejector. Ejector ensures pressure drop in fluid, resulting in vacuum that is strong enough to draw erodent particles through suction tube - bottom of which is in submerged sand bed. Erodent and carrier fluid mixed in ejector and slurry jet accelerated onto specimen surface. Specimen can be rotated on a horizontal axis to a preset angle between 30° and 90°. Complete specimen and holder enclosed in perspex test chamber. Impact velocity 6.5 ms⁻¹, erodent concentration 7% (by mass) of 500 µm diameter silica sand in distilled water; 32.5 Kg of erodent/hour impacted specimen surface.

70-79 *Influence of environmental composition and electrochemical potential on the slurry erosion-corrosion of aluminium.*
Y. LI, G.T. BURSTEIN & I.M. HUTCHINGS

Jet impingement slurry erosion-corrosion rig and electrochemical cell to measure and control potential of specimen.

80-85 *Cavitation erosion of NiTi explosively welded to steel.*
R.H. RICHMAN, A.S. RAO & D. KUNG

Specimens were firmly clamped in a holder and exposed to cavitation in a fixture similar to that described by Preece & Hansson (1982). Cavitation was induced by longitudinal oscillations at 20 kHz with amplitude $\pm 25 \mu\text{m}$. Separation between vibrating tip and stationary specimen was 0.5 mm.

86-93 *Fretting of titanium nitride and diamond-like carbon coatings at high frequencies and low amplitude.*

K. SCHOUTERDEN, B. BLANPAIN, J.P. CELIS & O. VINGSBO

Fretting tester:

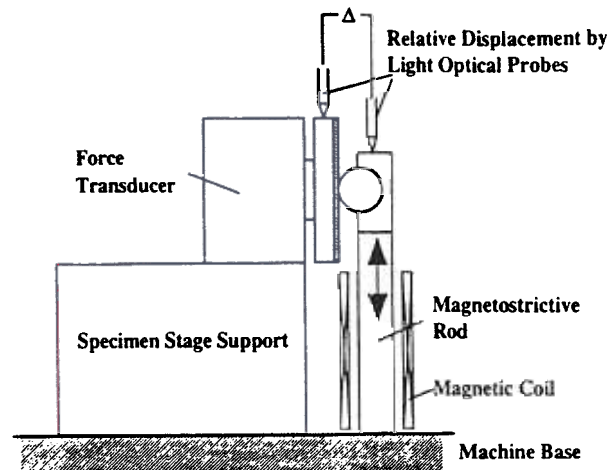


Fig. 1. Schematic representation of the fretting tester.

Fretting tester based on a giant magnetostrictive rod which can be operated under well-controlled conditions up to the kHz frequency range and at low displacement amplitudes (peak-to-peak value of $0.1\text{--}10 \mu\text{m}$). Length of rod very accurately controlled by oscillating current through coil surrounding rod. Specimens mounted with vertical contact surface.

94-100 *Fretting of polyimide coatings. Part I: Structure and moisture effects.*

C. KANG & N.S. EISS

Sphere-on-flat fretting tests, 52100 steel ball of 1.588 cm diameter and polyimide-coated disc. Coating life = time taken for ball to wear through coating and make contact with metallic substrate.

Temperature 23°C , fretting amplitude = $200 \mu\text{m}$, sliding frequency = 40 Hz, normal load = 32.8 N, humidity < 10%, 42% and > 90%.

101-111 *An analysis of fretting-fatigue failure combined with numerical calculations to predict crack nucleation.*

C. PETIOT, L. VINCENT, K. DANG VAN, N. MAOUCHE, J. FOULQUIER & B. JOURNET

Two cylindrical fretting pads (10 mm diam) clamped against both surfaces of a flat uniaxial fatigue specimen tested under constant amplitude loading at 20 Hz.

Imposed oscillatory motions between pads and specimen are linked to imposed oscillatory fatigue stress in specimen.

112-117 *Laboratory assessment of the effect of white layers on wear resistance for digger teeth.*
L. XU, S. CLOUGH, P. HOWARD, D. StJOHN

Samples taken from worn tooth. Three-body wear tests were performed using a standard DSRW tester for low stress abrasion and a paddle tester for high stress impact-abrasion.

DSRW tester: Samples surface dimension of 25.4 mm x 76.2 mm, wheel rotating speed = 200 rev m⁻¹, applied load = 130 N. Durations of 1000 and 6000 revolutions of rubber wheel rotation.

Paddle tester: originally designed for measuring ore abrasiveness, modified for 3-body impact-abrasion wear testing. Samples 20 mm x 20 mm x (6-12) mm, 3 mm exposed above holders which were situated at both ends of paddle arm. One sample was the reference and other was the test material.

Each test for 15 min using 3 Kg of blue metal gravel. Both paddles and the drum rotated in the same direction with speeds of 270 rev min⁻¹ for the paddle arms and 45 rev min⁻¹ for the drum, which gives a minimum impact speed of 4.5 ms⁻¹ for gravel particles on the specimen.

118-128 *Friction and wear reduction of Al₂O₃ ceramics by laser-induced surface alloying.*
K.-H. ZUM GAHR, Ch. BOGDANOW & J. SCHNEIDER

Unlubricated oscillating sliding wear:- ball-on-block tribometer (Optimol SRV). Al₂O₃ and SiC balls 10 mm diameter Normal load 20-60 N. Oscillation frequency = 20 Hz, stroke = 0.5 mm, average sliding speed = 0.02 ms⁻¹. duration = 1.4 x 10⁵ cycles, total wear path length = 144 m.

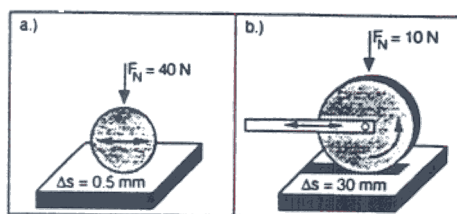


Fig. 1. Tribosystems and operating conditions for (a) oscillating sliding wear and (b) abrasive sliding wear.

Abrasive wear: abrasive wheel test (Erichsen type 533). Wheel of 50 mm diameter loaded by 10 N, covered by 120 mesh SiC abrasive paper and moved back and forth across flat surface of specimens. After each double stroke (2 x 30 mm) the wheel was rotated by ~ 1° to achieve fresh abrasive grits in the contact area. Amount of wear was determined after 2000 double strokes and a length of wear path of 120 m, respectively.

129-137 *Effect of grain boundary glass composition and devitrification on the abrasive wear of Al₂O₃.*
C.P. DOGAN & J.A. HAWK

Single pass sliding wear test using a scratch test device built by US Bureau of Mines.

More aggressive, two-body abrasive wear was measured utilising a pin abrasion test designed by US Bureau of Mines to simulate abrasive wear in crushing and grinding operations. (Test described: Blickensderfer & Laird, 1988).

138-147 *Mechanism of wear reduction of alumina by tribopolymerisation.*
B.S. TRIPATHY, M.J. FUREY & C. KAJDAS

Pin-on-disc machine described Furey et al 1994. 1/8 inch diameter ball sliding on 1 inch disc.

148-155 *Wear of boron carbide ceramics by abrasive waterjets.*
K.A. SCHWETZ, L.S. SIGL, J. GREIM & H. NOCH

Abrasive waterjet formed by mixing abrasive particles with a high velocity waterjet (approx 1 mm diameter) in a chamber and subsequent focussing of the 'abrasive waterjet' in a tube. AWJ capable of cold cutting even hard and tough materials.

156-164 *Wear transitions in monolithic alumina and zirconia-alumina composites.*
Y.S. WANG, C. HE, B.J. HOCKEY, P. LACEY & S.M. HSU

Sliding wear tests: commercial four-ball wear machine modified to accommodate ball-on-three-flat configuration. Ceramic ball, 12.7 mm diameter upper rotating specimen in contact with 3 stationary flats - aligned so that normals form tetrahedron with centre of upper ball. Room temperature, paraffin oil lubrication.

154-177 *Effect of grain boundary dopants and mean grain size on tribomechanical behaviour of highly purified α -alumina in the mild wear regime.*
S.R. HAH, T.E. FISCHER, P. GRUFFEL & C. CARRY

The friction and wear expts performed on pin-on-disc tribometer, stationary pin with spherical tips loaded by a dead weight against the rotating disc in laboratory air. Pin and disc made of same material. Pin ground to give hemispherical tip of 6 μm diameter and polished by diamond paste ranging from 6-0.25 μm diamond particles. The applied loads were 9.8 and 29.4 N, which is in the mild wear regime. Sliding speed = $10 \pm 0.2 \text{ mms}^{-1}$ wear volumes determined only for hemispherical pins.

178-188 *Erosion characteristics of alumina ceramics at high temperatures.*
J. ZHOU & S. BAHADUR

Erosion experiments: vertical sand-blast high temperature erosion rig (details in Zhou & Bahadur 1989).

