International Journal of Fracture Fatigue and Wear, Volume 3

Proceedings of the 4th International Conference on
Fracture Fatigue and Wear, pp. 227-232, 2015

DEBRIS MODELS USED FOR WEAR SIMULATIONS

Tongyan Yue and Magd Abdel Wahab

Ghent University, Laboratory Soete, Belgium

Abstract: In fretting wear, debris is usually trapped between contact surfaces due to the micro relative slip. Therefore, debris plays an important role in fretting wear, which can protect or harm interfaces according to different dominant wear mechanisms. Experimental methods for investigating debris, however, are time consuming and difficult to provide the instantaneous information during the wear process. Getting contact information by numerical modelling method is therefore necessary. Meanwhile, a suitable debris model is an indispensable part of a complete prediction tool for fretting wear. This paper reviewed the experiments of fretting wear and the numerical models of debris in wear, especially in fretting wear conditions.

Keywords: Debris, Fretting wear; Numerical modelling

1 INTRODUCTION

Fretting wear is a surface damage between two contact surfaces, with oscillated micro relative slip under contact pressure. The index e, which is the ratio of relative slip δ to half contact width a between interfaces, is used for identifying the transition from fretting to reciprocating wear [1]. If $e > 1$, the contact surface is exposed to the surroundings, and thus the debris created from matrix material can eject from interface easily. While if $e < 1$, there is an unexposed area that the debris could stay in since the magnitude of applied normal load is sufficiently high and the amplitude of displacement is small [2]. Therefore one important characteristic of fretting wear is debris staying in the contact surfaces during the process of wear.

In real applications, fretting wear may happen in every tribo-system suffered from cyclic load, such as stem/cement contact of hip joint [3], blade/disk contact of dovetail joint in turbine [4], interface between strands in hosting ropes [5], or surfaces between electrical connectors [6]. For cemented total hip joint authors of reference [7] found that cement surface was severely damaged in contact with stem surface by doing in-vitro simulation. Moreover the cement debris trapped in the micro-pores may cause aseptic loosening of the femoral component. In the electrical connectors aspect, research of [8] showed that, in Au coated copper electrical contacts, the contact resistance increased significantly when the oxide debris covering the contact surface as a result of fretting wear.

Due to the important role debris playing in the practical application, researchers tried to explain the process of fretting wear from debris aspect. The motivation of present work is to review the research of wear debris in both experimental and numerical modelling aspects. This paper is divided 4 parts; after the introduction section, the experimental research of debris is reviewed. Then, the numerical methods employed for debris modelling is presented in section 3. Finally, a conclusion is presented.

2 EXPERIMENTAL RESEARCH FOR DEBRIS

According to the research by Hurricks [9] in 1970, the process of fretting wear between metal could be divided into three stages: (a) initial adhesion and metal transfer (b) generation of debris and (c) the steady-state wear. In 1973, the delamination theory of wear was presented by Suh [10]. This theory was also based on three points: (a) the behavior of dislocations at the surface, (b) sub-surface crack and void formation, and (c) subsequent joining of cracks by shear deformation of the surface. It took actual micro-mechanism based failure and damage processes into consideration, which was more close to practical situation. The next year Waterhouse and Taylor [11] studied fretted surfaces of 0.7 carbon steel, commercially pure titanium, and Al-Zn-Mg alloy, which showed that loose wear debris caused by the propagation of sub-surface cracks was similar to that postulated in the delamination theory of wear. Thus, delamination wear was proved as one of wear mechanisms happens in the fretting wear. Later on, C. Colombié et al [12] studied fretting wear tests of different materials, i.e. steel on steel and chalk on glass, and found that the generation and maintenance of debris layer with abrasion of debris layer governed the wear of matrix material, which means abrasion wear also could be a wear mechanism for fretting wear.

