WEAR of MATERIALS 1989

Volume One

edited by
K. C. LUDEMA

Volume One
Pages 1-448

WEAR of MATERIALS 1989

presented at

THE INTERNATIONAL CONFERENCE ON WEAR OF MATERIALS
DENVER, COLORADO
APRIL 9-13, 1989

sponsored by

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
THE AMERICAN SOCIETY FOR TESTING AND MATERIALS
ASM INTERNATIONAL
THE AMERICAN CERAMIC SOCIETY
THE SOCIETY OF TRIBOLOGISTS AND LUBRICATION ENGINEERS
THE METALLURGICAL SOCIETY — AIME

edited by

K. C. LUDEMA
UNIVERSITY OF MICHIGAN

THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
United Engineering Center 345 East 47th Street New York, N.Y. 10017

ISBN No. 0-7918-0304-X

Library of Congress
Catalog Card Number 77-72209

FOREWORD

A need for a conference specifically devoted to the subject of wear was identified in the mid-seventies. It was felt that such a conference would provide a forum which could enhance and foster the understanding of wear and related phenomena. Out of these considerations the International Conference on Wear of Materials was born. The current Conference is the seventh in the series which began in 1977, in St. Louis, Missouri.

Recently I had the occasion to review the Proceedings of the six prior Conferences. I went through, paper by paper, noting the titles, reading most of the abstracts, and scanning many of the papers. What I found in the course of this activity impressed me and, I believe, demonstrates that the Conference series has satisfied the primary goal. It has provided an effective forum which has contributed to the knowledge and understanding of wear.

These volumes are a chronicle of the trends in wear research and understanding. Contributions from most, if not all, of the recognized leaders in tribology can be found in their pages. One can easily trace the evolution of ideas and concepts regarding wear through these volumes, as well as the scientific debate that is a healthy and needed element. There are papers contained in one volume that address points and challenges associated with a paper in a prior volume. Advances in experimental techniques and improvement in methodology and discipline are also quite apparent. On the practical side, there is evidence of change. A growing number of examples of correlation between laboratory tests and actual performance is being accumulated, as well as the success of modeling approaches to engineering problems. If you have the time, I would suggest a similar review of the Proceedings of the prior Conferences. I think you will find it interesting.

While I have not had the opportunity to review the current Proceedings in a similar fashion, I have had the opportunity to see many of the abstracts that were submitted. I feel comfortable that the current Proceedings will continue this chronology.

The Proceedings are only one aspect of the Conference. The sessions, themselves, and the informal discussions that occur throughout the Conference contribute to the value and mission of the Conference as well. The present Conference has 18 formal sessions of received papers covering both experimental and theoretical areas of wear studies, engineering and research-oriented aspects, and wear behavior of different material systems. In addition, there are several other types of sessions as well.

In 1987 a tutorial session on wear was added to the program to enhance the value of the Conference and is part of the 1989 Conference as well. Bill Ruff, Bill Glaeser, Ken Budinski, and I have again taken the role of instructors in this program. New with the current Conference is the addition of a Poster Session, including a micrograph competition, sponsored by ASM International. It is hoped that this will provide another effective means of technical exchange and interaction and, if so, become a permanent feature.

At this Conference, we have five invited speakers whose participation we greatly appreciate and welcome:

- T. E. Fisher — "Scientific Issues in the Tribology of Ceramics"
- A. W. J. DeGeė — "Wear Research for Industry: Examples of Application of the IRG Transition Diagram Technique"
- K. Kato — "Basic Studies of Micromechanisms in Wear"
- H. Czichos — "VAMAS Update"
- J. Dodd — "A Century of Progress and Set-Backs in the Development of Wear Resistant Alloys"

The first four are given at plenary sessions, the fifth is at the Conference Dinner.