Test temperatures = 25, 200, 400, 500, 650 and 800 °C.

SiC particles, grit size 120 (average diameter = 151 μm) accelerated in air. Concentration in fluid stream = $0.0066 \text{ g mm}^{-2} \text{ s}^{-1}$.

Impingement velocity = 50 ms^{-1} (40-90 ms^{-1}).

Impingement angle = 10° - 90° .

Duration of each test = 70 min with a total of 250 g particles impacted.

189-193 *Wear of Ti-Si-N coated ceramic cutting inserts.*
J.L. HE, C.K. CHEN & M.H. HON

Cutting performance tests on CNC lathe machine.

Cutting speed = 150 m/min; cutting depth = 4.0 mm; feed rate = 0.15 mm/rev; feed direction = longitudinal; work piece = FC-25 gray cast iron; cutting fluid = dry and Aral-Sarol 345.

Rate and flank wear was measured in terms of wear scar width as a function of cutting distance.

194-201 *Erosion behaviour and evaluation of erosion resistant AT₃₀Z.*

J. MOU, Z.Y. MAO, J. LI & S.Y. GUO

Airborne particle erosion test at room temperature - ASTM-G32-77 standard.

Erodent = angular SiC particles (120-150 μm)

Impingement velocities = 20, 25, 30, 35, 40, 45, 50, 55, 65, 78, 90, 100, 110 and 120 m s^{-1} .

Impact angles = 15°, 30°, 45°, 60°, 75° and 90°.

Before erosion, samples were polished by diamond paste.

After each erosion test, surface was cleaned by ultrasonic wave method, mass loss measured to 10^{-5} g. Average of 3 data taken.

202-211 *Surface topography evolution during sliding wear of 2009 Al-Si Cp/17.4 PH.*

A.P. SANNINO & H.J. RACK

Wear testing by pin-on-ring configuration.

Tribology experiments followed ASTM G 99-90 specifications with relative velocity between surfaces, load applied on pin, sliding distance and environment (atmosphere, humidity and temperature) fixed throughout test period.

Normal load = 14.2 N; sliding velocity = 0.36 ms^{-1} ; sliding distance = 3600 m; environmental conditions: Air, 50% humidity, 25 °C.

The wear tests were carried out in an incremental manner, ie 1000 rotations per increment and 10000 rotations in total. After each increment, wear debris was collected, the DRA (discontinuously reinforced Al) pin and stainless steel disc were cleaned in acetone, weighed in a balance to 0.01 mg and then remounted in the wear tester at same location.

212-221 *The growth and bonding of transfer film and the role of CuS and PTFE in the tribological behaviour of PEEK.*

J. VANDE VOORT & S. BAHADUR

Friction and wear tests - four station pin-on-disc machine with the stationary polymer pin in contact with a rotating steel disc. Polymer pins 15 mm long with contact surface 5 mm x 6 mm. Tool steel disc (AISI 02) 77 mm diameter x 5 mm, finished by abrasion against emery paper to a surface roughness of 0.11 $\mu\text{m Ra}$.

Tests conducted under dry ambient conditions in a track diameter of 63 mm; sliding velocity = 1 ms^{-1} ; load = 19.6 N. Wear measured at specific intervals by weighing pins to 0.0001 g.

Friction force measured from output of a pair of strain gauges mounted on the arm supporting the pin. For each condition mean taken of 2-4 tests. Variation of coefficient of friction was ~ 20%; of wear was ~ 30%.

222-226 *Oxidation and its influence on low pressure polyethylene wear.*
Yu.M. PLESKACHEVSKY, A.L. ZAITSEV & V.V. SMIRNOV

Friction tests of polyethylene on friction apparatus. Metal counter body oxidised.
Specific loads = 0.35 MPa, 2.5 MPa; sliding speeds = 0.6 ms⁻¹, 0.47 ms⁻¹, respectively, using shaft-partial insert & cylinder-cylinder systems.

The overlapping coefficient was 0.17-1, surface roughness of the steel roller was Ra = 0.5 µm, and for the hard alloy cylinder Ra = 0.025 - 0.03 µm.

227-235 *Studies of worn surfaces and the transfer formed in sliding by CuS-filled and carbon fibre-reinforced nylon against a steel surface.*
S. BAHADUR, D. GONG & J.W. ANDEREGG

Samples for XPS, SIMS and EDS analyses prepared by:
sliding between polymer (or PMC) pin loaded against steel disc, 0.5 mm thick, resting on flat surface of thick steel disc.

Load = 19.6 N, sliding speed = 1.0 ms⁻¹, duration = 10 h.

A thin disc was used as counterface so it could be cut to small size for examination. The transfer film on this surface was analysed by XPS and SIMS within 1-2 days of the sliding experiment.

236-240 *Friction of hydrogel and polyurethane elastic layers when sliding against each other under a mixed lubrication regime.*
L. CARAVIA, D. DOWSON, J. FISCHER, P.H. CORKHILL & B.J. TIGHE

Friction measured between slider (either flat or spherically ended), moving over flat layer (either the same material or different). Slider held at end of loading arm, pivoted on an air bearing; rotation of the arm was prevented by a piezoelectric force transducer which measured the friction force.

Deionised water was used in all the tests. The layer was fixed in a water bath which moved at a constant slow velocity and this was monitored by a displacement transducer (LVDT).

Full details of the friction apparatus are given elsewhere (Caravia et al 1993). Each friction test consisted of lowering the loaded slider onto the layer, allowing a measured time period of between 5-400s to elapse and then initiating sliding. 7 tests were carried out and the mean coefficient of friction and sample standard deviation were calculated. The results for different material combinations were then compared statistically using a one sided analysis of variance and student's test.

241-249 *Wear mechanisms of UHMWPE in total joint replacements.*
A. WANG, D.C. SUN, C. STARK & J.H. DUMBLETON

Wear tests were performed using three multi-station reciprocating ring-on-flat wear machines. The load configuration is shown in the diagram. The wear machines consist of 32 individual specimen chambers which are connected to 32 individual reservoirs each containing 300 ml of diluted serum solution and a soak control specimen.

During the test, the serum solutions were circulated between specimen chambers and reservoirs so the test temperature was always equal to the ambient of 21 °C.

Rectangular UHMWPE specimens (19 mm x 12.7 mm x 13 mm) were loaded against a cast CoCr wheel (71.9 mm diameter, 25.4 mm wide) which oscillated around a 60° arc.

Wheels were twice as wide as samples to eliminate edge contact. Wheels were highly polished to 0.05 µm Ra.

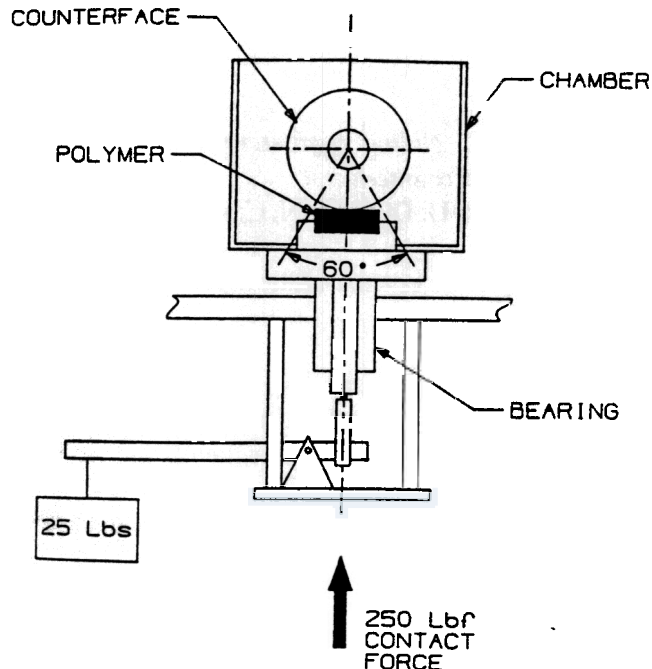


Fig. 4. Schematic of the loading configuration for the multi-station reciprocating ring-on-flat wear machines.

The applied load of 250 lbs (1100 N) gave rise to a maximum Hertzian contact pressure of ≈ 3000 psi (≈ 20 MPa) at the start of the test.

At weekly intervals, all test and soak-control specimens were taken out of test chambers, cleaned, dried and weighed to 0.01 mg. Test chambers and reservoirs were cleaned and filled with fresh serum solution. Then test continued until 5 million cycles. 3 specimens were tested for each group.

All polymer specimens were presoaked in the same serum solution at room temperature for 6 weeks prior to wear testing.

250-257 *The influence of contact stress on the wear of UHMWPE for total replacement hip prostheses.*

P.S.M. BARBOUR, D.C. BARTON & J. FISHER

Previous studies:

Rostoker & Galante, 1979 - metal disc on polymer block with distilled water as lubricant.

