Wear Data: What can be Made of it? Simulation Tuning

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Damage, be it breakage, deformation or wear is initiated by overstraining or overstressing. Full modelling of both these causes is not possible today and one resorts to "simulation" to produce the data needed by design engineers to predict function loss. The question then is: how reliable is the data furnished by simulation ? The answer is brought by the analysis of data produced in fretting tests which show that even very small variations in running conditions, in this case in amplitude, can change the nature of the damage. Simulation tests have to be undertaken with the utmost care.

1. INTRODUCTION

Basic research has naturally dominated the wear scientific scene. Recently, questions coming from the engineering world have oriented research efforts towards more practical problems. Emphasis on reliability, security, comfort, component life predictions, invites tribologists to consider surface performance [1]. The change was expected as the performance of machine components subjected to wear governs machine life. Such changes in outlook, however necessary, are long in coming and early results show that data alone on wear is not enough to answer the questions coming from the engineering world. Indeed, today:

- wear data is common,
- wear maps are plenty,
- wear laws flourish,
- some governing parameters are identified,
- modelling is discussed extensively,
- experimental or simulation programs are initiated,

but the problem is to find out what can be done with these new tools from a practical point of view and how can design engineers introduce them in their models.

2. MODELLING

Design engineers use models [2]. Some models rest on sound scientific foundations others on empirical laws. Both are used indifferently as long as they work. This is standard practice and design engineers, who are rarely trained in this subject, react towards wear as they do towards other subjects as wear is just one headache amongst others.

They don't see why such a fuss is made by tribologists over it. They do not understand the formidable differences in wear rates that we publish. The 3 orders of magnitude spread that we commonly report does not make sense to either a brake specialist who sees at most a difference of 50 % in life between two brake pads or to a tyre specialist who notes a variation of 30 % between two different tyre lives.

Tribologists and designers approach the problem differently. The first seek refuge behind their pin and disc machines and applaud at the low wear rates they measure for a given material combination. The second foam at the mouth as they wear out their machines in no time with the same material combination. Both produce figures which supposedly can feed models, unfortunately they do not correlate. The tribologists' experiments, or models, must give results closer to practice. This might entail retiring most of the pin and disc machines, used for this purpose, or at least changing their running conditions. The question is: what should they be replaced by?

3. WHAT REALLY SHOULD BE MODELLED ?

From an engineering point of view, models should bring answers to 2 questions:

- will the machine work?
- will it last?

3.1 Will the machine work?

Clear answers are given in fully lubricated (thick film) mechanisms as sound physical models exist [3]. Semi or fully empirical guides are common elsewhere [4]. The range of application of these guides is not always known. Interpolation is possible, when interpolation parameters are identified, which is not always the case. Extrapolation is dangerous [5]. In most instances, design engineers rely on experience to make machines work.

3.2 Will it last ?

Life of fully lubricated systems is (theoretically) infinite. Life of machine parts is limited by loss of function.

Tribologists are usually called when the machine works but when it does not last, that is when it loses function too rapidly.

4. FUNCTION LOSS

The pin of a pin and disc machine has no engineering function. It can go on wearing even when the pin holder also starts rubbing against the disc. The machine will go on working. A machine component loses function if:

- it breaks: through crack initiation and propagation (usually with very little debris or none). Part failure through breakage initiated in contacts is common in hertzian contacts and in fretting, or when subjected to fatigue.
- if it loses guidance and/or kinematic compatibility: through deformation and/or wear (usually with a significant amount of debris). Some parts wear without loss of function. Brake pads for instance can lose up to 3/4 of their original thickness and still give perfect service. Kinematic compatibility is maintained. In others, small localised wear cannot be tolerated. A small change in the cam nose profile, for instance, can strongly

impair engine performance. Guidance is lost.