While I have the honor of being the Chairman of this 1989 Conference, it is not the result of my singular effort but the result of a large team. First of all I would like to acknowledge the efforts of the Steering and Planning Committees Members in this activity:

D. Rigney, Vice-Chairman and Steering Committee Member
O. Vingsbo, Program Chairman and Steering Committee Member
R. Blickenderfer, Secretary and Steering Committee Member
K. Ludema, Editor and Steering Committee Member
A. W. Ruff, Steering Committee
W. Glaeser, Steering Committee
S. K. Rhee, Steering Committee
S. Bahadur, Steering Committee

The activities of the Paper Solicitation Coordinators are recognized and appreciated:

P. A. Swanson	N. S. Eiss, Jr.
J. Larsen-Basse	C. S. Yust
P. Blau	T. Mathia
A. W. J. DeGee	B. Briscoe
H. Czichos	K. Tanaka
D. Dowson	H. M. Hawthorne
C. Allen	A. Sethuramiah
K. H. Zum Gahr	T. Sasada
Q. D. Zhou	J. J. Liu
Q. J. Xue	V. A. Belyi

In addition, the efforts of Dr. Peter Blau, in arranging and coordinating the Poster Session, are gratefully acknowledged.

I and the Committee would like to express our thanks to the ASME Staff, in particular Ms. Leslie Friedman and the Technical Publishing Department for their help in organizing and arranging the conference. Our thanks and recognition also go to our sponsoring and supporting societies: ASME, ASTM, ASM International ACerS, STLE, TMS-AIME. I want also to express my thanks to Ms. J. Stark, my secretary, who has helped me in performing my duties.

Finally I would like to express my thanks to all those presenting, attending, and acting as session officers. Without your participation, the conference would not be a success.

R. G. Bayer
Chairman, 1989 Conference
Senior Engineer-Project Manager
IBM Corporation
Endicott, New York

THE EDITOR'S PAGE

These Proceedings of the seventh biannual Conference on Wear of Materials contain 96 papers of very high quality. I thank the 194 authors and co-authors for their excellent work, and for their patience in enduring the editor's hasty pen. The 127 reviewers also deserve thanks for (usually) supporting that pen! They are listed at the end of these paragraphs. Two reviewers did so much work that they should be classified as Associate Editors, and they were Rob Blickensderfer and Bill Ruff.

This, the "seventh" event has the ring of completeness, and it may be well to review what has been accomplished. These conferences began with two attempts in the early 70's within the ASME Lubrication Division to organize conferences on wear. The topic of wear was still mysterious at that time, and had no particular home. The Wear Committee of the Lubrication Division recognized the importance of doing something about wear, but their major focus was on wear as the *failure of lubricants* more than on wear as a *loss of material*. Each approach uses very different methods. In due time, the latter approach prevailed in the organizing of the first of this series of conferences (in 1977). However, it soon became apparent that the naming of the series, Wear of Materials, attracted a very different following than do conferences related to lubrication. The result has been that the Wear of Materials conferences became rather detached from the Lubrication (now Tribology) Division of ASME. In fact, few authors send papers from these conferences to the Journal of Tribology (of the ASME) whereas about a quarter of the papers are sent to Wear Journal.

These conferences were organized and conducted in a manner that is not widely used. Specifically the intent was to achieve the following:

(1) shorter than usual time from submission of manuscript to publication;
(2) full peer review of all papers presented at the conference;
(3) complete and bound proceedings available at the conference.

You may have noted that the Editor's Page of previous conferences contained information on how many papers were reviewed and what transpired in the review process each time. The statistics for this conference are given in the table below. We publish this information to emphasize the point that although these are *conference* papers, they are actually reviewed and more rigorously so than are papers in archival journals. For some supervisors and members of faculty review committees the important number is the % of the submitted papers that were accepted. This usually stands at about 70%. Accordingly, for the 1989 Proceedings

211	abstracts were submitted
20	abstracts were rejected (inappropriate topics)
191	papers were invited
35	manuscripts never came
156	manuscripts came in
7	were withdrawn by the authors before review
149	were read by the editor
15	were rejected by the editor and not sent out for review
134	were sent out for peer review, of which 30 were rejected
15	were accepted as written, of which 1 was withdrawn
41	were revised slightly by the author and accepted
	48 required extensive rewriting, of which
16	were accepted as rewritten
24	required further revision and were then accepted
	7 were rejected
96	papers were accepted, and are in the Conference Proceedings

The review process remains a mystery to many authors. Perhaps the most difficult point is determining what is or is not within the scope of a conference. To a great extent an editor sets the bounds of the scope by the selection of reviewers. Indeed, as some authors have pointed out, the editor has the authority to render a judgment that is opposite to that of the group of reviewers. However, I had taken the position that the voice of the reviewers should be very prominent, not only in setting the quality of a paper but in sensing (guiding?) the direction of the field as well.