Rose et al, 1983 - metallic ball sliding over polymer plate with biological lubricant - more representative of knee than hip.

McKellop et al, 1978 - polymer pin or plate with serum lubrication at lower stress range (3.45 and 6.90 MPa) - more representative of hip.

Present study: Pin on plate.

Test 1: Stress levels = 7.8, 18.6, 28.3 MPa; load = 80, 160 & 240 N with contact face = 3.4 mm diameter, lubricant = bovine serum.

Pins 12.5 mm long by 12.5 mm diameter One end machined at an angle of 30° to form truncated cone.

Test 2: Stresses 3.4, 7.1 and 11.4 MPa, contact face = 5.3 mm diameter, lubricant = bovine serum.

258-262 *Wear of UHMWPE sliding against untreated, titanium nitride-coated and 'Hardcor'-treated stainless steel counterfaces.*

B. DERBYSHIRE, J. FISCHER, D. DOWSON, C.S. HARDAKER & K. BRUMMITT

Three tests were carried out using a six-station pin-on-plate reciprocating machine (described Derbyshire et al 1994).

Test 1: 2 TiN-coated and 3 standard stainless steel plates installed in reciprocator baths.

Test 2: 'Hardcor'-treated and 3 standard stainless steel plates.

Reciprocator baths contained de-ionised water, levels maintained by dripfeed.

Test 3: 2 TiN-coated, 2 'Hardcor'-treated and 2 standard stainless steel plates - baths containing bovine serum.

Each test pin loaded to 80 N, nominal contact stress = 12 MPa. An unloaded soak-control pin accompanied each test pin during the test so that changes in test pin weight due to random fluctuations in liquid absorption could be compensated.

Pins removed and cleaned at weekly intervals. Tests run for 260-400 km with a stroke length 40-44 mm corresponding to peak sliding speed = 0.31-0.35 ms⁻¹.

Wear volume loss calculated from weight loss assuming density of UHMWPE. Mean and standard deviation of wear factors calculated and means statistically compared using 'students t-test' for both lubrication conditions.

263-270 *Sliding wear behaviour and microstructure change of deformation-processed Cu-20 vol%Nb in situ composite.*

Z. CHEN, P. LIU, J.D. VERHOEVEN & E.D. GIBSON

Dry sliding test on pin-on-disc wear tester.

Cu-Nb composite pin against steel disc.

pin - rectangular section 1.57 x 10 mm.

Average diameter of wear track - 88.5 mm; disc rotated at 600, 800, 1000, 1200 and 1400 rev min⁻¹. Sliding speed 2.78-6.49 ms⁻¹.

Normal mechanical load 0.98-8.82 N; normal pressure 0.06-0.56 MPa

Volume loss used for wear rate.

271-279 *Microstructural properties of wear-resistant alloys.*

H. BERNIS

Microindenting. Microscratching.

280-289 *The competing wear mechanics and wear maps for steels.*

L. RAPOPORT

Pin-on-disc machine, sliding velocity = 0.67 ms^{-1} . Friction coefficient, wear loss and temperature measured. Experiments lasted $3.6 \times 10^4 \text{ s}$; and $6.8 \times 10^3 \text{ m}$; discs weighed to $0.1 \text{ }\mu\text{g}$. Pin and disc of similar steel, discs quenched and tempered to different hardnesses.

Tests carried out at same normalised force to obtain comparable results.

Normalised force = 5×10^{-4} , 1.6×10^{-4} , 2.8×10^{-4} , 4×10^{-4} , $5 \times 10^{-4} \text{ N}$.

290-301 *Sliding behaviour of Pb-Sn alloys.*

X.J. WANG & D.A. RIGNEY

Steel ball against rotating Pb-Sn alloy disc.

Diameters: disc = 25.4 mm, ball = 6.4 mm; disc thickness = 6.4 mm.

Before testing, sliding surfaces of discs polished using $0.05 \text{ }\mu\text{m Al}_2\text{O}_3$.

Balls and discs cleaned in ultrasonic cleaner using acetone and then distilled water.

Friction force measured by 4 strain gauges arranged in full bridge system.

Most tests in vacuum, some in air, Ar-5% H_2 , N_2 and with mineral oil.

A low sliding speed, about 10 mm^{-1} , was used, so the increase in temperature from sliding friction was small. The normal load was 0.1-1.0 kg and the sliding distance was 10-2000 cycles (0.5-100 m).

Sliding surfaces and sections were characterised by optical microscopy and SEM, microhardness was tested, wear debris was analysed by XRD and TEM.

302-311 *Dry sliding wear mechanisms in a $\text{Ti}_{50}\text{Ni}_{47}\text{Fe}_3$ intermetallic alloy.*

J. SINGH & A.T. ALPAS

Dry sliding wear block-on-ring. Rectangular blocks $5 \times 10 \times 10 \text{ mm}^3$ slid against bearing steel ring. Applied load varied in steps 2-400 N at constant sliding speed 0.4 ms^{-1} . Or sliding speed $0.04\text{-}6 \text{ ms}^{-1}$ with constant applied normal load = 20 N. Weights of both block and ring measured at intervals to determine weight loss as function of sliding distance. Surfaces were characterised by SEM and XRD of wear tracks and debris.

312-324 *The effect of alumina fibre reinforcement on the wear of an Al-4.3%Cu alloy.*

C. PERRIN & W.M. RAINFORTH

Wear testing on tri-pin-on-disc (full details Rainforth et al 1992). Employs three 1 cm diameter pins with truncated cone machined at one end, providing 3 mm diameter contact face. Pins were held in a top plate which was prevented from rotating by two half-bridge strain gauges, which measured the friction coefficient, while the annular disc rotated. Only a few mm of pin projected from the top plate surface so there was maximum system stiffness. The head was placed on top of the disc, located by a central spindle. Loads were applied by dead weight secured directly to the top plate containing the pins.

Polishing of pins and counterface disc to $R_a < 0.1 \text{ }\mu\text{m}$.

Tests were conducted for both dry and conventional mineral oil lubricated sliding conditions as a function of normal load. Wear factor was calculated by $\text{weight loss} = \text{volume removed} / \text{unit load} / \text{unit sliding distance} (\text{mm}^3 \text{N}^{-1} \text{m}^{-1})$.

DRY: sliding speed = 1 ms^{-1} , sliding distance = 10 km; loads = 6, 15, 23, 30, 40 N/pin.

LUBRICATED: sliding speed = 1 ms^{-1} ; sliding distance = 500 km; loads = 40, 70, 100, 130, 160 N/pin.

325-333 *Self-formation of protective oxide films at dry sliding mild steel surfaces under a medium vacuum.*

H. KONG, E.-S. YOON & O.K. KWON

Friction and wear measured with ball-on-disc wear-rig. Applied for Korean Patent (K 1003) 1994 for *A wear-rig for measuring friction and wear under special environments*.

Vacuum chamber constructed of stainless steel and evacuated by mechanical and diffusion pumps. Specimens: Disc 110 mm diameter, 6 mm thick and 12.7 mm ball. The disc specimen is mounted on a main spindle driven by AC servo motor connected to magnetic coupling. Rotational speed regulated by servo motor controller. During disc rotation, ball slides on constant diameter track, sliding velocities up to 10.0 ms^{-1} . Normal load applied to ball and for linear motion of the loading device under vacuum a linear bearing and stainless bellows assembly are incorporated.

Friction force measured with strain-gauged load cell, which restrains rotational movement of the ball holder at right angles to the deadweight loading. Test disc polished to $0.1 \mu\text{m Ra}$.

All tests - dry sliding surfaces, speeds $0.1\text{--}1.0 \text{ ms}^{-1}$, normal loads 4.9–29.4 N for fixed sliding distance = 3600 m. Wear volume calcd by measuring average width of wear track on the disc with optical microscope.

334-341 *Surface durability of steam treated sintered iron alloys.*

A. MOLINARI & G. STRAFFELINI

Disc on disc apparatus (Amsler type machine) in dry conditions, counterface discs of AISI 4340 steel. All discs 40 mm diameter, 10 mm thick. Sliding speed = 0.314 ms^{-1} , distance = 1420 m. Normal load = 100–15 N. Average of 3 specimens tested at each load. Friction coefficient was continuously recorded. Wear investigated by optical microscopy, SEM, EDXS and mass loss.

342-349 *Abrasion resistance of the columnar zone in high cr white cast irons.*

Ö.N. DOGAN, G. LAIRD & J.A. HAWK

Abrasive wear resistance, pin abrasion test (Blickensderfer & Laird, 1988) designed to simulate high-stress abrasion. Rod samples 0.635 cm diameter, abraded on 150 mesh ($105 \mu\text{m}$) garnet cloth, applied load = 66.7 N. Pin of ASTM A514 type B steel abraded on adjacent path on same garnet paper. Each test run for 8 drum revolutions, distance = 12.8 m, weight loss measured, analysis by SEM.