Hence, from an engineering point of view, function loss through contact damage must be traced rather than wear which gives only one side of the story. Further events which lead to function loss, either through crack initiation and propagation or deformation and wear are encountered simultaneously in contacts which operate under widely different running conditions. As an example, both cracks and wear are found in gears and fretting assemblies. It is therefore necessary to look at the parameters which govern these types of damages.

5. GOVERNING PARAMETERS

Paragraph 4 suggests that performance prediction, or function loss prediction is centred around parameters which favour either crack behaviour, or deformation and wear which have to be identified. These can be grouped under three headings [6]:

- imposed running conditions
- material (first-body) properties and limits
- induced running conditions

which are discussed below.

5.1 Imposed running conditions

The imposed running conditions (table 1) are those generated in the machine (gears, brakes ...)

Loads are sometimes expressed in terms of pressure (Pa). The contact load acts within the contact, the external load takes in all other loads, seen by the structure. This distinction is necessary because contact stresses do not act alone in many applications. Kinematics are important; continuous unidirectional rolling or sliding operations (ball and slider bearings), non-continuous unidirectional (gears) and alternating contacts (fretting) generate different conditions at the interface which control the velocity accommodation mechanisms (i.e. how the velocity is accommodated across the interface) which have been shown to govern wear [7]. The role of temperature and environment on material (first and third bodies) properties and changes are obvious and will not be discussed here.

5.2 Material properties and limits

Material properties orient the test towards one form of damage (cracks) or an other (deformation or wear), (table 2). The stress intensity factor thresholds (K_{ith} (i=1,2)) which define the conditions for crack propagation, and the % elongation to fracture which is a measure of the "strain reserve" before material rupture are added to the familiar yield stresses and strains and rupture strength.

The Wöhler fatigue limit σ_D is discussed in § 8.1.

5.3 Induced running conditions

The induced running conditions (table 3) are quantities which characterise the condition of the loaded material. While all elements of the stress and strain tensors should appear under the induced running condition heading, special notice must be given to the internal skin stress and strain σ_{xx} and

Parameters	Units	Observations
Loads	Newtons	Contact and external
Kinematics	m/s	frequency, amplitude
Temperature	°C	
Environment	Composition	

Table 1 - Imposed running conditions

Parameters	Units	Observations
K_{ith} (i=1,2)	Pa$\sqrt{m}$	S.I.F. threshold
A%	Non d.	% elongation to fracture
σ_D	Pa	Wölher fatigue limit
σ_R	Pa	Rupture strength
σ_y	Pa	Yield stress
ϵ_y	Non d.	Yield strain

Table 2 - Material properties and limits

Parameters	Units	Observations
σ_{xx}	Pa	skin stress
ϵ_{xx}	Non d.	deformation
K_i (i=1,2)	Pa$\sqrt{m}$	stress intensity factors

