Progress with a Wear Prediction Model for Design in Sliding Systems

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1. Introduction

At the Philips CFT, work is being carried out on the development of models that allow the wear lifetime to be estimated at an early stage in the design of a sliding mechanical part. This is of great potential benefit to design engineers working on concepts for new products or machinery, who are faced with choosing appropriate materials, contact geometries and contact conditions that will meet the lifetime requirements. Wear prediction models can allow serious design errors can be avoided at an early stage in the design process, thus minimising the chances that expensive redesigns will be needed at later stages.

2. Initial Model

The initial model for the prediction of sliding wear is based loosely on Rabinowicz' work on the "adhesive wear coefficients" of pure metals under dry sliding conditions in air[1]. In the current work, Rabinowicz' model has been modified to allow predictions of the steady-state[2] wear- (K-) factor[3] to be made for metallic materials commonly used for engineering purposes. Even though there are certain preconditions attached to the validity of the wear prediction (see note 2 below), the predicted values of the K-factor must of course be considered as approximate rather than absolute. For this reason, the K-factor predictions made by the model are converted to logarithmic decades before comparisons are made with the K-factors that are needed on the basis of the lifetime requirements of the design. The wear prediction model takes the following form :

$$K = A * \left[\frac{C * L}{Hv * H}\right] \tag{1}$$

Where:
K = steady-state wear-factor (K-factor) in [m^2/N].
A = constant.
C = "Compatibility factor".
L = "Lubricity factor".
H = "Hardness ratio factor".
Hv = Vickers hardness number of the material in question.

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[1] E.Rabinowicz in chapter: "Wear Coefficients - Metals" of Wear Control Handbook, Ed. M.B.Peterson & W.O.Winer, ASME, 1980.

[2] The steady-state wear-factor, or K-factor, is defined here as the value of K for conditions under which the wear rate as a function of time is constant. In practical design terms, this is taken to mean that the load on the mechanical contact in question is lower than that needed to cause bulk plastic deformation in the contact region, and that the running-in portion of the wear-time curve has been passed.

[3] The wear-factor or K-factor is defined here as : K = (wear volume) / (normal load * sliding distance). Units for K are [m^2/N].

The value of K given by equation *(1)* is converted to a K-factor range-number as follows :

K-factor range number = $\log_{10}(K) + 18.5$

The K-factor range numbers correspond to the following K-factor values :

Range number	K-factor [$* 10^{-15}\ m^2/N$]
1	0.001 - 0.01
2	0.01 - 0.1
3	0.1 - 1.0
4	1.0 - 10
5	10 - 100
6	100 - 1000
7	1000 - 10000

2.1 Compatibility {C}, Lubricity {L} and Hardness ratio {H} factors

The purpose of the compatibility factor {C} is to take into account the tendencies of the metals in a given contact to adhere strongly to each other. According to Rabinowicz, this is indicated by the metallurgical compatibilities of the metals, i.e. their solid solubilities. The compatibility factor can vary from 1 to 100. If the two materials are the same, e.g. two steels of identical composition, they are said to be 100% compatible and the value of {C} will be 100. Materials with only limited solid solubility, e.g. steel and copper, will have lower compatibility values.

In order to develop a model suitable for common engineering metallic materials, it was necessary to take account of the "self-lubricating" abilities of certain materials. An example of such a material is graphitic cast iron, where the lubricity is improved by the presence of graphite. With other materials, chemical reactions taking place at the sliding interface between two materials can produce lubricious compounds leading to a reduction in the wear rate. Examples are (under favourable conditions) certain titanium nitride coatings (TiO_2 formation) and Cobalt-cemented tungsten carbide[4]. The purpose of the lubricity factor {L} is to take account of such effects. If the materials in the contact have negligible self-lubricating ability under the appropriate operating conditions, L = 1. Lower values indicate greater lubricity.