350-359 *Utility and limitations of tribosimulation for quality control and material preselection.*
E. SANTNER & G. MEIER ZU KÖCKER

Pin-on-disc test (for pin-on-disc simulation).

Discs - steel, pins PTFE, diameter of 4mm, load = 10 N, sliding velocity = 0.1 ms^{-1} , room temperature, laboratory atmosphere of 50% relative humidity.

Mean contact pressure = 0.8 N mm^{-2}

Friction coefficient of material which performed well in practice = 0.39 and of the material that didn't = 0.65.

360-370 *Microtribology of metal particle, barium ferrite and metal evaporated magnetic tapes.*
B. BHUSHAN & V.N. KOINKAR

Microscratching, microwear and nanoindentation hardness measurements used 3-sided pyramidal single-crystal natural diamond tip with an apex angle of 80° and tip radius of 100 nm, load $10 \mu\text{N}$ - $150 \mu\text{N}$.

Diamond tip mounted on gold coated stainless steel cantilever beam with normal stiffness $\sim 30 \text{ Nm}^{-1}$. For scratching and wear studies, the sample was scanned in a direction along the axis of the cantilever beam at a scanning speed of $1 \mu\text{ms}^{-1}$ (0.5 Hz). An area of $2 \mu\text{m} \times 2 \mu\text{m}$ was scanned at various normal loads for selected number of cycles. Ambient atmosphere $22 \pm 1^\circ\text{C}$, $45 \pm 5\%$ relative humidity and Class 10000.

For comparisons, macroscopic friction measurements were made using a reciprocating friction tester (BUSHAN 1990). 8 mm wide tape segment ($\sim 20 \text{ mm}$ long) reciprocated over a smooth Mn-Zn ferrite rod ($\sim 5 \text{ nm rms}$) with a wrap angle of 30° , at a tape tension of 1.25 N and average speed of 28 mm s^{-1} .

Normal load required to reciprocate tape was measured. Coefficient of friction calculated using a belt equation.

371-378 *Dynamical analysis of the wear behaviour of steels during the pendulum single particle gouging wear tests.*
J. JIANG, M. YAO, F. SHENG & X. GAO

Test rig modified from commercial Charpy impact tester. Hammer equipped with radially protruding tip which cuts crescent-shaped groove in horizontal surface of specimen positioned at lowest point of pendulum swing.

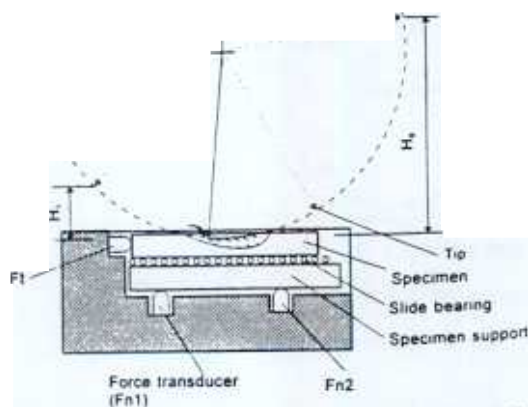


Fig. 1. Schematic diagram showing the configuration of the test rig.

The groove size is determined by radial position of tip and vertical position of specimen, both independently adjustable. Energy consumed in a grooving event determined from reduced upswing H_0-H_1 , of pendulum with help of standard gauge in tester. The tangential, F_t and normal F_{n1} and F_{n2} forces acting on specimen during grooving are measured using load transducers, made of epoxy resin attached with strain gauges. F_t used to calculate wear energy consumed.

Pendulum input energy = 150 Nm; entry velocity = 3.13 ms^{-1} ; momentum = 939 Nms^{-1} .

Grooving tip of WC/Co in shape of square-based pyramid with 45° apex angle and tip truncated to flat $1 \times 1\text{ mm}$ surface. During grooving, tip oriented with a facet normal to grooving direction. Characterisation by profilometer, number of cross-sectional profiles. Volume of material removed at different distances calculated.

379-390 *Dry sliding wear of particulate-reinforced aluminium alloys against automobile friction materials.*
G.J. HOWELL & A. BALL

ARBOGA 2512 vertical drilling machine modified. Rotor materials attached to and revolve with drill spindle to wear against friction linings (stationary counterface). Torque cell beneath counterface continuously monitors frictional force at wear interface. Load applied through a leverage system using a load cell under the friction lining material to monitor and calibrate correct loadings.

Phase 1: load = 1.034 MPa (recommended in SAE J661a); sliding velocities = 0.52 ms^{-1} - 3.16 ms^{-1} , max 500 m.
Phase 2: loads = 517 kPa, 1.034 MPa. Speeds = $0.52\text{--}3.16\text{ ms}^{-1}$, max 500 m.

Both samples weighed to gauge wear/unit pressure/unit distance. Optical microscopy and SEM.

391-396 *Tribological transitions due to heat dissipation during braking on contaminated rails.*
A.R. SAVKOOR & H. OUWERKERK

Oerlikon test machine (Savkoor et al 1990).

Test configuration:

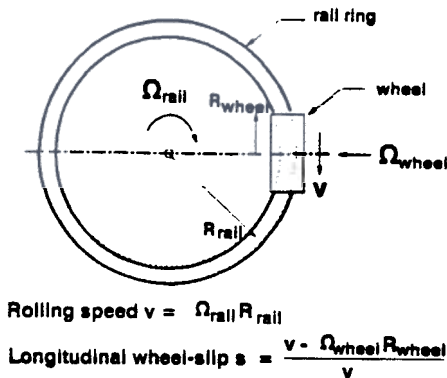


Fig. 1. Schematic representation of the test configuration (Oerlikon machine).

Simulates down-scaled contact configuration of railway wheel running on rails. Rail simulated by horizontally mounted ring, ~1.5 m diameter; top surface of typical rail profile. Test wheels 100-200 mm diameter. Wheels mounted on subframe and rotate in vertical plane. The small spin component of ring rotation is compensated by providing a small camber angle (tilt) of the wheel plane with respect to vertical (not shown in fig). Rail-ring and wheel both driven. Ring speed can be varied to achieve circumferential rail speeds 10-120 kmh⁻¹. Test wheel rolls on top surface of rail-ring under normal contact load adjusted by dead-weights. Both made of high carbon rolling stock steel, mean hardness ~280 W. Longitudinal slip of wheel set for test 0.80%. Friction behaviour with dry surfaces and contaminant solution.

397-404 *Using profilometry for the quantitative assessment of tribological function: PC-based software for friction and wear prediction.*

A.A. TORRANCE

Test apparatus for friction measurements. Standard rocker loaded against dummy camshaft having circular "cams" concentric with its axis. This maintains constant load between rocker and "cam".

Dummy camshaft held between headstock of lathe and dead centre mounted on tailstock. Rocker mounted on trunnions to ensure it aligns correctly to camshaft. Trunnion assembly mounted on 3-axis Kistler dynamometer fixed to saddle of lathe. Load can be applied to the rocker by tightening a screw against a spring.

Lubrication from small oil bath, fixed beneath cam. The dynamometer gives a continuous accurate read-out of normal and tangential forces which were recorded on a chart recorder. Before and after test profiles and hardness measured.

405-412 *Applications of scanning acoustic microscopy in analysing wear and single-point abrasion damage.*

P.J. BLAU & W.A. SIMPSON

Sliding wear tests - single crystal stainless steel alloy; polycrystalline intermetallic alloy. Single-point abrasion test, fine-grained ceramic SiC 30 x 20 x 10 mm tile, stainless steel single crystal of 20 mm diameter polished section.

Custom-designed reciprocating tester, normal force 2.0N, average sliding speed = 5 mm s⁻¹, stroke length 10 mm. Slider = high grade SiN ball, 9.53 mm diameter.

Ni₃Al-based intermetallic = polished disc subjected to unidirectional sliding in air against 9.53 mm diameter WC sphere in pin-on-disc apparatus at 650 °C. Normal load = 10 N; speed = 0.64 ms⁻¹ (description of apparatus in Blau & Devore 1991).

SiC tile polished with 1 µm diamond lapping paste. (hardness 39.5 GPa). A Revetest™ scratch testing machine (CSEM, Neuchâtel, Switzerland) was used with a spherically ended, conical diamond indenter, 0.2 mm tip radius. Specimen scratched with normal force of 20 N under room temperature conditions. Scanning acoustical microscopy.

413-416 *Lubricating mechanism of sulfurized olefin on Ni-P brush plating layer.*

Y. MA, Z. GU, Y. WU, J. LIU & L. ZHENG

Friction and wear tests on ball-on-disc machine. Disc rotating, ball stationary. Ball of AISI 52100 steel heat treated to HV 770, diameter = 12.7 mm, surface roughness $R_q = 0.025 \mu\text{m}$. Disc of AISI 1045 steel heat-treated to HV 401. $R_q = 0.41 \mu\text{m}$. The disc which was used as the base of Ni-P brush plating layer was heat treated to hardness HV 305 and then was treated by ion nitridation, because brush plating layers showed much better tribological behaviour on a nitrided 1045 steel substrate than on untreated substrate.