Table 3 - Induced properties and limits

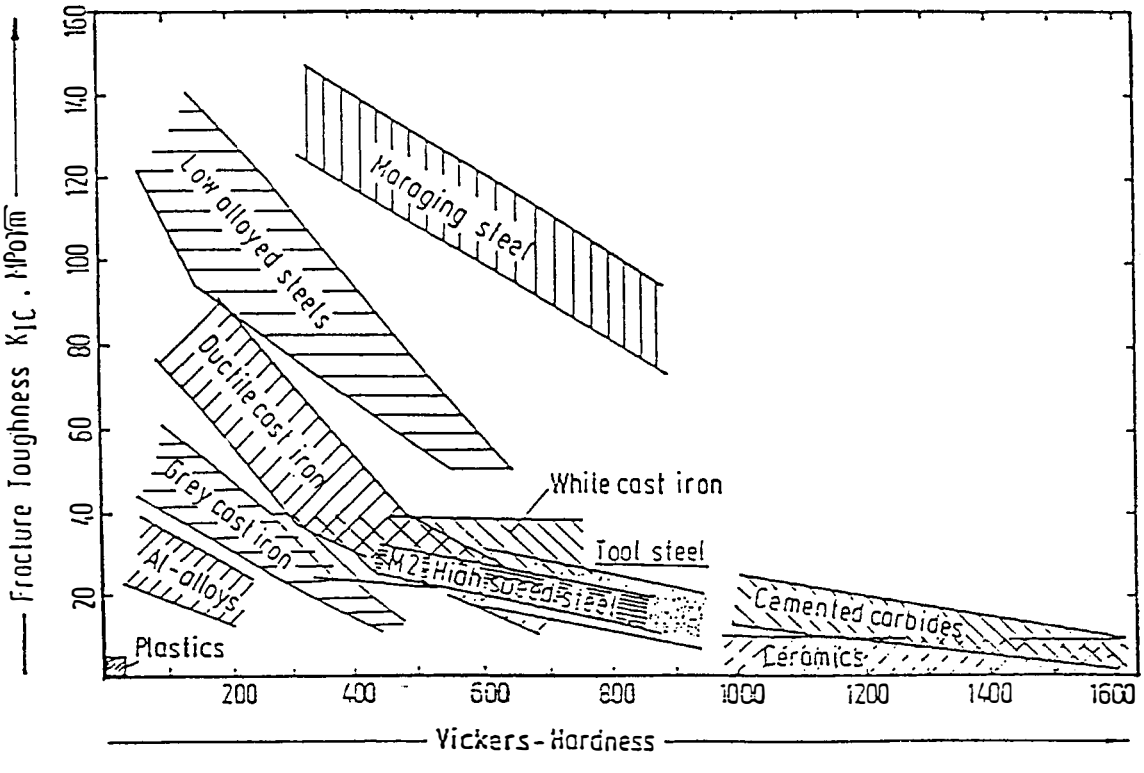


Figure 1 : Schematic representation of fracture toughness as a function of yield stress of plastics, ceramics, and metallic alloys (ref. 8).

ϵ_{xx}. σ_{xx} is the internal surface stress which in a hertzian contact for instance is strongly dependent on maximum normal pressure p_o, on the coefficient of friction f and on the location within the contact as shown in the equation below:

$$\sigma_{xx} = - p_o \{(1 - x^2/a^2)^{\frac{1}{2}} + 2fx/a\}$$

where a is the hertzian half-width and x the abscissa of the point considered.

6. OVERSTRESSING AND OVERSTRAINING

Materials fail through overstressing and overstraining. Over-stressing leads to crack formation or rupture either instantaneously or after fatigue. Material transformation is noted only in the immediate crack lip vicinity. Particle detachment or debris formation is a secondary effect. Overstressing is noted for instance when, under very high friction, low toughness materials fail by rupture; they crack, rather than slide with respect to one another. Overstraining leads to toughness loss and particle detachment. Crack initiation or crack propagation are secondary effects. Overstraining is observed for instance when, under moderate friction, high toughness materials slide with respect to one another and deform (plastically). The relation between overstressing and overstraining when damage is present is not limited to classical stress strain laws.

Overstressing and overstraining are governed by both imposed and induced running conditions, but also by material properties and limits. Toughness is the first material factor which comes to mind when overstressing and overstraining are discussed.

7. TOUGHNESS

The relation between toughness and hardness or yield stress is illustrated in a graph (fig.1) taken from Zum Gahr [8]. If,as shown in the figure, the difference in toughness between different "as received" materials is great, it drops considerably following work hardening. In other words the difference in toughness between work hardened materials is significantly smaller.

Under rubbing conditions, in initially low toughness materials, such as some ceramics and glasses:

- if friction (and thus σ_{xx}) is high, cracks form rapidly as first-bodies have little residual plasticity, their percent elongation to rupture A% is low.
- if friction (and thus σ_{xx}) is low, cracks are avoided, sliding takes place; as the material cannot overstrain, small localised overstressed particles are detached from the bulk.

Low toughness materials fail essentially through overstressing. Depending on the global stress level either cracks or debris can be generated.