Varenberg et al. [13] investigated the role of oxide debris in fretting wear in tribo-systems of steel on bronze and steel on steel. They found that the wear mechanisms are different according to different types of friction pairs. For the combination of steel and bronze, the adhesive wear mechanism was dominant and the debris acted as a kind of lubricant, which could reduce damage of fretting wear, while for the pair of steel on steel the abrasive mechanism was prevailing, the debris could accelerate the damage. The same year M.Z. Huq et al [14] found that the normal load and relative humidity of the ambient air also had influence on the movement of debris in fretting wear of coatings. The recent paper of J. D. Lemm [15] presented findings that for contact pairs of steel where they had different hardnesses, a critical hardness differential threshold existed. Above this threshold, the wear was predominantly related to the harder specimen, which meant the surface hardness of steel impacted on the debris retention in fretting wear process. Furthermore, even for the same fretting coupling, an aluminum alloy (A357) on 52100 steel which studied by K. Elleuch and S. Fouvry [16], the form and composition of debris were various relating a displacement amplitude threshold that is independent of sliding velocity and temperature effect.

Based on the experimental results above, it could be concluded that fretting wear is a very complex phenomenon of surface damage and that debris plays various role, which depend on the materials of tribo-system (types, hardness), loading conditions (normal load and displacement amplitude applied) and environment conditions. However due to the micro range of displacement between interfaces and micro or even nano scale of debris, doing experiment is difficult to capture the movement of debris during the process of wear synchronous, hence researchers turn to numerical modelling to analyse the role debris playing during wear process.

3 NUMERICAL MODELLING OF DEBRIS

3.1 Numerical modelling of debris

Authors of reference [17] developed the dry contact model with debris for the heavily loaded rolling and sliding contacts as shown in Fig. 1, which could predict elastic-plastic debris denting process when the debris passes through the contact area.

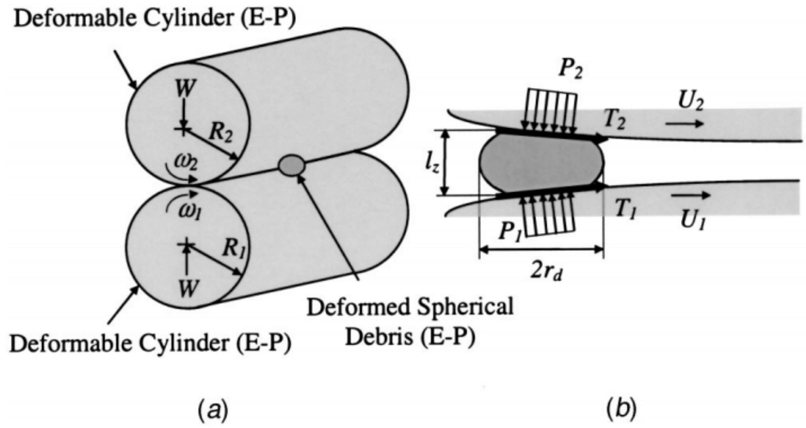


Fig. 1 Dry contact model with debris: (a) two cylinders in contact; and (b) debris forces [17]

According to the dry contact model, the relationship of surface profile and deformation of mating surface is given by:

$$\boldsymbol{H}(\boldsymbol{X},\boldsymbol{Y}) = \boldsymbol{H_0}(\boldsymbol{X},\boldsymbol{Y}) + \frac{\boldsymbol{X^2}}{\boldsymbol{2}} + \frac{\boldsymbol{2R_xP_h}}{\boldsymbol{\pi E'}} \iint \frac{\boldsymbol{P(X'-Y')}}{\boldsymbol{(X-X')^2-(Y-Y')^2}} \boldsymbol{dX'dY'} \tag{1}$$

Where $\boldsymbol{H}$ and $\boldsymbol{H_0}$ are the dimensionless mating surface curvature and the constant used for calculating $\boldsymbol{H_0}$, respectively. $\boldsymbol{X}$ and $\boldsymbol{Y}$ are the dimensionless coordinates in rolling direction and cross rolling direction, respectively. $\boldsymbol{P_h}$ and $\boldsymbol{P}$ are the maximum Hertzian pressure (Pa) and dimensionless pressure, respectively. Also $\boldsymbol{R_x}$ is the reduced radius of curvature in rolling direction, which can be calculated as:

$$R_x{}^{-1} = R_1{}^{-1} + R_2{}^{-1} \tag{2}$$

Where R_1 and R_2 are the radius of contacting cylinders. And E' is the equivalent modulus of elasticity:

$$\frac{2}{E'} = \frac{1-v_1{}^2}{E_1} + \frac{1-v_2{}^2}{E_2} \tag{3}$$

Where E_1 and E_2 are young's modulus of the cylinders. The debris shape when it goes along the contact is given by:

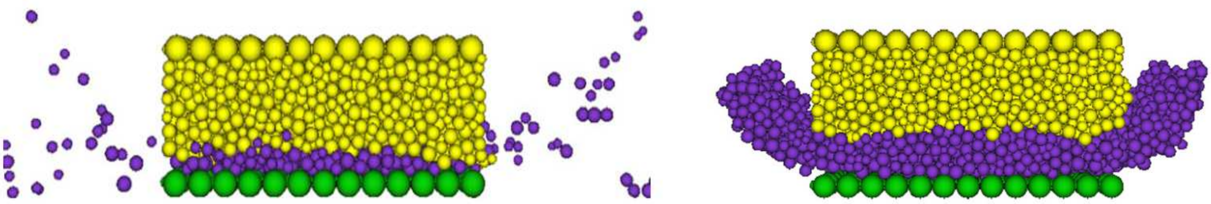
$$D_S = \frac{L_Z}{2}\sqrt{1 - \frac{(X-X_c)^2}{R_d^2} - \frac{(Y-Y_c)^2}{R_d^2}} \quad (4)$$

Where L_Z is the dimensionless debris height, R_d is the dimensionless radius of the deformed debris, X_c, Y_c are the dimensionless center coordinate of the debris in the rolling and cross rolling directions, respectively.

By finite element method (FEM) and fast fourier transform method, authors [17] studied the debris material properties, location and the friction between the debris and matching surfaces and they found that these parameters played important role in the debris size and that high contact pressure between debris and contact surface can cause plastic deformation.

Jinbin Han et al. [18] proposed an irreversible cohesive zone model based on cohesive zone model to simulate delamination wear in a coating system. The proposed modelling approach had the advantage that details of the delamination wear process can numerically be studied, and that a unified framework from delamination initiation and propagation was provided. Based on this model, the influence of displacement amplitude, normal load and hardness on sliding wear were studied and the wear rate obtained had good agreement with the Archard model. However the main difficulty of this model is obtaining the exact values of parameters used in this model by experiments, such as cohesive strength, cohesive length and cohesive energy.

Fillot and co-authors [19] presented an analytical wear model based on particle detachment mechanism and mass equilibrium. They used the mass equilibrium equation to link the detachment and ejection of debris based on third body concept to investigate the process of wear. In article [20], the same author presented a numerical model based on the same idea, i.e. detachment of particles and flow of debris. Instead of FEM, the discrete element method was employed since FEM was not yet suitable to model the detachment and movement of the discontinuous particles. In this paper, authors studied the role played by adhesion in wear, and found that if the particle adhesion was less, the detached particles ejected the interface easily, which brought more wear, while wear was reduced when the particle adhesion increased since the flow of detached and ejected particles decreased during the process, as shown in Fig. 2 (a) and (b), respectively.



(a) *(b)*

Fig. 2 The contact interface when a stable layer of third body is obtain.
(a) the particles are not adhesive, (b) the particles are highly adhesive [20]

3.2 Fretting wear modelling with debris

Due to the critical impact of debris in fretting wear process, some researchers developed models of debris in fretting wear. Elleuch and Fouvry found [21] that the debris ejection controlled fretting wear and developed a debris flow chart approach, shown in Fig. 3, which illustrated that the total wear kinetics could be described as a function of debris generation and ejection rates. And by increasing the sliding amplitude, the flow of debris trapped in the interface increased, which meant that the debris flow velocity should have a relation with the applied displacement amplitude.