Non-cyclic lubrication: liquid paraffin or liquid paraffin with sulferized olefin to 3 wt% S.

Procedure for testing load carrying capacity: sliding speed set; 2 minutes running period under 120 N; then stepwise loading at a rate of 120 N per 30s. The load corresponding to a steep rise of friction coefficient was recorded as the scuffing point. P-V curves obtained by scuffing point is sliding speed. Friction coefficients calcd from measurement of friction force simultaneously with test of load carrying capacity.

Wear rate of discs determined at constant sliding speed 1 ms^{-1} , load 600 N, 30 minutes duration by measuring surface topography of wear track on disc. Average of 3-4 tests taken.

Analyses of lubricating films by AES and XPS.

417-425 *Sliding wear of a plasma-sprayed Al_2O_3 coating.*

J.E. FERNANDEZ, R. RODRIGUEZ, Y.WANG, R. VIJANDE & A. RINCON

Two block-on-ring friction and wear testers.

1. Alpha-LWF-1 tribometer shape and dimension of specimens:

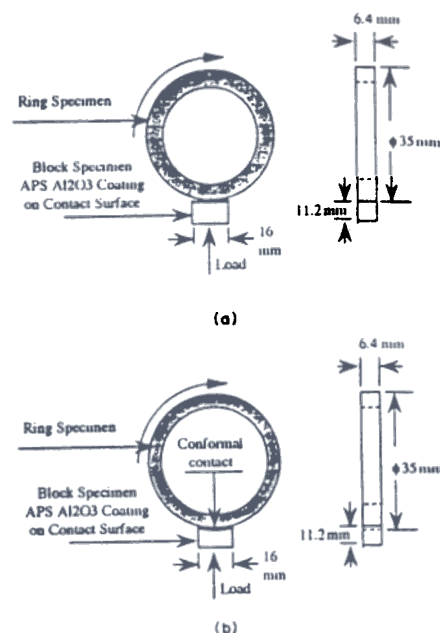


Fig. 1. Contact geometry of Alpha-LWF-1 Tribometer: (a) linear contact; (b) conformal contact.

speed range 0-200 rev m^{-1} (sliding vel range 0.0.366 ms^{-1}).

normal load scope = 0.-2000 N. coated block specimen was pressed against rotating steel ring specimen by normal load.

2. Self-made block-on-ring friction and wear tester. It has a conformal contact geometry of the specimens similar to b, with conformal contact area = 1 cm^2 , but larger diameter for the outer circle of the ring (diameter = 62 mm). The ring specimen is driven to rotate against the block specimen by a 4.3 kW DC motor. The speed of the ring can be varied 0-3000 rev min^{-1} (linear velocity 0-9.375 ms^{-1}). The block specimen is pressed against the rotating ring specimen by a lever loading system. Normal load ≤ 150 N dry; ≤ 1500 N lubricated. Friction forces are measured by a strain sensor fixed on an elastic arm. Mean taken of 3 tests for each data point.

426-435 *Wear at microscope scales and light loads for MEMS applications.*

U. BEERSCHWINGER, T. ALBRECHT, D. MATHIESON, R.L. REUBEN, S.J. YANG & M. TAGHIZADEH

Specimen-on-disc arrangement chosen. Supposed that microscopic wear can be simulated using a macroscopic test rig and specimens with contact areas and loads at microscopic scale.

Test rig - simultaneous investigation of several specimens, different materials, contact areas and loading. Up to 80 triangles worn at same time by placing them into cut holes in the specimen holder arranged in 5 circular tracks.

Different track for specimens with each surface coating. Max substrate speed = 15 rev/s; sliding vel = 0.29 ms^{-1} . Triangular macroscopic test specimens, 1.5 mm side length, variety of circular microstructures micromachined and range of coatings.

Contact areas = 20 μm^2 - 1 mm^2 ; contact pressures = 10⁶ MPa - 2 MPa. Substrate matl used as disc.

436-441 *The effect of cesium dioxide on the friction and wear properties of flame spraying nickel-based alloy coating.*

Y. LIAN, L. YU & Q. XUE

HQ-1 model block-on-ring friction and wear tester (similar to Timken, made in PRC).

Configuration:

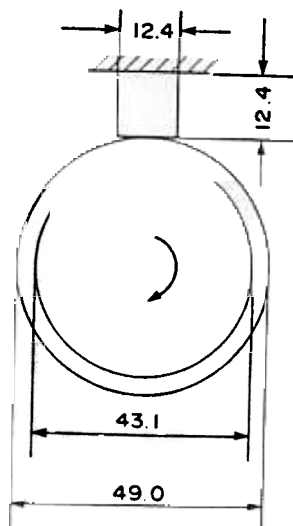


Fig. 1. The configuration of the specimens for the friction and wear test.

Upper specimen - block - stationary $19.0 \times 12.4 \times 12.4 \text{ mm}^3$.

lower specimen - ring - rotating, diameter = $49.0 \times 43.1 \text{ mm}$, bearing steel.

ambient, unlubricated conditions 200 rpm (linear = 0.51 ms^{-1}).

load 98 N or 196 N; duration 20 minutes.

wear measured by weight loss to $1 \times 10^{-7} \text{ kg}$.

Friction coefficient calculated by friction force/normal load. Friction force recorded automatically on strip-chart. Average of 3 data taken.

Analysis: XRD, Electron probe microanalysis, XPS.

Part 2

443-437 *Wear models and predictive equations: their form and content.*

H.C. MENG & K.C. LUDEMA

No testing done.

458-468 *A microstructurally based method for stress estimates.*

D.A. HUGHES, D.B. DAWSON, J.S. KORELLIS & L.I. WEINGARTEN

Flat plate friction on tester designed at Sandia, based on modified strip drawing process.

A long hardened 4340 steel counterface slider (platen) with a cross-section of 35 x 35 mm, is attached to a servo-hydraulic mechanical test machine. Two hydraulic pistons on opposing sides of the platen hold the copper test samples against the platen and apply a normal force to the copper-steel-copper sandwich. The platen is pulled down by the machine and sliding occurs. The test machine controls and measures sliding speed and distance, and normal and shear forces. It provides a known measurement of bulk normal and shear stresses as well as friction coefficient

Width and length (25 x 25 mm) of copper sliding surface less than platen to minimise edge effects.

Normal pressure: 12.0; 21.5; 16.7 MPa; sliding speed 25, 25, 0.25 mms⁻¹; sliding distance = 120 mm.

Analysis: SEM & EDAX, TEM.

469-475 *Wear-corrosion study of white cast irons.*

S.W. WATSON, B.W. MADSEN & S.D. CRAMER

Rotating cylinder-anvil apparatus (PIT 1988) to measure pure abrasion, corrosion and synergistic contributions of the processes on high carbon low-alloy steel.

Rotating cylinder wear specimens (diameter = 2.5 cm, length = 0.5 cm).

The rotation rate is controlled by a variable speed motor. Contact pressure applied by 2 opposing anvils: SiC rod of diameter = 0.84 cm, load $\leq$ 37 Kg through hydraulic loading system. Also polarisation cell for electrochemical experiments. Contact surface area was measured after each experiment so that the pressure on each anvil could be calculated (~42.7-54.5 MPa).

Analysis by: Potentiodynamic scans, SEM.

476-484 *Methods of measuring wear-corrosion synergism.*

S.W. WATSON, F.J. FRIEDERSDORF, B.W. MADSEN & S.D. CRAMER

Literature review and discussion. No testing performed.

485-494 *The erosion-corrosion of nickel-base diesel engine exhaust valves.*

C.G. SCOTT, A.T. RIGA & H. HONG

Engine tests using 8-cylinder diesel engine test procedure. Developed to evaluate factors known to influence valve failure in 2-cycle diesel engines, under controlled laboratory conditions. Each cylinder was fitted with 4 exhaust valves, giving a total complement of 32 valves.

495-499 *Inorganic tribosynthesis of solid lubricants under frictional interaction of refractory metals carbides and chalcogens.*

A.L. ZAITSEV & Yu.M. PLESKACHEVSKY

End-face friction apparatus. Friction of like hard alloy cylindrical specimen, diameter = 9 mm, observed in contact between flat bases of cylinders. Duration = 600 s to investigate relationship between load-speed performance and beginning of stable formation of tungsten chalcogenides.

Wear was measured by weight loss to ± 0.05 mg.

Analysis: X-ray, chemical, metallographic, optical microscopy.

