MODELING FRETTING WEAR: A PRIMARY STUDY FROM IRREVERSIBLE THERMODYNAMICS

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SUMMARY
Thermodynamics affords a possibility to describe effects of various factors on fretting. A phenomenological model is introduced, the entropy of the sub-processes: heat conduct, diffusion, viscous flow of materials and chemical reaction for the process is discussed and a simplified model is put forward. The predictions for a designed flat-to-flat test are submitted that the pattern of worn scares should change with increase of the ratios of slip amplitudes to contact widths and the products at centre and boundary of contact should express difference. The verification experiments carried out on SRV correspond to the predictions well.

Keywords: Entropy; Irreversible thermodynamics; Tribology system; Fretting wear

1 INTRODUCTION
One vital and persistent goal in engineering is to develop performance relationships between all the variables and parameters in a system, in mathematical form [1, 2]. Recent development of automatic design and nano-technology makes the requirement for systematic quantitative tribology theory more exigent. On the other hand, theory of tribology stagnates in the level of experiment regression [3] and it has lagged far behind the demand of engineering and the development of the science [1, 4].

During the past years, many un-prefigured results have been revealed experimentally. Adaptable self-lubrication techniques, which utilize the products generated by tribo-catalyzed chemical reaction as lubricants, were tested in fretting [5] and sliding [6, 7] conditions. The effects of solid mechanical interaction on the dynamics and the products of chemical reaction (tribo-chemistry) were explored [8, 9]. Experiments also revealed that external electric fields heavily influence the friction and wear properties of a tribo-system [10, 11]. Thermomechanical interactions were paid attention because the failure of gear scuffing in heavy-load high-speed transmission condition [12]. These researches show that parameters of mechanics, material, electricity, chemistry and calorifics have great influence on the friction and wear of a system. To obtain an equation model, which covers the above factors, is not only the demands of engineering, but also a mark of the mature of tribology.

Tribologists never stop their efforts on the goal. A system approach was proposed in 1979 [13]. Pieces of paper were published, which marked the primary try to study tribo-system from thermodynamics points of view [14, 15]. But all of the studies previously did not answer the fundamental question: how to integrate all of the factors with different physical dimensions into one equation.

Dai and his co-authors have published serious results on the exploration. We discussed the structure of tribological system from irreversible thermodynamic point of view [16, 17] and suggested the evolution code of tribo-system: series connect structure, branched structure and circulation structure; we proposed entropy as a key parameter to present the effect of all factors which have different physical dimensions and different tensors of the thermodynamic forces [18]. The parameter, entropy, can character directly or indirectly the change of wear, phase transformation, absorption and desorption, density and evolution of the defects and dislocations, chemical reaction and the degradation of energy. The interactions among the factors were discussed based on the Curie’s relationship [19, 20]. These researches were carried out for general tribology system.

Here we take fretting wear as an example and try to illustration an application of the theory to this tribological problem. Although fretting damage was studied for more than 50 years, it is still one of the greatest modern plagues for industry: aircraft, heat exchanger in power station, automobile, electric contact, orthopedic implants, etc. The fretting maps and mechanical analysis reveal the relations of contact geometry to the amplitude of slip, relations and useful information for qualitative understanding of fretting damage phenomena [21]. No general agreement on its model and mechanisms is formulated [22], but researchers recognized that chemical actions and mechanical interactions, which have different physical dimensions, are considered as two major factors [23, 24].

In this paper, we carried out a primary work on modeling fretting from the thermodynamic point of view, which includes three parts: basic thermodynamics for tribology system. The relationships of the parameters with the entropy production of sub-processes for fretting wear are discussed. A physical model was

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designed. The relations of the worn morphology with the relative fretting amplitudes and the chemical products at different worn areas were predicted. Finally experiments were carried out to verify the predictions.

2 THERMODYNAMICS AND ENTROPY IN FRETTING PROCESS

2.1 Thermodynamics in tribology system

Irreversible thermodynamics was demonstrated as one of the most powerful tools for the study of complex system, where the phenomena and the interference are evoked and caused by the several causes (or thermodynamic forces) [25]. This affords a possibility of a description of the friction, wear, and heat dissipation, chemical reaction, diffusion and viscous flow of the contacted materials occurring in tribological processes. In this paper we based our model on the balance equations and the stability conditions of the irreversible thermodynamics [26], and introduced a phenomenological model (equation) which included all subprocesses and factors of tribo-system in one equation. Then we design a physical model and predict its results, the work aims to find the relations of the parameters in the equation to the sub-processes of tribology.