The mechanics of reviewing were rather simple. I read each paper to determine whether I could reasonably ask a reviewer to spend time on the paper and who might be called upon to review the paper. I rejected 7 at this point. I sent copies of most others (not those of which I am co-author) to 4 reviewers. Where possible, two went to seasoned people in the field(s) represented in the paper, one went overseas, and one went to a new author in the field (these are not mutually exclusive categories). When the reviews returned, I read the paper carefully in the light of the notes and recommendations of the reviewers. I then advised the author on what should be done next. When revisions were necessary I also read the revised edition.

One very gratifying type of interaction I have had with authors and reviewers is the frequent scholarly discussions on how papers can be improved. It is this impulse that guarantees high quality publications. I wish I could have devoted more time to that aspect of editing. Too much time is devoted to keeping good records so that no paper/review/revision/insertion, et al., becomes lost. We missed a couple again this time, for which I apoligize. I had a very able secretary in the person of Laurie Hildreth to assist me, as well as Kevin Hagelin who served as lay-up quality editor, and Karen Terpstra who was our typist. These were supported by funds from the ONR (Marshall Peterson) and NSF (Jorn Larsen-basse). The goals of this conference could not have been carried out without their support and I am grateful for that support.

I end this page on a note concerning the future. I have closely edited more than 1000 papers in my time as editor. I enjoyed it immensely but it is a very heavy and intensive task in the fall of each even-numbered year. The time has come for a change. Either the format of the Conferences will change or the editing will proceed on a different schedule, or both. Perhaps someone else will slide into my place and begin his/her 1000 papers! There are many possibilities to consider. The Organizing Committee has been discussing several alternatives and will announce its decision at the Conference in Denver.

Ken Ludema
February 25, 1989

Name of Reviewer	Location
C. Allen	Univ. of Cape Town, South Africa
L. Ajayi	Univ. of Michigan, Ann Arbor, MI
E. A. Almond	Natl. Physics Lab., Teddington, UK
A. Anderson	Tribo-diagnostics, Dearborn, MI
M. Antler	Bell Labs., Columbus, OH
J. Ayers	Naval Res. Lab., Washington, D.C.
S. Bahadur	Iowa State Univ., Ames, IA
A. Ball	Univ. of Cape Town, South Africa
G. Barber	Univ. of Mass., Amherst, MA
R. Bayer	IBM, Endicott, NY
H. Berns	Ruhr Univ., Bochum, FRG
R. C. Bill	NASA-Lewis, Cleveland, OH
E. Blank	Ecole Polytechnicique, Lausanne, Switzerland
P. Blau	Oak Ridge Natl. Labs., Oak Ridge, TN
B. J. Briscoe	Imperial College, London, UK
R. Blickensderfer	U.S. Dept. of Int., Bureau of Mines, Albany, OR
D. H. Buckley	Case Western Univ., Cleveland, OH
K. Budinski	Eastman-Kodak Co., Rochester, NY
S. G. Caldwell	Teledyne-Firth Sterling, Lavergne, TN
T. Childs	Univ. of Bradford, W. Yorkshire, UK
P. Clayton	Oregon Graduate Center, Beaverton, OR
H. Conrad	North Carolina State Univ., Raleigh, NC
J. Conway	Penn State Univ., Univ. Park, PA
A. K. Cousens	Cambridge Univ., UK
H. Czichos	BAM, Berlin, FRG