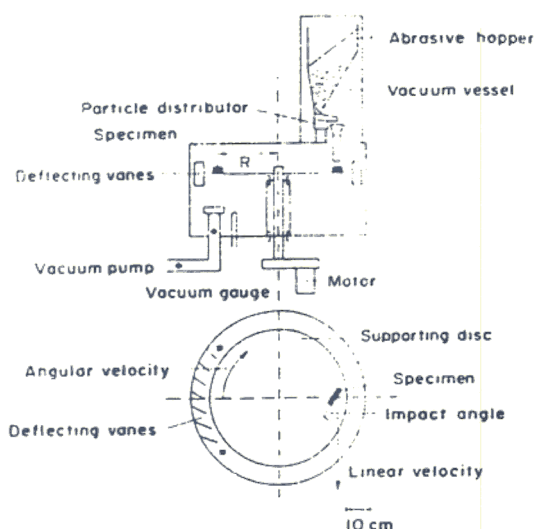
500-510 *Generalised law of erosion: application to various alloys and intermetallics.*

A. MAGNEE

Erosion tribometer: The samples are vertically displayed at the periphery of (and above) a horizontal disc on a homogenous circular motion. The disc contains rectangular notches to hold samples at an impact angle of 15-90°.

The impacting material flows through a controlled distributor at constant flow rate. Impacting material falls on the periphery performed by the rotating samples. The whole equipment is operated under vacuum.

Impacting mass, speed and angle were constant during the experiment.



511-515 *The cavitation erosion of Fe-Mn-Al alloys.*

S.C. CHANG, W.H. WENG, H.C. CHEN, S.J. LIN & P.C.K. CHUNG

Cavitation test: Ultrasonic vibration system model 184 V made by Branson Sonic Powder Company. Vibration at 20 kHz, amplitude = 50 μm . Disc samples diameter = 18.8 mm, thickness = 10 μm held below tip of horn in distilled water and 3.5% NaCl (aq).

516-523 *Computer simulation of erosion-corrosion interactions at elevated temps.*

M.M. STACK, Q. SONG-ROEHRLE, F.H. STOTT & G.C. WOOD

No testing performed.

524-530 *Analysis of fretting conditions in pinned connections.*

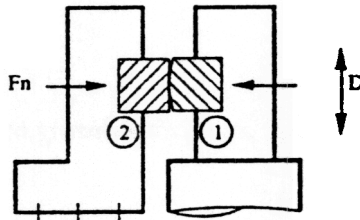
K. IYER, G.T. HAHN, P.C. BASTIAS & C.A. RUBIN

Finite element analysis. No testing performed.

531-536 *Mixed fretting regime*

Z.R. ZHOU & L. VINCENT

Fretting rig:



The normal force F_n was varied between 200 and 1000 N. The imposed displacement was varied from ± 8 to ± 100 μm . The tangential force versus the imposed amplitude can be measured as a function of the number of fretting cycles (frequency 1 or 5 Hz). Contact mode was a sphere (1) of radius 0.5 m, against a flat (2).

Examination was by optical microscopy and SEM of contact surfaces and cross-sections of specimens. Two aluminium alloys were used for the fretting tests.

537-543 *Single wire fretting fatigue tests for electrical conductor bending fatigue evaluation.*

Z.R. ZHOU, S. GOUDREAU, M. Fiset & A. CARDOU

The fretting fatigue rig is actuated by a motor-eccentric system (1). A slider (2) is connected with the eccentric and can move horizontally. A strain gauged clamp (3) is fixed to the slider and holds one end of the Al wire specimen. The other end of the specimen, about 1 m long, is

with gauged clamp (4), fixed to framework (5). Displacement amplitude is controlled by eccentric (1) and can be varied by switching shafts. Eccentricities 100-900 μm have been used.

A static tensile load is imposed on the Al wire. It is adjusted via the screw-spring system (6), with the eccentric in the zero position (the initial displacement is equal to zero). After that, the Al wire is fixed by a frame (5). The static tensile stress could be any value compatible with the material strength. Initial minimal level kept constant at 59 MPa. A transverse load is imposed through a loading screw (7). Its value is given by load cell (8), located on plate (9). High precision rods (10) are used to ensure proper, frictionless, vertical motion of the loading system. The load is applied to the wire with two cylindrical blocks (11). Their radius of curvature has the same value (0.35 m) as the one measured on the keeper edge. They are made of aluminium with a yield strength of about 1.7 times that of the aluminium wire specimen.

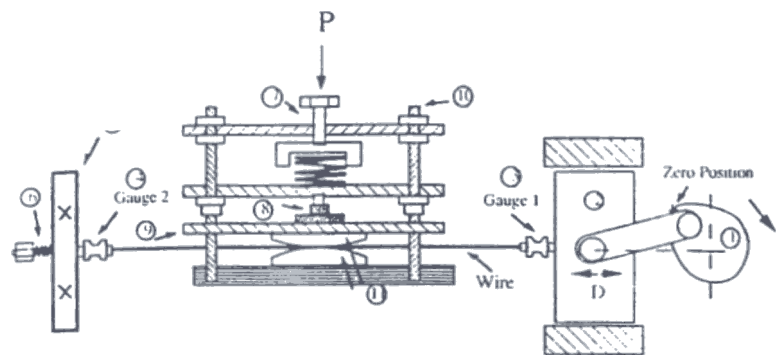


Fig. 5. Fretting fatigue test bench.

544-550 *Observations on the role of the steel disc counterface during the sliding of various structural ceramics.*

A. RAVIKIRAN & B.N. PRAMILA BAI

Ceramic pins were slid against a steel disc.

Pin-on-disc machine:

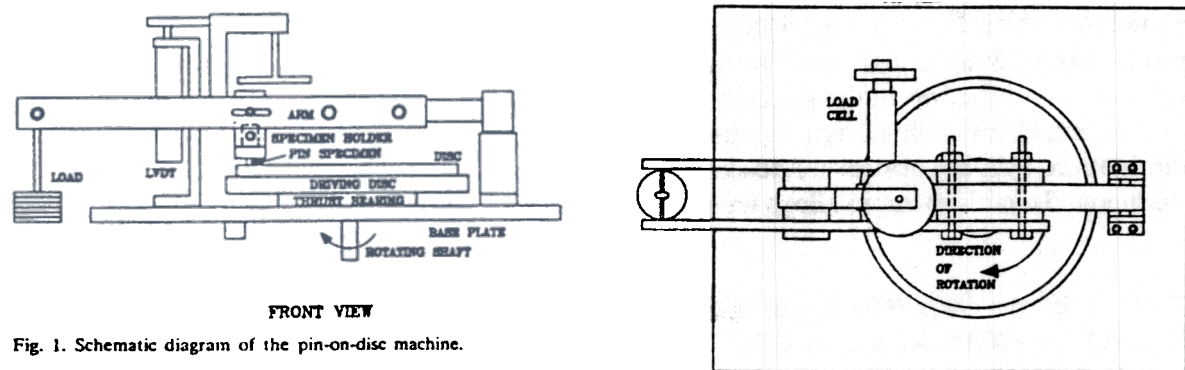


Fig. 1. Schematic diagram of the pin-on-disc machine.

Applied pressure: 15.5 MPa, speed range = $0.1\text{--}12.0\text{ ms}^{-1}$ in ambient air, friction force and displacement measured continuously using a load cell and linear variable differential transformer. Observation by optical microscopy and profilometer.

551-562 *Damage processes in ceramics resulting from diamond tool indentation and scratching in various environments.*

A.W. RUFF, H. SHIN & C.J. EVANS

A specially designed nanoindentation and scratching system was used. It involved an electromagnetic driver with attached diamond tool (indenter) and a position-determining eddy current sensor.

563-570 *Dry sliding wear of Al alloy 2024 - Al_2O_3 particle metal matrix composites.*

M. NARAYAN, M.K. SURAPPA & B.N. PRAMILA BAI

Pin-on-disc, cylindrical pin specimens diameter = 8 mm, length = 20 mm against a steel disc. Step loading at constant speed = 1.5 ms^{-1} . At each incremental load of 10 N the pin was slid for 1 min. Experiments were repeated 3 times for each data point.

Worn surfaces and debris examined by SEM - sub-surfaces were examined in cross-section.

571-580 *Tribological behaviour of silicon nitride materials under unlubricated sliding between 22°C and 1000°C .*

A. SKOPP, M. WOYDT & K.-H. HABIG

High temperature pin-on-disc tribometer.

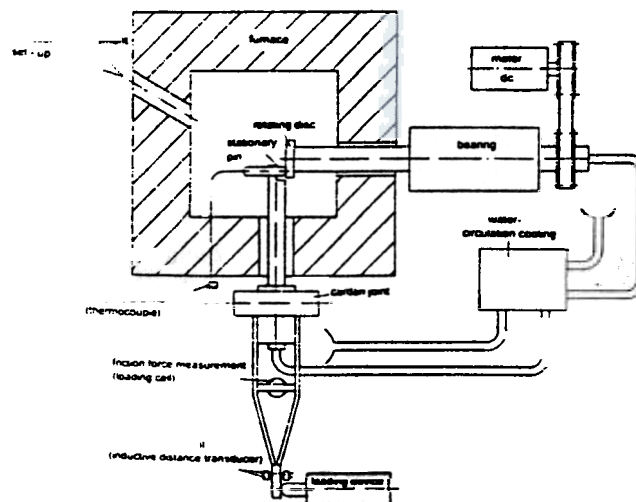


Fig. 1. High-temperature tribometer and test configuration.