Based on the FE tools of fretting wear presented by McColl in [22], researchers of this group revised this model to simulate the debris as a layer structure accumulated on the contact surface [23] in 2007. In Fig. 4, two contact interfaces exist in this model. In the interface between bottom of debris and $\boldsymbol{\Gamma_1}$ the contact constraint was assumed rigid connection, while for the interface between $\boldsymbol{\Gamma_2}$ and $\boldsymbol{\Gamma_3}$ the basic Coulomb friction model was applied for the contact property. During simulation of fretting wear, the evolution behaviour of debris, such as thickness and width, and the normal movement of debris layer was investigated. This simulation tool predicted debris effects on wear damage by redistributing the contact pressure and relative slip between contact surfaces based on Archard wear model and Hill's yield model.

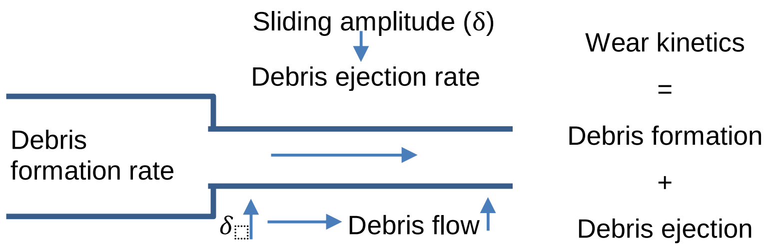


Fig. 3 The debris flow chart approach of wear kinetics under gross slip fretting wear conditions [21]

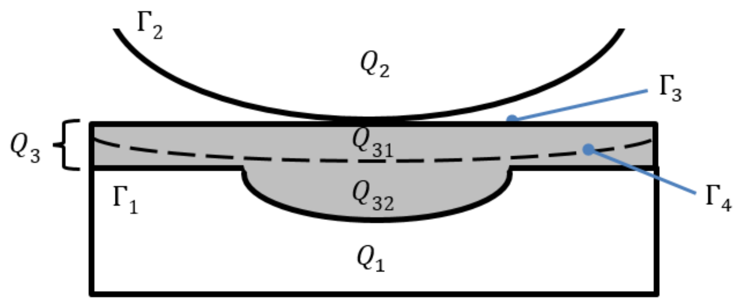


Fig. 4 The simplified fretting wear contact model with a debris layer, $\boldsymbol{Q_1}$ and $\boldsymbol{Q_2}$: the contacting bodies, $\boldsymbol{Q_3}$: debris, $\boldsymbol{Q_{31}}$: loose debris layer and $\boldsymbol{Q_{32}}$: compacted debris layer. $\boldsymbol{\Gamma_1}$: top surface of $\boldsymbol{Q_1}$, $\boldsymbol{\Gamma_2}$: bottom surface of $\boldsymbol{Q_2}$, $\boldsymbol{\Gamma_3}$: top surface of debris, $\boldsymbol{\Gamma_4}$: boundary between $\boldsymbol{Q_{31}}$ and $\boldsymbol{Q_{32}}$ [23]

Two years later, the authors presented a multi-scale modelling method for fretting wear simulation [24]. The macro model is wear simulation based on Archard wear model, and the micro model is asperity contact model based on the roughness characteristics, shown in Fig. 5. $\boldsymbol{\lambda}$ is the wavelength of the asperity spacing which is estimated by the roughness information of the contacting surfaces. $\boldsymbol{d_{sub}}$ is the instantaneous thickness of the debris layer. Both normal load $\boldsymbol{p^{sub}}$ and displacement with amplitude $\boldsymbol{\lambda/2}$ were applied to the micro model. Micro model was used to determine the local plastic deformation under debris layer and furthermore to gain the insightful understanding of fretting wear mechanics. Though some assumptions were made, i.e. a) asperities were distributed uniformly, b) asperities were spherical with uniform radius which were determined by the roughness information, and c) asperities were rigid, this multi-scale model successfully predicted the fretting wear simulation with evolution of interface between debris and substrate, which is closer to the realistic situation.