S. Danyluk	Univ. of Illinois, Chicago, IL
M. Doerner	IBM, San Jose, CA
K. Dufrane	Battelle, Columbus, OH
N. S. Eiss	VPI & SU, Blacksburg, VA
R. Esling	Institut fur Werkstoffkunde, Aachen, FRG
C. Ettles	RPI, Troy, NY
S. Fayelle	Ecole Centrale de Lyon, Ecully, France
D. M. Fegredo	CANMET-Dept. of Energy, Ontario, Canada
I. Finnie	Univ. of California, Berkeley, CA
A. Fischer	Ruhr-Univ., Bochum, FRG
T. Fischer	Stevens Inst. of Tech., Hoboken, NJ
M. Fiset	Univ. de Laval, Quebec, Canada
K. Friedrich	Univ. of Delaware, Newark, DE
N. Gane	CSIRO, Victoria, Australia
M. Gardos	Hughes Aircraft, Culver City, CA
W. M. Garrison	CSIRO, Melbourne, Victoria, Australia
D. Gawne	Brunel Univ., Middlesex, UK
B. Gecim	GM Res. Labs., Warren, MI
W. A. Glaeser	Battelle, Columbus, OH
D. Godfrey	Consultant, San Rafael, CA
K. H. Habig	BAM, Berlin, FRG
G. Hamilton	Univ. of Reading, UK
M. Hashish	Flow Industries, Kent, WA
H. M. Hawthorne	Natl. Res. Council, Vancouver, B.C.
S. Hogmark	Upsalla Univ., Uppsalla, Sweden
K. Holmberg	Tech. Res. Ctr., Espoo, Finland
E. Hornbogen	Ruhr Univ., Bochum, FRG
E. Hsue	IBM, Endicott, NY
G. Huard	Natl. Res. Council, Boucherville, Canada
I. M. Hutchings	Cambridge Univ., UK
H. Ishigaki	Univ. of Osaka Prefecture, Sakai, Japan
L. K. Ives	NIST, Gaithersburg, MD
S. Jahanmir	NIST, Gaithersburg, MD
V. K. Jain	Univ. of Dayton, Dayton, OH
S. Johansson	Upsalla Univ., Upsalla, Sweden
K. Kato	Univ. of Toyko, Sendai, Japan
T. Kayaba	Hachinoke Inst. of Tech., Hachinoke, Japan
F. Kennedy	Dartmouth College, Hanover, NH
P. Kennedy	Naval Air Development, Warminster, PA
A. Krell	Academy of Sciences. Dresden, DDR
P. L. Ko	Natl. Resarch Council, Vancouver, B.C.
O. Knotek	Inst. fur Werkkstoffekunde, Aachen, FRG
J. Larsen-Basse	NSF, Washington, D.C.
M. Lee	General Electric Research, Schenectady, NY
A. Levy	Lawrence Labs., Berkeley, CA
S. J. Lin	Natl. Tsing-hua Univ., Hsinchu, Taiwan
C. Y. Lhymn	Materials Res. & Mfg., Erie, PA
B. Madsen	U.S. Dept. of Int., Bureau of Mines, Albany, OR
Z. Y. Mao	Zhejiang Univ., Hangzhou, China
R. L. Mehan	General Electric, Schenectady, NY
J. McCool	Penn State Univ., King of Prussia, PA
P. K. Mehrotra	Kennametal Inc., Greensburg, PA
A. Misra	IBM, San Jose, CA
K. Miyoshi	NASA-Lewis, Cleveland, OH
M. A. Moore	Fulmer Labs, Slough, UK
A. Ninham	Univ. of Cambridge, UK
K. Ogino	Kinki Univ., Osaka, Japan
T. Page	Univ. of Newcastle upon Tyne, UK