Also under rubbing conditions, in initially high toughness materials, such as metals or metal alloys, with high A%, crack initiation or debris production is not instantaneous. High toughness materials gradually over-

strain, lose toughness and generate debris as above. High toughness materials are first transformed through overstraining and fail later through overstressing.

Function loss thus depends on the cause of the damage, be it overstressing and overstraining, and on its intensity. This is exemplified in the practical case of fretting assemblies. The running conditions which lead to either form of damage are discussed.

8. OVERSTRESSING AND OVERSTRAINING IN FRETTING

Fretting results illustrate the effects of overstressing and overstraining. It takes little change in running conditions to go from overstressing to overstraining yet the damage observed is significantly different. This explains the contradictions and the difficulties met in the interpretation of fretting results.

In fretting, cracks initiate at contact edges through overstressing, and the transformed zones which result from overstraining are found in the contact zone. Depending on imposed conditions, and particularly on load and amplitude, either edges are overstressed, or contact centres overstrained. Contact conditions are different in both places and material properties differ after only a few cycles. Mixed conditions can of course be encountered.

8.1 Crack initiation and propagation

Crack initiation is predictable as it is governed by overstressing. The maximum internal tensile stress σ_{xx}, is compared to the tensile fatigue limit stress σ_D produced in classical material tests. If $\sigma_{xx} < \sigma_D$, initiation is avoided. If $\sigma_{xx} > \sigma_D$, cracks are expected and the incubation time, taken here as the sum of the initiation and propagation times, depends on the difference between σ_{xx} and σ_D and on the sensitivity of the materials to cyclic strain hardening.

In most laboratory fretting fatigue studies, initiation often leads to failure as the entire test specimen is stressed. Each new crack decreases the specimen effective section, thus weakening the specimen, and crack initiation normally leads to propagation and failure. In many industrial contacts, stresses are high in the contact vicinity but drop rapidly away from that zone causing propagation to stop [9]. Laboratory conditions are often more severe than those found in practice. Full fracture mechanics analyses are therefore needed to predict failures initiated by overstressing alone. Experimental values, listed in the material properties and limits table (§5.2), are needed to conduct such studies.

8.2 Debris

In metals, debris emerge from a very hard modified structure made out of very stable phases [10]. Modifications start during the first passes of the wear test and rapidly the locally consolidated surface can no longer accommodate the deformation imposed by the contact load and it cracks [11]. Debris spring from the fragile transformed layer. Damage is initiated by overstraining and ends through overstressing. Modelling of the debris formation process

is not within reach today. The rate of change of structure under well defined contact conditions is needed before any modelling can be considered. This is a study in itself. Note further that particle detachment is only the first step in the production of a wear particle and that a global wear model would have to model particle progress from its detachment to its elimination from the contact and wear track [2].

9. SIMULATION

Paragraphs 8.1 and 8.2 show that in spite of the considerable progress in understanding surface damage and of the identification of the phenomena which govern at least some of its different forms, it is not yet possible to predict surface performance (or function loss) under fretting and other running conditions. This progress is nevertheless useful in setting up experimental programs which will bring the necessary indications to the design engineers, and in interpreting fretting results.

9.1 Friction loops and friction logs

In fretting individual force/displacement (FD) cycles, or friction loops, take on different shapes during a fretting test (fig.2).

- a closed (cc) conservative FD cycle, associated with elastic accommodations. Tangential contact stiffness is given by the slope of the FD line.
- an elliptic (ec) slightly dissipative FD cycle, found in contacts which exhibit either partial slip or interfacial crack friction or both.
- a trapezoidal (tc) cycle, characteristic of gross slip, the near horizontal segments are dissipative, the near vertical segments are conservative.

Friction loops can be drawn for each cycle of a given test. These loops, when positioned on a 3D friction coefficient/displacement/cycle number plot, form a friction log (fig.3). Depending on materials and conditions, that log can exhibit the 3 individual loops illustrated above. Experience showed that plotting force and displacement versus the log of the cycle numbers gives the best test description.

