QUALITY OF REPORTING EMPIRICAL REULTS IN TRIBOLOGY

Kenneth Holmberg
VTT Technical Research Centre of Finland

There are many trends in the development of our more and more advanced technological society of today that emphasize the importance of tribology, that is the importance of controlling friction and wear. They are related to human safety such as controlling catastrophic failures in transportation; they are environmentally related such as reducing energy in machinery; they are related to industrial competitiveness such as controlling unexpected shutdowns in plants; they are product related such as optimizing material performance; and they are scientifically related such as understanding friction and wear mechanisms even on molecular and atomic level.

But is the tribology society prepared to meet these challenges? Certainly, we have much knowledge about friction, wear and lubrication mechanisms. We have good theories and we develop them to be even more generic and precise. But all theories and generic knowledge needs to be confirmed empirically, by experiments. And here we have a problem. How good is really the quality of the empiric methods in tribology today?

There are some questions that have bothered me for some time. There is published an increasing amount of papers in tribology today. But a big part of them are such that are never or almost never referred to in the literature. Doesn't this mean that their contribution to our general knowledge of tribology is very small, if any?

We are used to present and publish papers including friction and wear results with a great scatter, clearly not acceptable in most fields of natural sciences. But we just accept this by saying, "this is tribology". Don't we have adequate methods or skills to produce more precise empiric results?

One reason for the frequently appearing poor quality of empiric results reported is related to the very large diversity in the form in which they are published. Let me here discuss two aspects of it. One is related to reporting wear and the other to specifying experimental conditions in tribology.

Reporting wear

In comparisons of the tribological performance of e.g. different material pairs is friction often used as the parameter for comparison even if the wear performance would be more adequate. This is natural since for friction we have a good and universal parameter to use, the coefficient of friction, μ. But wear is reported in the literature in a great number of different forms and this makes comparison of wear behaviour from different studies and experiments difficult. A quick look at wear reporting in the recent literature resulted in the large variety of wear parameters, symbols and units shown in Appendix 1.

To give the wear behaviour its right role in tribological comparing evaluations we would need a more universal form of reporting wear, in a similar way as the coefficient of friction. One good candidate is the often used "wear rate, k", where

$$k = W / (F_n \cdot s)$$

where W is the wear volume, F_n the normal load and s is the sliding distance. This is a logical parameter since it relates the amount of wear (wear volume) to the input of mechanical energy into the contact (load and sliding distance). In the other often used wear reporting form, the "wear coefficient, K", is the hardness introduced in accordance with Archards equation. The advantage is that it results in a dimensionless parameter, in the same way as the friction coefficient. On the other hand, it results in a loss of generality. It includes only one influencing material parameter, it includes the necessity to know/measure the surface hardness and it excludes the representation of wear of e.g. coated and multilayer surfaces as well as materials that do not have hardness such as elastomers.

It is interesting to note that there is a similarity in the logic behind the two parameters, the coefficient of friction and the wear rate, as shown in Figure 1.

Friction is a force that is resisting motion. It has turned out by experience the there is a relationship between the friction force and the normal load. This is often close to linear but can vary a lot with speed, temperature, surface roughness, contact geometry, and surface material properties such as yield strength, elastic modulus and fracture toughness etc. Dividing the friction force with the normal load gives the coefficient of friction, μ, at a certain moment, t_1.

Wear is a process where a volume of material is detached form the surface. It has turned out by experience the there is a relationship between the wear volume and the normal load. This is often close to linear but can vary a lot with speed, temperature, surface roughness, contact geometry, and surface material properties such as yield strength, elastic modulus and fracture toughness etc. Dividing the wear volume with the normal load and multiplying it with the sliding distance gives the wear rate, k, at a certain sliding interval, $t_0 - t_1$.