M. B. Peterson	Wear Sciences Inc., Arnold, MD
M. Pouch	Sandia Labs, Albuquerque, NM
N. Prasad	IIT, Bombay, India
S. E. Prichard	Falconbridge Limited, Ontario, Canada
E. Rabinowicz	M. I. T., Cambridge, MA
S. K. Rhee	Allied Automotive Tech. Center, Troy, MI
S. L. Rice	Univ. of Central Florida, Orlando, FL
D. A. Rigney	Ohio State Univ., Columbus, OH
A. Rosenfield	Battelle, Columbus, OH
A. W. Ruff	NIST, Gaithersburg, MD
A. Sadat	Univ. of Texas, Arlington, TX
T. Sasada	Toyko Inst. of Tech., Toyko, Japan
K. Sato	Chiba Univ., Chiba, Japan
I. Schmidt	Ruhr Univ., Dochum, West Germany
G. Schmitt	Airforce Materials Lab., Dayton, OH
W. Schumacher	Armco, Middletown, OH
H. G. Scott	CSIRO, Victoria, Australia
M. C. Shaw	Arizona State Univ., Tempe, AZ
J. Sheasby	Univ. of Western Ontario, London, Canada
D. Shen	Zhejiang Univ., Hangzhou, China
G. Sheldon	Wash. State Univ., Vancouver, WA
H. Sliney	NASA-Lewis, Cleveland, OH
S. Soderberg	Univ. of Upsalla, Sweden
T. Spalvins	NASA-Lewis, Cleveland, OH
P. Swanson	Deere & Co., Moline, IL
D. Tabor	Cambridge Univ., UK
E. Takeuchi	Toyko Met. Ind. Tech. Center, Toyko, Japan
K. Tanaka	Univ. of Kanazawa, Japan
T. R. Thomas	Teeside Polytechnic, Middlebrough, UK
A. A. Torrance	Trinity College, Dublin, Ireland
R. C. Tucker	Union Carbide Corp, Indianapolis, IN
S. Turrenne	Natl. Res. Council, Boucherville, Quebec, Canada
A. B. VanGroeneu	Phillips Research Labs, The Netherlands
O. Vingsbo	Univ. of Houston, Houston, TX
H. Voss	Tech. Univ., Hamburg-Harburg, FRG
P. H. Vroegop	Twente Univ. of Tech., The Netherlands
J. Warburton	Central Electricity, Bristol, U.K.
R. B. Waterhouse	Former Sheriff of Nottingham, UK
S. F. Wayne	GTE Labs., Waltham, MA
J. Wert	Vanderbuilt Univ., Nashville, TN
E. Whitenton	NIST, Gaithersburg, MD
C. Yust	Oak Ridge Nat. Lab., Oak Ridge, TN
Q. Zhou	CAAMS, Beijing, China
K. Zum Gahr	Inst. of Mat. Science, Karlsruhe, FRG

CONTENTS

WEAR MODELING

THEORETICAL ESTIMATION OF ABRASIVE WEAR RESISTANCE BASED ON MICROSCOPIC WEAR MECHANISM

K. Hokkirigawa and K. Kato
Department of Mechanical Engineering
Tohoku University
Sendai, Japan

ABSTRACT

An abrasive wear mechanism, based on microscopic observations of abrasive wear processes in the scanning electron microscope, was analyzed and a wear mode diagram was proposed. An abrasive wear equation was developed in order to estimate macroscopic wear volume (or the wear resistance) quantitatively. Macroscopic abrasive wear tests on virgin surfaces were carried out for nine kinds of metals under unlubricated or lubricated condition in order to confirm the validity of the introduced wear equation.

Following results were obtained.

(1) An abrasive wear equation, based on the microscopic wear mechanism, was theoretically introduced and is as follows;

$$V = \frac{\phi_{eff}}{k\psi_m} \left(\frac{\alpha_w \beta_w}{m_w^2} + \frac{\alpha_c \beta_c}{m_c^2} \right) \frac{WL}{H}$$

where V : wear volume L : sliding distance
W : normal load
H : hardness of abraded material
ϕ_{eff} : proportion of effective asperities
k, ψ_m : shape factors of asperities
α_w, β_w, m_w : factors describing wedge forming mode of abrasive wear
α_c, β_c, m_c : factors describing cutting mode of abrasive wear

(2) The theoretical estimations of abrasive wear resistance calculated by this wear equation agreed well with the experimental results qualitatively and quantitatively.

INTRODUCTION

Abrasive wear of metal surface by the asperities on hard surfaces or by other hard particles is very important in various wear types because of its severity. Rabinowicz [1] has proposed the following abrasive wear equation by using a simple model in which the asperities on the hard surface are conical and the total groove volume is equal to the wear volume;

$$V = \frac{\overline{\tan\theta}}{\pi} \frac{WL}{H} \qquad (1)$$

where V is wear volume, W is normal load, L is sliding distance, H is hardness of abraded material, θ is attack angle and $\overline{\tan\theta}$ is a weighted average of the $\tan\theta$ values of all contacting asperities.