Plots can be drawn for different loads, amplitudes, frequency and of course material combinations. They are therefore capable of measuring the sensitivity of the contact to changes in any one of these parameters. The different friction logs shown in figure 3 were all obtained with the same load, frequency, the same materials but for different amplitudes. Completely different damage types were obtained in figure 3 when the amplitude varied from 15 to 50 micrometers.

9.2 Fretting maps

Crack initiation and propagation, and debris formation seen in fretting, have different origins even if they occur within the same contact and with the same original material combination. Fretting maps originated by Vingsbo [12] were further developed in this study (fig.4). The first, the running condition fretting

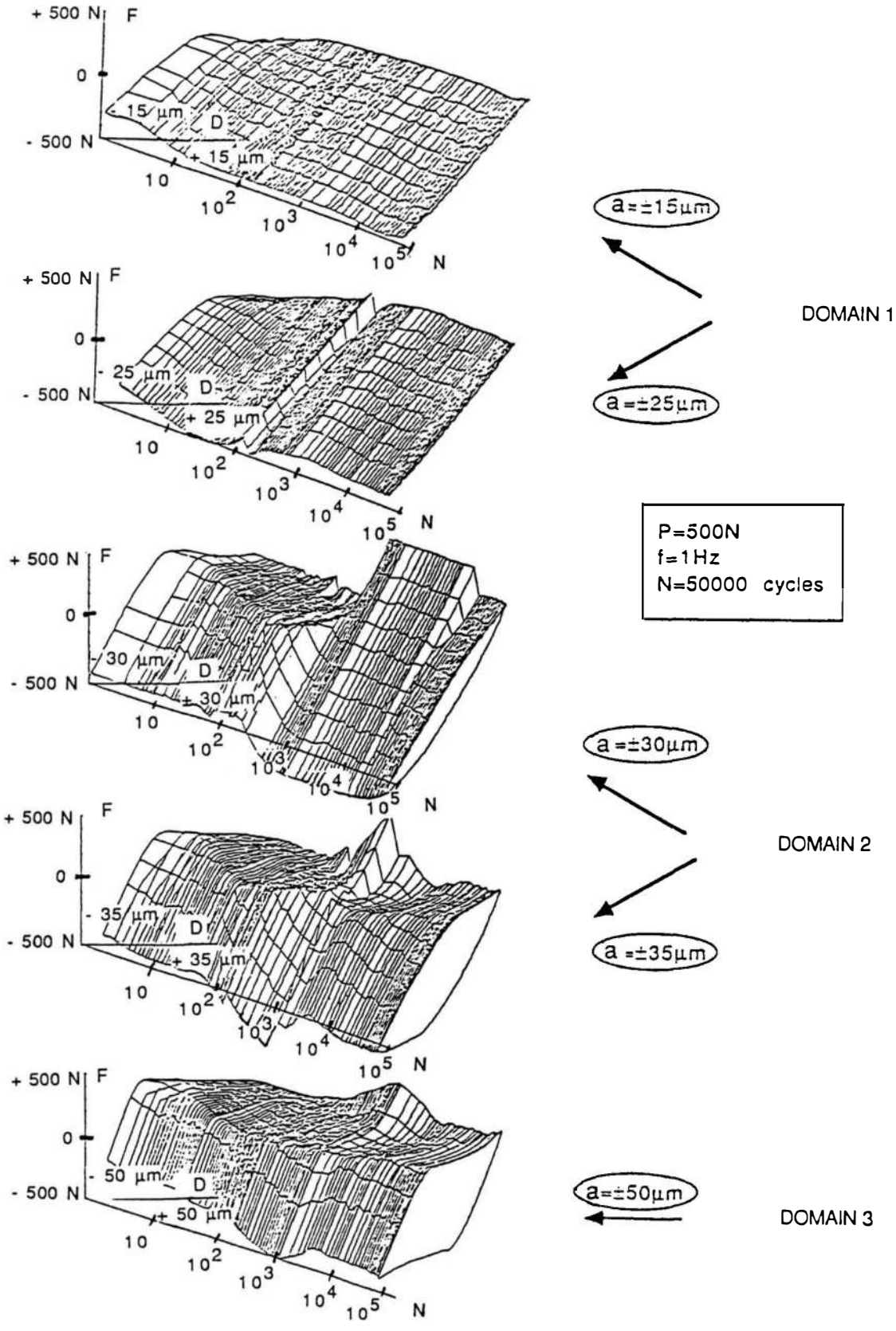
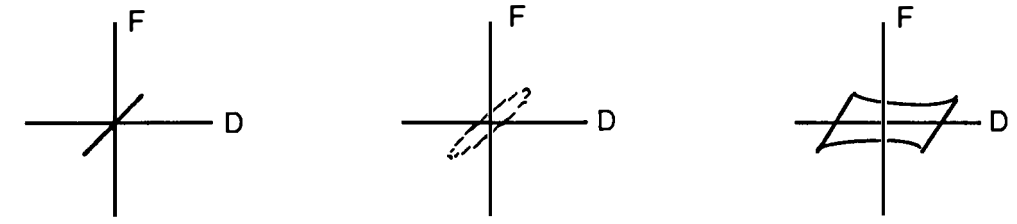