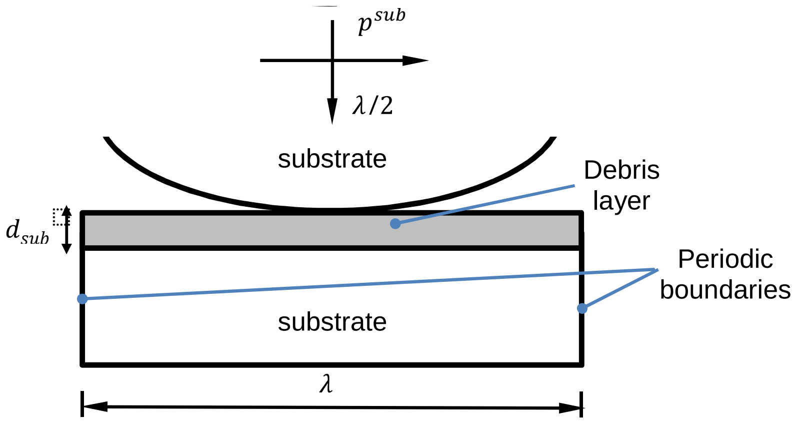


Fig. 5 The asperity model used in [24]

In 2011, Basseville et al. [25] presented a fretting wear model which explicitly included the rectangular particles of fixed number as the third body, shown as Fig. 6. The wear model for both substrate and particles was from dissipated energy method, and the link between substrate and particles was based on the conservation of matter, i.e. the amount of matter lost due to wear was added to the debris. Though authors simplified fretting wear process for this model, such as neglecting the oxidation, choosing the fixed number of particles, the simulation showed that debris may be trapped in the contact interface in partial slip condition while they ejected from the interface when gross sliding or mixed slip occurred, which provide debris movement information of fretting wear from physical aspect.

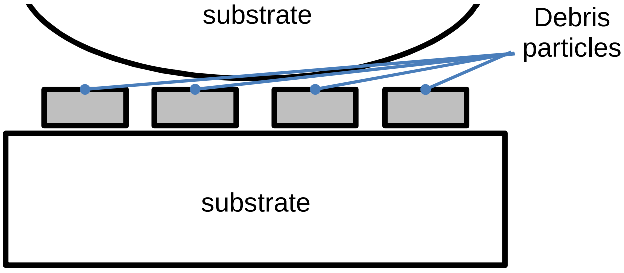


Fig. 6 Schematic of the fretting wear model applied in [25]

More recently, Benjamin D. Leonard et al. [26] developed a fretting wear modelling with the effect of the third body by the combined finite-discrete element method. In this model, FEM was employed for the calculation of substrate bodies, while the debris and contact interactions between debris and substrates was simulated by the discrete element method. In this article they presented two models, i.e. a) the flow of the third body between flat rigid plates for analysing the viscous properties, b) a worn Hertzian contact due to partial slip with third body for studying contact variables of the interfaces. Though the third body of this model was just imported in the worn surface but without attending the process of fretting wear, by modelling of contact between substrates, contact between substrate and the debris, and contact between debris particles themselves. This model studied influence of wear particles on the stress distribution in the contact surface from particle shapes, number of cycles, etc. aspects.

4 CONCLUSIONS

Debris of wear, especially of fretting wear, plays various role in the wear process. By experiments, it is found that debris can reduce the damage of fretting wear or bring aggravation. Several wear mechanisms could exist in fretting wear process according to different tribo-systems, loading conditions, or the surrounding conditions. Given to the importance and complexity of debris, researchers also applied numerical modelling method, i.e. analytical method, FEM, multi-scale techniques and finite-discrete method, to predict the movement of debris in wear or fretting wear. Though a significant progress has been achieved in modelling the debris in wear process, improvement would be realised in the mechanical property definition of debris, the contact property between debris and substrate, modelling the evolution behaviour of debris etc. in the future.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of China Scholarship Council.

6 REFERENCES

[1] S. Fouvry, P. Kapsa and L. Vincent, Quantification of fretting damage, Wear, 200 (1–2), 186-205, 1996.

[2] N. Arun Prakash, R. Gnanamoorthy and M. Kamaraj, Fretting wear behavior of controlled ball impact treated aluminium alloy under dry sliding condition, Surface and Coatings Technology, 207 450-460, 2012.

[3] P. Herberts and H. Malchau, Long-term registration has improved the quality of hip replacement: a review of the Swedish THR Register comparing 160,000 cases, Acta Orthopaedica, 71 (2), 111-121, 2000.