Stationary pin against rotating disc, both of specimen material. 8 commercially available silicon nitride materials tested.

Tests up to sliding distance = 1000 m.

Sliding velocity = 0.03, 0.1, 0.3, 1 and 3 ms^{-1} . Load = 10 N.

Temp = 22, 400, 800 and 1000 °C.

Friction force, total linear wear and furnace temperature measured continuously.

Wear volume calculated from wear scar dimensions and profilometric measurements.

581-593 *An exploratory study of vapour-phase lubrication of ceramics by monomers.*

J.C. SMITH, M.J. FUREY & C. KAJDAS

Vapour-phase tribopolymerisation experiments on a modified pin-on-disc machine. Fixed ball against rotating disc, both alumina. Dry nitrogen carrier fluid carrying liquid monomers vaporised using vacuum trap arrangement.

Test conditions: ball of 3.2 mm diameter, disc of 25 mm diameter.

Lubricant = vapour of selected vinyl monomers in dry nitrogen gas; variable lubricant delivery temperature; applied load = 5 N, sliding velocity = 0.25 ms^{-1} , sliding distance = 500 m; ambient temp = 20 °C, variable bulk temperature.

Wear scar analysed by optical microscopy. The wear volume lost was calculated, profiles measured using profilometer; 4 traces were taken for each track. Selected surfaces were examined using a Nicolet 6000 fourier transform infrared microspectrometer (FTIRM) coupled with a Spectra-Tech IR Plan sampling microscope with a x15 Cassegrain objective.

594-602 *Sliding wear behaviour of SiC whisker-reinforced aluminium composite.*

Y. IWAI, H. YONEDA & T. HONDA

SiC - Al composite disc diameter = 30 mm, thickness = 5 mm, rubbed against steel pin, flat surface diameter = 4 mm, under dry conditions.

Test environment: 30 °C, and 70% relative humidity in air.

Surface roughness of both specimens ~ 0.1 $\mu\text{m Ra}$.

Frictional force was measured by bending strain of a cantilever attached to the pin holder. The displacement of the pin was continuously measured with a laser displacement meter to detect variations in the wear process.

Mass loss was measured to 0.01 mg and converted to volume loss.

Worn surfaces and wear particles were observed by SEM, electron probe microanalysis (EPMA), XRD and XPS.

603-612 *The effect of humidity and electrical fields upon the wear of high density polyethylene and polytetrafluoroethylene.*

A. McNICOL, D. DOWSON & M. DAVIES

Tri-pin-on-disc test machine.

3 polymer pins 10 mm length, diameter = 9.5 mm with truncated conical form at one end.

Initial circular wearing face diameter = 3 mm.

3 pins in steel sample holder, equidistant on circumference of circle diameter = 76 mm, loaded against rotating stainless steel disc.

The 3 sample pins ran on the same wear track. Normal force applied using dead weights placed directly onto sample holder.

Test conditions - extreme humidities.

A dc power supply was connected between sample holder and counterface inducing an electrical field normal to counterface and parallel to the sample pins. The field could be applied in either direction.

Load 120 N (40 N pin⁻¹), rotational velocity = 60 rpm (0.24 ms^{-1}).

Counterface roughness = 0.012 ± 0.002 .

Representative of hip joints.

Wear determined by mass loss, average of 3 pins in same test.

Volume loss calculated.

A radial surface profile and at least 4 radial, and latterly tangential, surface roughness (Ra) and mean asperity slope measurements of the wear track were taken initially and at each step using a Rank Taylor Hobson Talysurf 5 profilometer.

613-623 *Study on tribological behaviour of plasma-treated PEEK and its composites.*

R. ZHANG, A.M. HAGER, K. FRIEDRICH, Q. SONG & Q. DONG

Pin-on-ring testing machine. PEEK-based pin 4 mm x 4 mm x 10 mm. Steel ring roughness 0.1-0.2 μm CLA.

Sliding friction coefficient and specific wear rate were measured.

Wear was monitored with displacement transducer to 1 μm .

Friction coefficient was determined by measuring the normal load with a load cell and frictional torque with a torque transducer.

Load pressure = 1 MPa, sliding speed = 1 ms^{-1} , temperature = 25 °C, time = 1h (or 1 day).

The friction coefficient was calculated as an average of 5 one hour tests and 2 one day tests.

Mean specific wear rate was taken as an average of 2 one day tests.

Analysis: SEM, FT-IR spectroscopy, differential scanning calorimetry.

624-631 *On sliding friction and wear of PEEK and to composites.*

Z.P. LU & K. FRIEDRICH

Pin-on-disc test machine at temperatures below and above room in a temperature chamber.

Pins of test material: stationary steel rings, roughness 0.2-0.3 μm Ra.

3 or more samples and average taken.

Examination by SEM.

632-637 *Microstructural variations and tribology of molybdenum-type high speed steel ion implanted with high current density nitrogen beams.*

A.V. BYELI, O.V. LOBODAEVA, S.K. SHYKH & V.A. KUKAREKO

Pin-on-disc friction tests without lubrication to measure wear resistance and friction torque.

Spherical pin of cubic boron nitride rubbed against stainless steel or iron disc.

Normal load = 12 N, linear velocity = 20 cms^{-1} , 10 measurements for every point.

Examination by optical microscopy, XRD.

638-647 *The influence of laser line hardening of carbon steel AISI 1045 on the lubricated wear against steel AISI 52100.*

H. VISSCHER, M.B. DE ROOIJ, P.H. VROEGOP & D.J. SCHIPPER

Pin sliding against plate. Pin is crowned roller as used in roller bearings. Mineral paraffin lubricant.

Reciprocating tribometer. Normal load = 500 N. Sliding velocities 15 and 60 mms^{-1} .

Normal load, sliding speed, temperature, sliding distance, friction force and wear depth measured continuously.

Samples weighed to 0.01 mg. Weight loss used to calculate volume loss.

Profile traced perpendicular to wear by stylus profilometer.

648-657 *The role of strain rate response in plane strain abrasion of metals.*
S.V. KAILAS & S.K. BISWAS

SiC wedges were allowed to indent polished test flats under normal load, then flats slid in horizontal plane. The inclined planes of the wedge symmetrical about plane normal to flat and sliding direction.

Load cell to measure tangential force.

Wedges angles 150°, 120° and 90° correspond to attack angles 15°, 30° and 45°.

Sliding speeds 1.66×10^{-5} , 1.66×10^{-4} and $1.66 \times 10^{-3} \text{ ms}^{-1}$.

Normal load, 148, 98 and 49 N, lubricated tests.

Experiments were repeated 5 times and average taken.

658-667 *Mechanism of seizure of aluminium silicon alloys dry sliding against steel.*
A. SOMI REDDY, B.N. PRAMILA BAI, K.S.S. MURTHY & S.K. BISWAS

Steel ball slid on aluminium silicon alloys at different temperatures, 25 °C, 100 °C, 200 °C and 400 °C.

Surface roughness of test block 0.1-0.2 μm CLA.

Steel ball diameter = 20 mm.

Velocity = $3 \times 10^{-3} \text{ ms}^{-1}$, normal load = 10 N.

Frictional force measured during scribing.

Average taken of 3 experiments.

ALSO pin-on-disc test. Pins diameter = 3 mm at rubbing surface slid against steel disc. Step loading method, 1 min sliding at each load, to obtain seizure load at a constant speed. Speeds of 0.8-7.0 ms^{-1} .

Examination by SEM and profilometry. SEM of cross-sections to observe sub-surface features and make microhardness measurements.

668-677 *Thermal mounding in high speed dry sliders: experiment, theory and comparison.*
M.D. BRYANT, J.-P. WANG & J.-W. LIN

Bush wear-testing machine.

Stationary carbon brush sliding against specially designed rotor tracks (radius 13.97 cm).

10-2500 rev min^{-1} with 20 N spring loads. Slider tracks were backed by either steel or polycarbonate; a copper alloy sheet 250 μm thick was bonded atop and supported by steel or PC layer. On the PC rotor, photoelasticity visualised the contact interface during sliding.

678-686 *Laboratory tests for wear of rail and wheel steels.*
D. MARKOV

Various Amsler-type testing machines for wear: MI-1, SMC-2, SMT-1.

Rolling-sliding friction with longitudinal slippage.

Rolling-sliding friction with constant friction force.

Rolling-sliding friction with lateral slippage.

Pure sliding friction.