Fig. 2 : 3D friction logs obtained for different amplitudes with 7075 aluminium alloys (ref. 13)

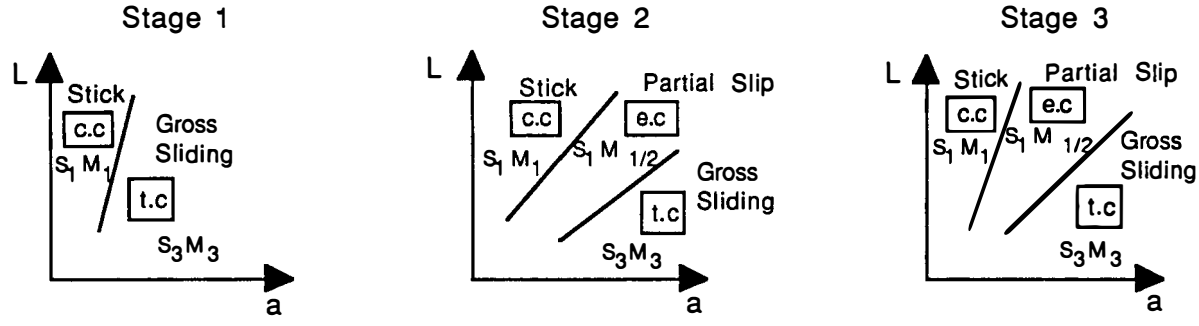


DOMAIN 1
Closed cycle (c.c)

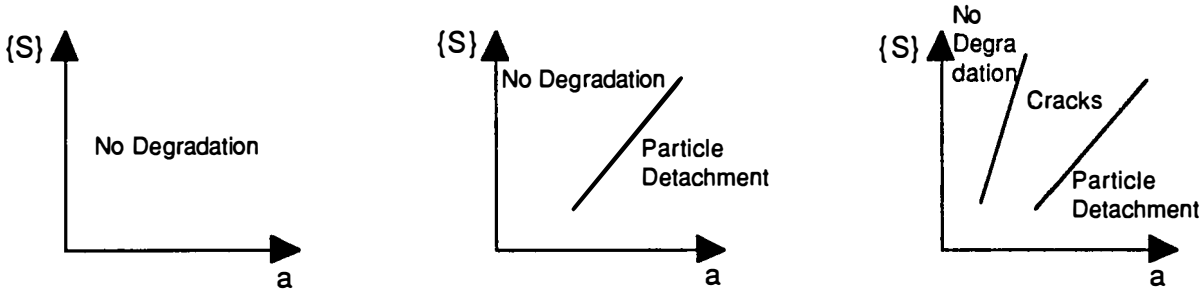
DOMAIN 2
Elliptical cycle (e.c)