[4] K. Anandavel and R. V. Prakash, Effect of three-dimensional loading on macroscopic fretting aspects of an aero-engine blade–disc dovetail interface, Tribology International, 44 (11), 1544-1555, 2011.

[5] D. Wang, D. Zhang, S. Wang and S. Ge, Finite element analysis of hoisting rope and fretting wear evolution and fatigue life estimation of steel wires, Engineering Failure Analysis, 27 (0), 173-193, 2013.

[6] M. Antler, Electrical effects of fretting connector contact materials: A review, Wear, 106 (1–3), 5-33, 1985.

[7] S. Barrans, L. Blunt, H. Zhang and L. Brown, Reproduction of fretting wear at the stem—cement interface in total hip replacement, Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 221 (8), 963-971, 2007.

[8] W. Ren, P. Wang, J. Song and G. Zhai, Effects of current load on wear and fretting corrosion of gold-plated electrical contacts, Tribology International, 70 (0), 75-82, 2014.

[9] P. L. Hurricks, The mechanism of fretting — A review, Wear, 15 (6), 389-409, 1970.

[10] N. P. Suh, The delamination theory of wear, Wear, 25 (1), 111-124, 1973.

[11] R. Waterhouse and D. Taylor, Fretting debris and the delamination theory of wear, Wear, 29 (3), 337-344, 1974.

[12] C. Colombié, L. Vincent, M. Godet, Y. Berthier and A. Floquet, Fretting: Load Carrying Capacity of Wear Debris, Journal of Tribology, 106 (2), 194-201, 1984.

[13] M. Varenberg, G. Halperin and I. Etsion, Different aspects of the role of wear debris in fretting wear, Wear, 252 (11), 902-910, 2002.

[14] M. Huq and J.-P. Celis, Expressing wear rate in sliding contacts based on dissipated energy, Wear, 252 (5), 375-383, 2002.

[15] J. D. Lemm, A. R. Warmuth, S. R. Pearson and P. H. Shipway, The influence of surface hardness on the fretting wear of steel pairs—Its role in debris retention in the contact, Tribology International, 81 (0), 258-266, 2015.

[16] K. Elleuch and S. Fouvry, Wear analysis of A357 aluminium alloy under fretting, Wear, 253 (5), 662-672, 2002.

[17] Y. S. Kang, F. Sadeghi and M. R. Hoeprich, A Finite Element Model for Spherical Debris Denting in Heavily Loaded Contacts, Journal of Tribology, 126 (1), 71, 2004.

[18] J. Han and T. Siegmund, Computational simulations of delamination wear in a coating system, Wear, 267 (9-10), 1680-1687, 2009.

[19] N. Fillot, I. Iordanoff and Y. Berthier, Wear modeling and the third body concept, Wear, 262 (7-8), 949-957, 2007.

[20] N. Fillot, I. Iordanoff and Y. Berthier, Modelling third body flows with a discrete element method—a tool for understanding wear with adhesive particles, Tribology International, 40 (6), 973-981, 2007.

[21] K. Elleuch and S. Fouvry, Experimental and modelling aspects of abrasive wear of a A357 aluminium alloy under gross slip fretting conditions, Wear, 258 (1-4), 40-49, 2005.

[22] I. R. McColl, J. Ding and S. B. Leen, Finite element simulation and experimental validation of fretting wear, Wear, 256 (11-12), 1114-1127, 2004.

[23] J. Ding, I. R. McColl, S. B. Leen and P. H. Shipway, A finite element based approach to simulating the effects of debris on fretting wear, Wear, 263 (1-6), 481-491, 2007.

[24] P. H. Shipway, E. J. Williams, S. B. Leen and J. Ding, A multi-scale model for fretting wear with oxidation-debris effects, Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 223 (7), 1019-1031, 2009.

[25] S. Basseville, E. Héripré and G. Cailletaud, Numerical simulation of the third body in fretting problems, Wear, 270 (11-12), 876-887, 2011.

[26] B. D. Leonard, A. Ghosh, F. Sadeghi, S. Shinde and M. Mittelbach, Third body modeling in fretting using the combined finite-discrete element method, International Journal of Solids and Structures, 51 (6), 1375-1389, 2014.