Eqn.(1) states that wear volume is proportional to the normal load and sliding distance, and is inversely proportional to the hardness for pure metals and annealed steels. However the actual wear volume is usually less than the calculated wear volume by eqn.(1). This implies that only a part of groove volume is removed as wear debris. Such a phenomenon has been observed microscopically by several researchers [2-16].

In the past, various abrasive wear equations were proposed [3, 4, 8, 10, 15-22]. Mulhearn et al. [17, 21, 22], for example, represented the shape of abrasive tip by a two-dimensional attack angle and proposed the critical attack angle where cutting started. Below the critical attack angle, wedge forming or ploughing was predominant. The wear equations based on the above two-dimensional wear models are very useful to explain the effects of several important factors on abrasive wear qualitatively, but they do not predict actual wear volume quantitatively.

It would be necessary to analyze the three-dimensional abrasive wear mechanism microscopically in order to enable ones to estimate the wear volume theoretically. The micro-mechanism of the wedge forming mode was observed by Kayaba, Kato and Nagasawa [23] by using a three-dimensional model asperity. A three-dimensional wear mode diagram was developed [13, 14], as shown in Fig.1, showing a possible regions of the wear mode of cutting, wedge forming or ploughing with the parameters of the degree of penetration of a spherical asperity and the shear strength at the contact interface related to that of the substrate. This degree of penetration is an expression of the two-dimensional attack angle. It can be seen in Fig.1 that, the critical degree of penetration, which corresponds to the critical attack angle, is much affected by the shear strength at the contact interface which may also be related to the lubrication condition.

The formation of the ridges on both sides of the wear groove is very important for the estimation of real wear volume. The degree of wear was measured recently [12, 13] for the wear mode of cutting, wedge forming or ploughing respectively by single point scratch tests in a scanning electron microscope (SEM), where the degree of wear was defined as the ratio of wear volume to the groove volume.

The yield criterion during abrasion was obtained by Kayaba, Hokkirigawa and Kato [24, 25]. This criterion indicates that the abrading tip will be strong enough to support the normal load and friction force only when the angle of the tip is larger than a critical angle which is determined by a ratio between hardnesses of the tip and the mating surface. Based on this criterion, the effect of the hardness ratio on the abrasive wear was analyzed theoretically by the authors [26].

In this paper, an abrasive wear equation was introduced theoretically based on our previous investigations of three-dimensional abrasive wear mechanism. In order to examine the validity of the introduced wear equation, macroscopic abrasive wear tests on nine kinds of metals under unlubricated or lubricated condition were carried out. The theoretical estimations of wear resistance calculated by the introduced wear equation agreed well with the experimental values.

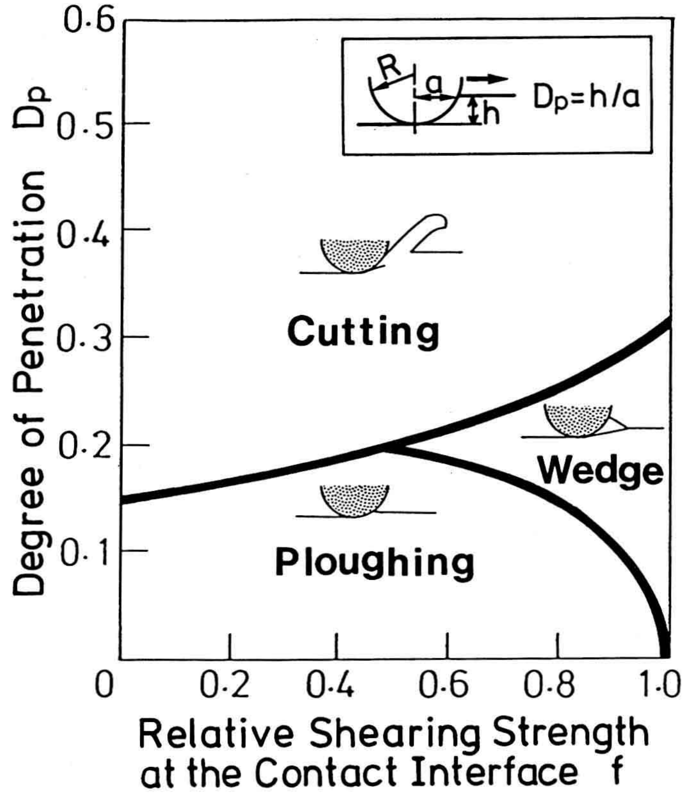

Fig.1 A wear mode diagram [14] : the degree of penetration is defined as the ratio of the depth of penetration to the half of contact width, and the shearing strength at the contact interface is defined as the non-dimensional value of the contact shear stress divided by bulk shear strength.