DOMAIN 3
Trapezoïdal cycle (t.c)

Figure 3 : Characteristic friction loops

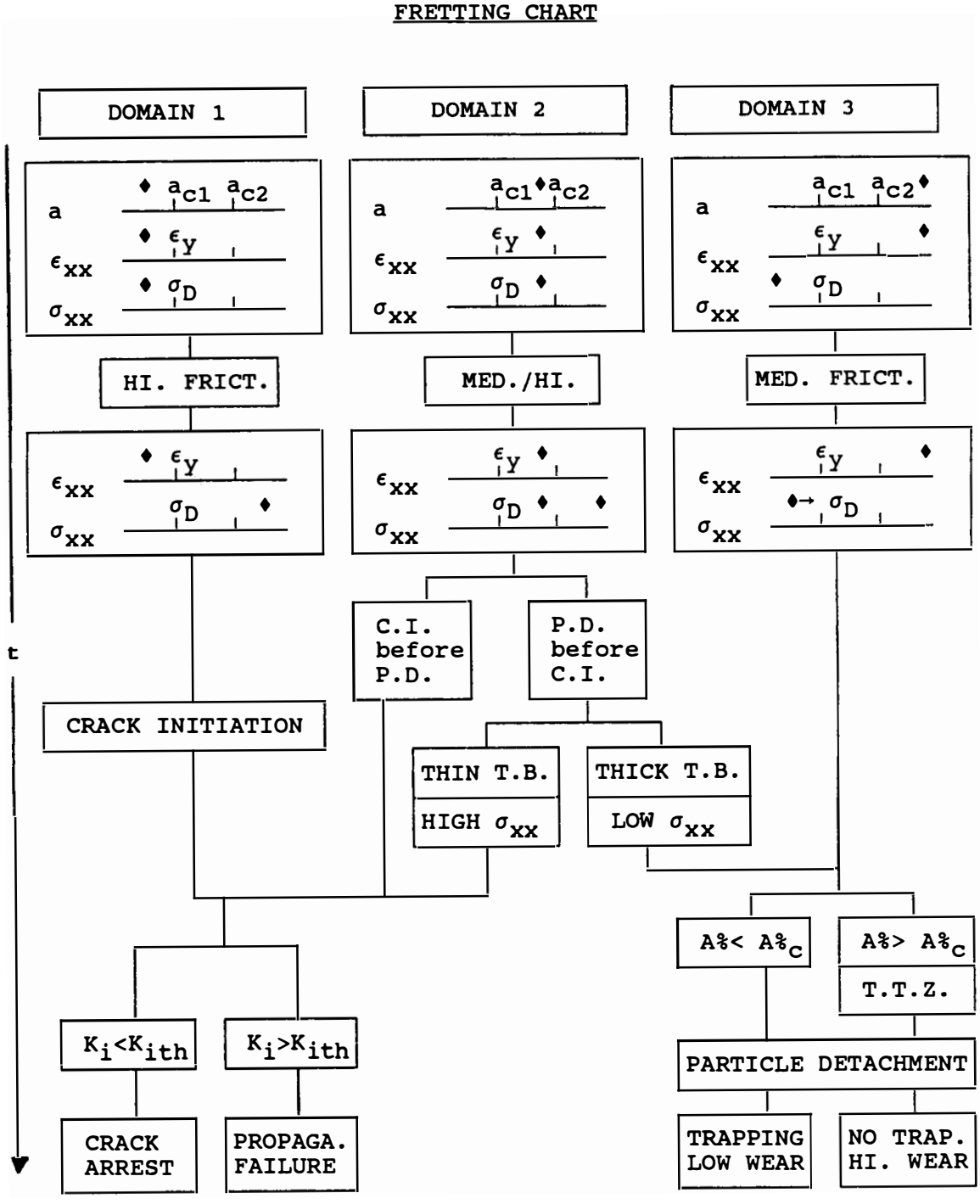


Running Condition Fretting Maps (L : Load, a : Amplitude)