Under the postulate of local thermodynamic equilibrium, thermodynamic phenomena are described by means of balance equations for extensive quantities, namely mass, momentum, movement of momentum, energy and entropy. Balance of entropy for unit volume is of the form [27]:

\[ \frac{dS}{dt} = -\nabla J_s + \sigma \]

Where \( S \) and \( t \) are entropy per unit mass and time respectively; \( J_s \) is the conduction of entropy flux, which takes the form:

\[ J_s = S U + J_s = -\sum \frac{\mu}{T} J_i \]

is the strength of entropy source in the form of:

\[ \sigma = J_v \cdot \nabla \frac{1}{T} + \sum J_i \cdot [-V \frac{\mu}{T} + \frac{M}{T} F_j] - \frac{1}{T} \nabla \cdot \nabla U + \sum \frac{A_j}{T} \omega_j \]

\( \sigma_H, \sigma_D, \sigma_V, \sigma_C \)

The terms in the right part of the equation (2) present entropy flow caused by convection, heat conduct and diffusion respectively. The equation (3) shows that the entropy production of the system is the summation of the entropy productions of the sub-processes, heat conduct \( \sigma_H \), diffusion \( \sigma_D \), viscous flow of materials \( \sigma_V \) and tribo-chemical reaction \( \sigma_C \), which are the product of the thermodynamic force multiplying corresponding to general flow respectively.

Development of a nonlinear thermodynamic system drifting off the Equilibrium State is evaluated by the stability of the irreversible processes, which is mathematically described by the second derivative of the entropy. This makes balance of entropy in local form equivalent to the balance of second-order entropy production:

\[ \frac{\partial}{\partial t} (\delta^2 S) = -\nabla (\delta^2 J_s) + \delta^2 \sigma \]

In the condition of near equilibrium for critical point, if the boundary conditions keep constant, we can re-write equation (4) as:

\[ \frac{\partial}{\partial t} (\delta^2 S) = -\nabla \cdot 2 \delta \sigma \cdot \delta \sigma + \sum 2 \delta X_i \cdot \delta J_i = 0 \]

The left part of equation (6) expresses the entropy flow, which major caused by the wear derbies generated and moved out, and the right part presents the entropy production in the system, by sub-processes, head conduct, viscous-flow, diffusion and chemical reactions.

2.2 Entropy production of sub-processes in fretting

Heat conduct is the major dissipative process in dry friction, but a theoretical analysis [28] for the temperature field under fretting pointed out that the steady temperature is the major term so that the entropy production for heat conduct should be \( \sigma_H = 0 \).

If we consider the chemical potential of the isotropic materials as constancy for uniform temperature, The entropy production of the diffusion processes \( \sigma_D \) can also be neglected.

The entropy production of viscous flow \( \sigma_V \) presents the effects of the plastic deformation on the dissipative process. Studies show that plastic deformation greatly affected the fretting wear. This means that the entropy production of the viscous flow is determined by the value of plastic deformation. The entropy production is written as [29]:

\[ \sigma_V = \left( \frac{1}{T} \Pi \cdot \nabla U = -\frac{1}{T} \sum \frac{\partial}{\partial y_j} \frac{\partial}{\partial y_j} \right) \]

\[ = \frac{1}{T} (\Pi_{11} \frac{\partial u_1}{\partial y_1} + \Pi_{12} \frac{\partial u_2}{\partial y_2} + \Pi_{21} \frac{\partial u_1}{\partial y_2} + \Pi_{22} \frac{\partial u_2}{\partial y_2} + \Pi_{13} \frac{\partial u_1}{\partial y_3} + \Pi_{14} \frac{\partial u_1}{\partial y_4} + \Pi_{23} \frac{\partial u_2}{\partial y_3} + \Pi_{24} \frac{\partial u_2}{\partial y_4} + \Pi_{33} \frac{\partial u_3}{\partial y_3} + \Pi_{34} \frac{\partial u_3}{\partial y_4} + \Pi_{44} \frac{\partial u_4}{\partial y_4}) \]

Research of the entropy production caused by tribo-chemical reactions \( \sigma_C \) lags far behind the need of modern tribology. Heinike’s studies showed that the chemical reaction under the mechanical interaction (tribo-chemical reaction) is far different from thermo-chemical reaction both dynamics and products. But the quantitative relation is rarely obtained.

Supposing a simplified situation for the fretting processes, where only one chemical reaction, oxidation, takes place. One kind of mass flow, wear of material, occurs, and the contact is flat to flat, so the entropy production can be described as:

\[ \sigma = \sigma_V + \sigma_C = -\frac{1}{T} \Pi \cdot \nabla U + \frac{A}{T} \delta \sigma \]

At the critical state, the equation (6) becomes:

\[ \nabla \cdot \delta \sigma \cdot \delta u = \delta (\frac{1}{T} \Pi) \cdot \delta (\nabla U) + \delta (\frac{A}{T}) \cdot \delta (\sigma) \]
A prediction may be given qualitatively according to the equation (9):

1. In equation (9), assuming entropy change per unit mass $\delta s$ is the same, increase of the left part in equation (9) means an increase of $\delta u$, which present the wear rate (mass loss per unit time). The heavier fretting wear will take place at the place and the time if the entropy production (right part) is higher.