687-690 *Combined influence of an inert gas environment and a mechanical action on a graphite surface*

F. ROBERT, D. PAULMIER, H. ZAIDI & E. SCHOULLER

Pin-on-disc in vacuum chamber. 10^{-4} Pa vacuum and pure Ar.

Graphite sample - disc; high speed tool steel as pin.

Initial roughness 2.4 and 2.1 $\mu\text{m Ra}$. $F_N = 4$ or 20 N, constant velocity = 0.03 ms^{-1} .

Wear particles examined by BET analysis.

691-699 *Wear of contact elements in electromechanical switches*

N.H. MYSHKIN, V.V. KONCHITS, Yu.E. KIRPICHENKO & L.V. MARKOVA

Cylinder-on-flat, 3 pairs of specimens simultaneously.

Parameters describing electrical, frictional and wear performances of contact pair recorded.

Reciprocating, cylindrical specimen: diameter = 2-35 mm, linear velocity = $5\text{-}30 \text{ mm s}^{-1}$

Contact resistance measured.

Wear rate determined by width of wear scar.

Examination by profilometry, optical microscopy, SEM and probe technique to estimate surface electrical conductivity.

700-716 *An integrated approach to the characterisation of surface wear, I Qualitative characterisation*

W.P. DONG & K.J. STOUT

3D wear analysis.

Looks at pin-on-ring, cylinder liner.

717-722 *Computer image analysis of wear debris for machine condition monitoring and fault diagnosis.*

T.B. KIRK, D. PANZERA, R.V. ANAMALAY & Z.L. XU

Abrasion (cutting wear particles), surface initiated fatigue (lamina-wear particles) and subsurface initiated fatigue (fatigue wear particles).

723-729 *Temperature fields in sliding contact by a hybrid laser speckle-strain analysis technique.*

M.A. SEIF & H.A. ABDEL-AAL

Rectangularly-sectioned pin specimen in dry sliding contact against rotating counterface disc in air.

730-742 *Impact wear of multiplated electrical contacts.*

P.A. ENGEL & Q. YANG

Impact wear tests - light pivotal laminar normally hitting specimen repetitively.

743-758 *Nanoindentation, microscratch, friction and wear studies of coatings for contact recording applications.*

B. BHUSHAN, B.K. GUPTA & M.H. AZARIAN

Ball-on-flat reciprocating.

Ball: diamond tip with 20 μm tip radius or sapphire ball diameter = 3 mm.

Coated silicon coupons reciprocated. Normal and frictional forces measured. Stroke length = 3.5 mm, frequency = 0.1 Hz, average linear speed = 0.7 ms^{-1} .

Normal force, $F_N = 10 \text{ m N}$, temperature = $22 \pm 1^\circ\text{C}$, relative humidity = $45\% \pm 5\%$.

759-765 *Erosion of surface coatings in hydrodynamic flows.*

B.J. BRISCOE, M.J. PICKLES, J.S. JULIAN & M.J. ADAMS

Radial flow cell - 2 parallel glass discs with fixed separation distance, sample deposit cast onto underside of upper disc.

766-770 *Lubricating properties of diamond-like coating.*

T.Le. HUU, H. ZAIDI & D. PAULMIER

Pin-on-disc in vacuum chamber, 10^{-4} Pa or introduced gas.

Steel substrate with DLC film attached to plate - rotating.

Linear velocity = 0.3 ms^{-1} , Normal force, $F_N = 6\text{-}10 \text{ N}$.

Pin of stainless steel, radius = 10 mm.

771-776 *Numerical descriptors for the analysis of wear surfaces using laser scanning confocal microscopy.*

R.V. ANAMALAY, T.B. KIRK & D. PANZERA

Surface analysis: coarse lapped, rough ground, milled.

777-783 *An investigation of the experimental conditions and characteristics of a nano-wear test.*

Z. JIANG, C.-J. LU, D.B. BOGY & T. MIYAMOTO

Point contact microscope. Diamond tip resolution < 1 nm, Normal force, $F_N = 0\text{-}2 \text{ mN}$.

784-789 *Effects of length, diameter and population density of tribological rolls on friction between self-rated silicon.*

E. ZANORIA, S. DANYLUK & M. McNALLAN

Ball-on-flat.

Flat: Single crystal silicon wafer 40 mm x 14 mm x 0.3 mm.

Sphere: polycrystalline silicon diameter = 0.635 cm.

Closed-end tube furnace with inlet for humid gas.

Slide distance = 2 cm, linear velocity = 1.5 cm s^{-1} .

Coefficient of friction measured as function of reciprocating cycles.

Examination by SEM.

SHORT COMMUNICATIONS

790-798 *Measuring the deformation of crystalline materials due to the impact of eroding particles.*
C. HENNING & D. MEWES

20 mm thick steel plates - specimens locally damaged by particle impacts.
Surface deformation measured by holographic interferometry.
Particles: bearing balls diameter = 2.4 mm, velocity = 25-35 ms⁻¹.

799-804 *Influence of a magnetic field on the wear and friction behaviour of a nickel/XC 48 steel couple.*
H. ZAIDI, L. PAN, D. PAULMIER & F. ROBERT

Pin-on-disc tribometer subjected to a magnetic field (perpendicular to rubbing surface).
Disc, diameter = 50 mm, 0.48% carbon steel.
Pin 5 mm x 8 mm section with flat end, nickel.
Wear loss measured by weight loss.
Duration 30 min - 1h, magnetic field = 0.5×10^4 Am⁻¹.
Sliding velocity = 0-1.5 ms⁻¹. Normal force, F_N = 0-10 N.
Analysis by SEM.

805-809 *IR study of the chemistry of boundary lubrication with high temperature and high pressure shear.*
C. WESTERFIELD & S. AGNEW

Specially designed diamond anvil reflection cell.
Steel pin rotated against diamond. Mineral oil, stearic acid, iron stearate, Lubrizol® 1095/
Lubricants.

810-820 *Weld overlay coatings for erosion control.*
B.F. LEVIN, J.N. DuPONT & A.R. MARDER

Erosion tester: particles in air stream.
Sample - weld overlay, 0.5 in x 0.5 in.
Temperature = 400 °C, erodant particle velocity 40 ms⁻¹, impingement angle 90° or 30° erodant,
angular Al₂O₃, 300 µm. Times = 5, 10, 20, 50 and 100 min.

CASE STUDIES

821-825 *Wear mechanism of a dental glass-ceramic.*
S. JAHANMIR & X. DONG

826-832 *Analysis of a tube-grid oscillatory contact: methodology for the selection of superficial treatments.*
J.M. VOISIN, A.B. VANNES, L. VINCENT, DAVIOT & B. GIRAUD

833-839 *Role of reinforcing ceramic particles in the wear behaviour of polymer-based model composites.*
J.M. DURAND, M. VARDAMOULAIS & M JEANDIN

840-843 *Case study of tribology at Tampere University of Technology: percussive rock drilling tube.*
T. HAKALA & A. RIITAHUHTA

844-849 *Measurements of real contact areas using PET films (thickness, 0.9 μm).*
I. NITTA

850-855 *Effect of oil additives on the performance of a wet friction clutch material.*
W. SCOTT & P. SUNTIWATTANA

856-861 *Fretting behaviour and porosity of Ti_2N coatings.*
K. De BRUYN, J.P. CELIS, J.R. ROOS, L.M. STALS & M. VAN STAPPEN

862-867 *Theoretical and practical aspects of the wear of vane pumps.*
Part A. Adaptation of a model for predictive wear calculation.
R. GELLRICH, A. KUNZ, G. BECKMAN & E. BROSZEIT

868-875 *Theoretical and practical aspects of the wear of vane pumps.*
Part B. Analysis of wear behaviour in the Vickers vane pump test.
A. KUNZ, R. GELLRICH, G. BECKMAN & E. BROSZEIT

876-882 *Failure analysis of the impeller of a slurry pump subjected to corrosive wear*
A. FAN, J. LONG & Z. TAO

883-888 *Machinability of a silicon carbide reinforced aluminium metal matrix composite*
J.T LIN, D. BHATTACHARYYA & C. LANE

889-896 *Tribological analysis and anti-galling design of ocean-floor pile reformation tool*
S.J. SHAFFER, W.A. GLAESER & J.T. OSTGAARD

897-900 *Acoustic emission in monitoring sliding contact behaviour*
J. MIETTINEN & V. SIEKKINEN

901-912 *The effects of machining conditions on the flank wear of TiN-coated high speed steel tool inserts.*
S.C. LIM, C.Y.H. LIM & K.S. LEE

913-921 *Load, speed and temperature sensitivities of a carbon-fibre-reinforced phenolic friction material.*
P. GOPAL, L.R. DHARANI, F.D. BLUM

922-937 *Amorphous and alloy film formation in sliding of silver on copper.*
M.S. BEDNAR & D. KUHLMANN-WILSDORF

938-944 *Abrasion resistance of transport roll surfaces.*
K.G. BUDINSKY