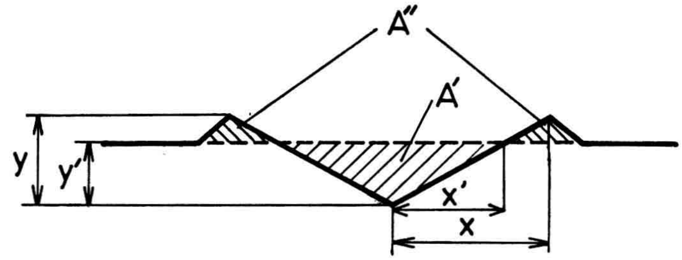

Fig.2 A model of profile of a groove.

ABRASIVE WEAR EQUATION BASED ON MICROSCOPIC WEAR MECHANISM

In order to obtain the following abrasive wear equation, the analytical method by Mulhearn and Samuels [17] was applied.

The groove profile shown in Fig.2 is assumed, with ridges on both sides. For this groove, the ridge-height factor, m, the degree of wear, β, and shape factor, ψ, are defined as follows;

$$m = y/y' \tag{2}$$

$$\beta = (A' - A'')/A' \tag{3}$$

$$\psi = x/y = x'/y' \tag{4}$$

The projected area of contact, A, is assumed here as follows;

$$A = k x^2 \tag{5}$$

where k is another shape factor.

By assuming that the real contact pressure is equal to the hardness, H, of abraded material, the normal load, ΔW, for this contact point can be expressed as follows;

$$\Delta W = H A = H k x^2 = H k y^2 \psi^2 \tag{6}$$

Considering multiple contact points, the mean normal load, $\overline{\Delta W}$, per one contact point can be expressed as follows;

$$\overline{\Delta W} = H k \int_0^{y_{max}} y^2 F(y)\,dy \int_0^{\psi_{max}} \psi^2 G(\psi)\,d\psi$$

$$= H k\, y_{rms}^2\, \psi_{rms}^2 \qquad (7)$$

where F(y) or G(ψ) is the probability density function of y or ψ , and y_{max} or ψ_{max} is the maximum value of y or ψ .

The total normal load, W, at all contact points between two sliding surfaces can be expressed as follows;

$$W = A_a\, q\, \overline{\Delta W} = A_a\, q\, H k\, y_{rms}^2\, \psi_{rms}^2 \qquad (8)$$

where Aa is the apparent contact area and q is the number of contact points per unit area.

The wear volume, ΔV, generated from the wear groove shown in Fig.2 is expressed as follows;

$$\Delta V = (A' - A'')\,L = A'\,\beta\,L = x'\,y'\,\beta\,L$$

$$= \frac{\psi y^2 \beta L}{m^2} \qquad (9)$$

where L is the sliding distance.

The value of β or m differs with each wear mode. Three principal abrasive wear modes have been observed: cutting, wedge forming and ploughing by single point scratch tests of metals in the SEM [11, 12, 13, 14]. The representative SEM images of these wear modes are shown in Fig.3. Wear volume can be neglected in the case of ploughing mode. Therefore here the abrasive wear modes of wedge forming and cutting are considered.

At the contact points where the wedge forming mode occurs, the wear volume, Vw, can be expressed as follows;

$$V_w = \alpha_w A_a q \frac{\beta_w L}{m_w^2} \int_0^{y_{max}} y^2 F(y)\,dy \int_0^{\psi_{max}} \psi G(\psi)\,d\psi$$

$$= A_a\, q\, L\, y_{rms}^2\, \psi_m \frac{\alpha_w \beta_w}{m_w^2} \qquad (10)$$

where α_w is the fraction of contact points where the wedge forming mode occurs, β_w is the degree of wear for the wedge forming mode, m_w is the ridge-height factor for the wedge forming mode and ψ_m is the mean value of ψ .