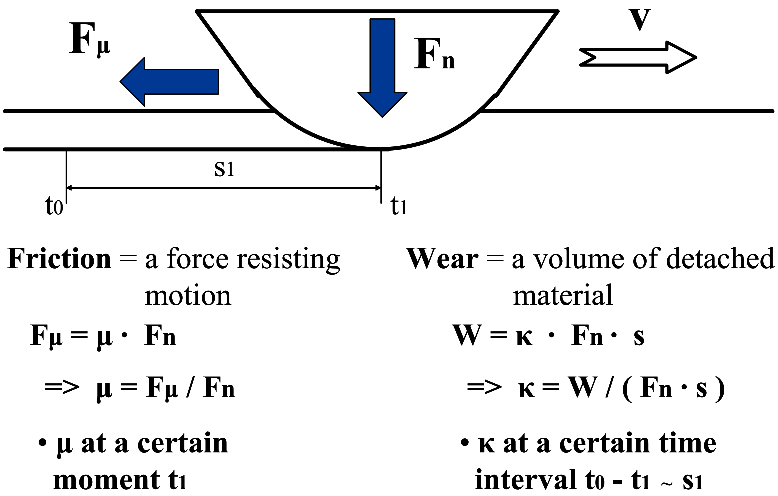

Figure 1. Illustration showing similarity in logic between coefficient of friction and wear rate.

It is clear that the wear rate is not easy to use in wear situations where load and sliding speed cannot easily be specified, such as in erosive wear. And in some cases it is also relevant to talk about wear depth, because this can directly influence on the tolerance that may be critical for the performance of devices. It would be an advantage and we would gain a lot in generality of our knowledge if the wear results in literature would be presented by only using e.g. the following parameters:
- in first place use the wear rate (e.g. k or κ) given as 10^{-6} mm^3 / (N • m),
- in cases were load or sliding distance cannot be specified use wear volume or wear mass and
- if the amount of geometry change is important use wear depth.

Is there any reason to use other parameters for wear or can most tribological contacts be represented by these? Of course we also have the fatigue failures, but they can well be represented by endurance life time as they already frequently are. The use of the wear rate, as a universal parameter for wear in parallel with the coefficient of friction, μ, would be logic. And perhaps here would be the place to take into use a Greek symbol for the wear rate such as κ to avoid confusion with the variety of uses of both k and K. The 25th IRG OECD Wear Group meeting in Uppsala suggested to take into use a new unit, Bowden (B) for 10^{-6} mm^3 / (N • m), which is in harmony with the above argumentation.

Specifying experimental conditions

One second reason for the difficulty to use tribological results in the literature and for the large scatter is probably that tribological contact conditions are described in many different ways. It is common that you find an article with very interesting experimental results and when you want to use them for your own case you notice that the report lacks e.g. information of the counter surface or of the roughness or humidity. And then it ends up in that you yourself perform the same experiments just to be sure.

It would be an advantage if there were a minimum level of tribotesting parameters that would be required before a paper is accepted for a journal or a conference presentation. These may not be so easy to determine but one can always try. Would the following perhaps be a starting point for minimum parameters to determine tribological test conditions?

Geometry
For both surfaces in contact:
- macrogeometry: given typically as radius or diameter of a curved surface
- microgeometry: surface roughness, given as adequate but also as R_a-value for comparison

Energy input
- load
- speed

Materials
For both surfaces in contact:
- material specification: metallurgical, physical or chemical
- possible coating material and its thickness, hardness and Young's modulus
- hardness and Young's modulus (hopefully we could in the future add fracture toughness of the surface)

Environment
- lubricant: viscosity and chemical composition of additives
- humidity
- temperature
- possible gases, radiation etc

Results
- friction as coefficient of friction, μ
- wear as wear rate, κ, and/or wear volume and/or wear depth
- surface observations of both surfaces in contact, including observations of surface layers and their extent
- observations of wear debris and when possible their average size and size distribution

Conclusions

There is both place and a need for improvements in the way wear results and experimental conditions are reported in the tribology literature. A better uniformity can be achieved in wear reporting by using e.g. the wear rate given by the unit 10^{-6} mm^3 / (N • m) and recommending the use of a minimum list of experimental parameters that should be defined before a paper is accepted for presentation in journals or at conferences.