Material Response Fretting Maps (S : Stress, a : Amplitude)

Figure 4 : Running conditions and material response fretting maps



N.B.: C.I. crack initiation, P.D. particle detachment,
T.B. third-body, t : time,
T.T.Z. tribological transformed zone

Fig. 5 Fretting chart: crack initiation and propagation, high and low wear

map (RCFM) identify the contact kinematic conditions: full adhesion, partial slip, gross slip. They can be drawn directly from the friction logs as the three kinematic conditions correspond respectively to the closed, elliptical, and trapezoidal cycles of figure 2. In RCFMs, load is plotted versus amplitude. The second, the material response fretting map (MRFM) identify damage forms: no degradation, cracks, and particle detachment. In MRFMs, skin stress is plotted versus amplitude, and damage areas are identified after surface examination. The positions of the lines which delimit the kinematic conditions and the damage areas can vary during the test. The curves presented in figure 4 are representative of many tests, run with different materials and different loads. They illustrate the effect of load on the kinematic conditions and on the type of damage encountered. Similar fretting maps can be drawn for different parameters.

10. FRETTING CHARTS

The examination of many different friction logs led us to set up fretting charts (fig.5) which show how combinations of imposed and induced conditions and material properties interact. A ball on flat geometry is chosen. Materials and running conditions, except amplitude are fixed. Two critical nominal amplitudes (different from actual slip) a_{c1} and a_{c2}, where $a_{c2} > a_{c1}$, are identified which define 3 domains:

Domain 1: $a < a_{c1}$ (no slip)

Domain 2: $a_{c1} < a < a_{c2}$ (partial slip)

Domain 3: $a > a_{c2}$ (gross slip)

Thus the critical amplitude a_{c1} (a machine parameter), is set opposite the yield strain ϵ_y (a material parameter), even though the deformation ϵ is not constant along the contact.

In domain 1 (fig.5), both σ_{xx} and ϵ_{xx} are small at start. Friction increases rapidly as the surfaces are in close contact, σ_{xx} rises, cracks are initiated and depending on the stress intensity factors, they will either stop (crack arrest) or propagate (propagation failure). In domain 3 (fig.5), σ_{xx} is low and ϵ_{xx} is high. Friction rises moderately as sliding is observed. If the % elongation to fracture A% of the material is small ($A\% < A\%_c$), the contact zone breaks up and debris is produced quasi-instantly; if it is large ($A\% > A\%_c$) the material strainhardens, is transformed (tribologically transformed zone, T.T.Z) and only then will produce debris [10]. In both cases the debris is either trapped in or eliminated out of the contact. Domain 2 is a combination of domain 1 and 3 and can, depending on whether crack initiation precedes or follows particle detachment, go towards crack propagation or wear as also seen in figure 5.

CONCLUSION

This paper has tried to answer the question "Wear data: what can be made of it ?". It was first shown that wear data is not really what the design engineers need. They want to know when a given component loses function, that is when it breaks or when it loses kinematic compatibility through either deformation or wear. The next answer is then to find out what parameters govern either breakage or

deformation and wear ? Three sets of tables are presented: the first lists the running conditions imposed to the contact, the second the material properties and limits, the third the conditions induced by the running conditions on the materials.

Damage, be it breakage, deformation or wear is initiated by overstraining or overstressing. Full modelling of both these causes is not possible today and "simulation" is needed to produce the data required by design engineers to predict function loss. The question then is: how reliable is the data furnished by simulation ? The answer is brought by the analysis of data produced in fretting tests which show that even very small variations in running conditions, in this case in amplitude, can change the nature of the damage. Simulation tests have to be undertaken with the utmost care.

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