2. For considered chemical reaction, the product does not have lubricous properties, so the heavier fretting wear will happen at place where $\sigma$ is higher in equation (9). This means that the wear rate will be higher at the boundary for where there is full supplication of oxygen and the product of chemical reaction will be different at the center and the boundary of the contact when the slip amplitude is smaller.

3. If the contact stress and width of specimen keep constant, the wear scar should be two concave hollows corresponding to the boundaries because higher entropy production caused by plastic deformation and tribo-catalyzed chemical reaction at the places. With increase of slip amplitude, the wear should be heavier for the enhancement of tribo-chemical reaction and the mechanical action. But the wear scar may change into one concave hollow when slip amplitude is greater than a certain value, which, theoretically, is half of contact width.

3 PHYSICAL MODEL AND TEST DESIGN

A flat-to-flat contact fretting pair (Fig.1) is designed to verify above predictions.

![Fig. 1: Illustration of flat to flat fretting contact](image)

The fretting tribo-system is made up of bodies M1, M2 and inter-surface layer M3 (Third body). The interface of M1 and M3 is marked as S13, that of M2 and M3 as S32. Here M1 and M2 are isotropic solid materials. Under simplified condition, the constitutive equation can be expressed by plastic-elastic mechanics.

M3 is composed by debris of metal and oxides. Both samples are made of titanium alloy [16] and polished by WAW 10 metallographic sand paper and kept their planarity under process of polishing in order to accomplish perfect contact. The widths B of up specimen M2 are 0.5, 1.0, 2.0 and 4.0 mm, and the width of down specimen M1 is 4.5 mm. Normal loads Fn are 100 or 200 N. The magnitudes of slip A are 0.06, 0.1, 0.14 and 0.25 mm. The experiments were carried out on SRV Friction and Wear Test Machine at ambient temperature in air.

4 EXPERIMENT RESULTS AND DISCUSSIONS

4.1 Pattern of worn scars to relative slip amplitude

The morphology of worn scars at different relative slip amplitude $S_{RA}$, which is defined as peak to peak slip amplitude $2A$ divided by contact width B, are shown in Figure 1 and 2. The curves of wear scars are measured by a profilometer along the slip direction.

The test shows in Fig.1 were carried out at contact width B = 0.5 mm, oscillating sliding frequency 55 Hz for 30 minutes. The outlines of the worn surface makes clearly that the worn morphologies is one concave hollow in the center when $S_{RA}$ equals to 0.6 and it becomes two concave hollows at the contact boundary, when $S_{RA}$ is 0.4 and 0.24. The same characters, shown in figure 2, are obtained when B equals to 1.0 (a, b, c) or 4.0 (d), oscillating sliding frequency 14 Hz for 20 minutes.

![Fig. 2: Wear scars of specimen (B = 0.5)](image)

![Fig. 3: Wear scars of specimen (B = 1.0 or 4.0)](image)

![Fig. 4: X-ray Photoelectron spectrum of products at center and boundaries](image)

Test results are summarized in figure 4, which shows that $S_{RA}$ is a key parameter in determining the pattern of worn surface and the critical value is about 0.5.

4.2 Chemical products in different worn zone

Figure 4 presents the X-ray Photoelectron Spectrum of element titanium at the center and the boundaries of the contact. It shows that the product, TiO$_2$, of tribochemical reactions at the boundary zone differs from the product, TiO$_x$, at the center, where x is greater then 1 but less then 2.

These results reflect the effects of oxygen density and mechanical canalization on the product obtained at fretting condition. The result is important evidence to reveal that higher fretting wear rate correspond to the
4.3 The plastic deformation

The plastic deformation of fretting pair was studied through metallography observation. Figure 5 shows clearly that the crystals of the specimen near contact surface were drawn and the plastic flow can also be found in the figure. It has been demonstrated that the plastic deformation is one of the most important factors during fretting.

5 CONCLUSIONS

A thermodynamic method is introduced to model fretting wear in illustration way. A flat-to-flat fretting contact is designed and verified. The test results correspond to the predictions well. Pattern of worn scar is determined by $S_{RA}$. When $S_{RA} > 0.5$, the scar is one hollow, otherwise it is two. More studies quantitatively should be conducted further.

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7 REFERENCES

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