Appendix 1

REPORTING WEAR IN THE LITERATURE

Parameters, symbols and units used in addition to wear volume, wear depth and wear mass.

Parameter	**Symbol**	**Unit**	**Reference**
Wear coefficient	-	$10^{-7} \cdot mm^3 / (N \cdot m)$	Abren et al., Wear 259(2005)771-778
Wear coefficient	k	-	Bhushan, Principles and Applications of Tribology, John Wiley, 1999, p.484
Wear coefficient	K	-	Suh, Tribophysics, Prentice Hall, 1986, p.13
Wear coefficient	k	-	Hsu & Shen, in Modern Tribology Handbook (Ed. Bhushan) 2001, Vol.1,p.323
Wear coefficient	k	-	Dunaevsky, in Tribology Data Hanbook (Ed. Booser) 1997, p.456
Wear coefficient	K	-	Kato, in Tribology of Mechanical Systems (Eds Vizintin et al., 2004, p.192
Wear coefficient	K	-	Hsu et al., J. Engeneering Tribology, IMechE, 216(2002)428
Coefficient of wear	k	$10^{-6} \cdot mm^3 / (N \cdot m)$	Klafke et al., Tribotest 11(2005)213-232
Coefficient of wear	K	-	Kato & Adachi, in Modern Tribology Handbook (Ed. Bhushan) 2001, Vol.1, p.279
Specific wear rate	-	$mm^3 / (N \cdot m)$	Ramalho et al., Wear259(2005)828-834
Specific wear rate	-	$10^{-5} \cdot m^3 / (N \cdot m)$	Biswas, J. Engeneering Tribology, IMechE, 216(2002)361
Specific wear rate	-	$10^{-6} \cdot mm^3 / (N \cdot m)$	Friedrich et al., J. Engeneering Tribology, IMechE, 216(2002)417
Wear rate	-	$m^3 / (N \cdot m)$	Barros'Bouchet et al., Trib. Int.38(2005)257-264
Wear rate	K	$10^{-6} \cdot mm^3 / (N \cdot m)$	Holmberg & Matthews, Coatings Tribology, Elsevier, 1994, p.53
Wear rate	K	-	Dorinson & Ludema, Mechanics and Chemistry in Lubrication, Elsevier, 1985, p. 357 & 362
Wear rate	k	mm^3 / s	Hsu & Shen, in Modern Tribology Handbook (Ed. Bhushan) 2001, Vol.1,p.326
Wear rate	-	mm^3 / m	Ruff, in Tribology Data Hanbook (Ed. Booser) 1997, p.436
Wear rate	K	$10^{-15} \cdot m^3 / (N \cdot m)$	Blanchet, in Tribology Data Hanbook (Ed. Booser) 1997, p.550
Wear rate	-	$10^{-12} \cdot m^3 / m$	Biswas, J. Engeneering Tribology, IMechE, 216(2002)363
Wear rate	-	$mm^3 / (N \cdot m)$	Miyoshi, Solid Lubrication, Marcel Dekker, 2001, p.262
Specific wear amount	Ws	$mm^3 / (N \cdot m)$	Kato, in Tribology of Mechanical Systems (Eds Vizintin et al., 2004, p.191
Wear constant	-	$mm^3 / m / N$	Ruff, in Modern Tribology Handbook (Ed. Bhushan) 2001,Vol.1,p.526
Wear factor	-	$mm^3 / (N \cdot m)$	Ruff, in Tribology Data Hanbook (Ed. Booser) 1997, p.436
Hard coating wear	-	mm^3 / m	Gangopadhyay, in Tribology Data Hanbook (Ed. Booser) 1997, p.595