At the contact points where the cutting mode occurs, the wear volume, Vc, can be expressed as follows;

$$V_c = \alpha_c A_a q \frac{\beta_c L}{m_c^2} \int_0^{y_{max}} y^2 F(y)\,dy \int_0^{\psi_{max}} \psi G(\psi)\,d\psi$$

$$= A_a\, q\, L\, y_{rms}^2\, \psi_m \frac{\alpha_c \beta_c}{m_c^2} \qquad (11)$$

where α_c is the fraction of contact points where the cutting mode occurs, β_c is the degree of wear for the cutting mode and m_c is the ridge-height factor for the cutting mode.

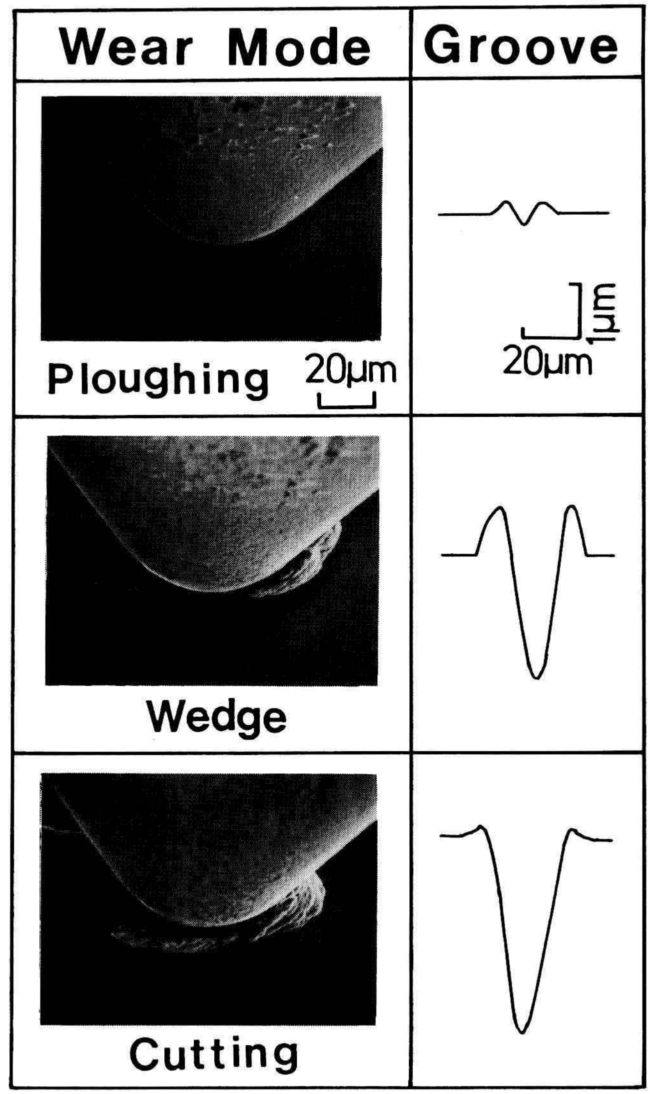

Fig.3 Three principal wear modes in abrasive wear[13]:pin specimen;diamond(R=30um), flat specimen;bearing steel.

From eqns.(10) and (11), the total wear volume, V, is expressed as follows;

$$V = A_a\, q\, L\, y_{rms}^2\, \psi_m \left(\frac{\alpha_w \beta_w}{m_w^2} + \frac{\alpha_c \beta_c}{m_c^2} \right) \qquad (12)$$

In addition, considering the fraction of effective asperities, ϕ_{eff} , which is defined as the fraction of contact points where the asperity can penetrate into the mating surface without plastic deformation of itself, eqn.(12) can be rewritten as follows;

$$V = A_a\, q\, \phi_{eff}\, L\, y_{rms}^2\, \psi_m \left(\frac{\alpha_w \beta_w}{m_w^2} + \frac{\alpha_c \beta_c}{m_c^2} \right) \qquad (13)$$