The current model also includes a third factor {H}, relating to the relative hardnesses of the materials in the sliding contact. Experiments[1] have indicated that the wear of a harder surface depends to some extent on the ratio of the hardnesses of the harder (h) to softer (s) surfaces, H_h / H_s. Allowing for the individual effects of the hardnesses of the two surfaces, the wear of the harder surface is reduced still further if the hardness ratio is high. The importance and validity of the hardness ratio factor is currently being investigated.

Because the wear prediction model is still under development, it is too early to provide a fully quantitative explanation of the factors C, L and H mentioned above. However, one example is given below :

Example: K-factor prediction for material A [see equation (1)]:

Material A : Cast bearing bronze, CuSn1 + 1% Pb, DIN werkstoff number 2.1052.04
Material B (counterpart) : Tool steel, X160CrMoV12 1, DIN werkstoff number 1.2379.02, hardened & tempered 61 HRC.
A = constant = $1.53 * 10^{-12}$
C = Compatibility factor = 10
L = Lubricity factor = 0.5 (because of the lead)
H = Hardness ratio factor = 1
Hv = Vickers hardness number for material A = 100

$K = A * [(C * L) / (Hv * H)] = 76 * 10^{-15}\ [m^2/N]$
=> K-factor range-number = 5

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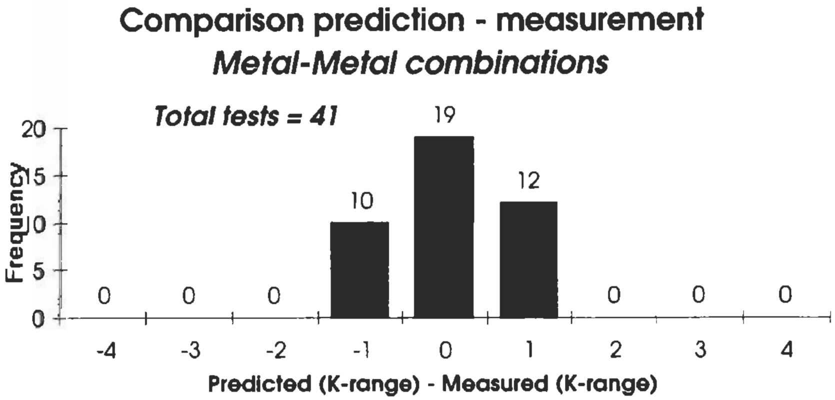
[4] S.E.Franklin, J.Beuger, Surface and Coatings Technology, 54/55 (1992), 459-465.

3. Experimental Validation

Only a limited number of tests have so far been carried out in order to validate the wear prediction model. However, the results of these tests are promising. Forty-one sliding wear tests have been carried out on a variety of metallic material combinations including aluminium, tin-bronze and aluminium-bronze alloys, a flake-graphite cast iron, and various low-carbon, tool, and low-alloy steels and stainless steels. These materials were paired against each other in unlubricated pin-on-disk tests in air. In all cases the load was 2N and the sliding speed was 0.1 m/s. The contact geometry was such that the bulk elastic limit was not exceeded for any of the materials tested. Each test was repeated five times in order to provide averaged results. The variation in these results did not exceed 0.5 * one order of magnitude. The average *measured* K-factors varied from 0.04 to 3000 * 10^{-15} [m^2/N], representing K-factor range numbers from 2 to 7. The differences between the predicted and the measured values of the K-factor range-numbers (Predicted K-range minus Measured K-range) are shown in the graph below. A value of zero means that the predicted and measured K-ranges were the same.



In the above results, 46% of the measured K-factor range-numers were the same as the predicted values, whilst 100% of the predictions were within one range number of the measured values.

4. Implementation

In practice, it is expected that a design will only be considered acceptable if the *predicted* K-factor range-number is lower than the *maximum allowable* range-number calculated on the basis of the lifetime requirements of the design. In this way, the chances of serious design errors being made can be minimised. Furthermore, by "shortlisting" promising designs and material combinations, it will become possible to plan and carry out (expensive!) practical simulation tests more efficiently.

5. Future Activities

Plans for 1997 include further validation, and eventual modification, of the wear prediction model. There are also plans to extend the model to include commonly-used polymer materials.