Energy-based Modeling of Fretting Wear in Steam Generator Tubes

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1. Introduction

Steam generator (SG) tubes serve as pressure boundary components in nuclear power plants and are susceptible to fretting wear at contact locations with support structures due to flow-induced vibration. The conventional Archard model[1] has limitations in describing impact or combined impact-sliding conditions. Although energy-based approaches have been proposed, total energy loss alone cannot consistently explain wear behavior under combined impact-sliding environments. Therefore, this study analyzes SG tube wear by separating tangential and normal energy loss components and proposes a component-separated energy-based wear model with improved predictive capability.

2. Energy-based Model

To overcome the limitations of the conventional Archard model, an energy-based approach has been introduced to quantify fretting wear. In this framework, the wear volume V is assumed to be proportional to the cumulative dissipated energy. The linear total energy model can be expressed as

$$V = KN\Delta E \tag{1}$$

where K is the wear coefficient, N is the number of wear cycles, and ΔE is the energy loss per cycle. The energy loss per cycle is defined as the difference between the kinetic energies before and after impact:

$$\Delta E = E_0 - E_f = 1/2\, mv_0^2 - 1/2\, mv_f^2 \tag{2}$$

where m is the mass, and v_0 and v_f are the velocities before and after impact, respectively.

Under pure sliding or normal impact conditions, a nearly linear relationship between wear volume and energy loss has been reported[2,3], supporting the applicability of Eq. (1). However, in combined impact-sliding environments, the assumption that wear is solely proportional to the total energy loss is insufficient to explain the observed nonlinear behavior. As shown in Fig. 1, the impact-sliding wear test results indicate that the wear rate increases exponentially rather than linearly with increasing total energy loss. This suggests that the linear total energy model cannot fully capture the nonlinear characteristics of wear growth under complex contact conditions.

To address this limitation, the present study proposes a component-separated energy-based wear model in which the energy loss is divided into tangential (ΔE_t) and normal (ΔE_n) components, each contributing to wear through separate terms. The proposed model is expressed as

$$V = K_s N \Delta E_t^n + K_i N \Delta E_n \tag{3}$$

where K_s and K_i are the sliding (tangential) and impact (normal) wear coefficients, respectively, and n is the tangential wear exponent. This formulation reflects the dominant role of shear-related energy dissipation in fretting wear and improves predictive accuracy under combined impact-sliding environments relevant to SG tubes.

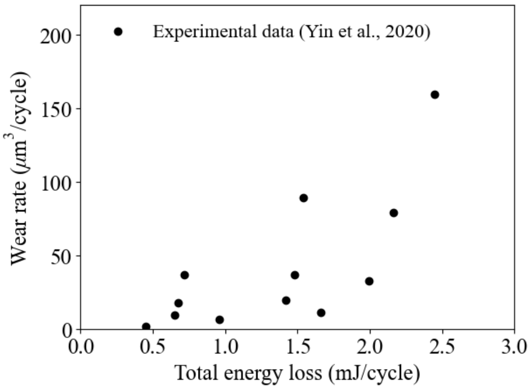


Fig. 1. Relationship between energy loss and wear rate under impact-sliding wear[4].

3. Impact-Sliding Wear Behavior and Model Validation

To validate the proposed model under impact-sliding conditions, published experimental data[4] for Alloy 690 SG tubes were employed. The model fitting results (Table I) show that the linear total energy model (Model 1) yields an R^2 value of 0.46, whereas the proposed nonlinear component-separated model (Model 2) achieves an R^2 of 0.90. In Model 2, the sliding wear coefficient (K_s) was found to be larger than the impact wear coefficient (K_i), and the tangential exponent exceeded unity, indicating a shear-dominated and nonlinear wear growth mechanism.

The comparison between predicted and measured wear rates (Fig. 2) demonstrates that Model 2 shows better agreement with the 1:1 line, with a substantial reduction in root mean squared error (RMSE) compared to Model 1. Furthermore, the absolute error distribution (Fig. 3) reveals that while Model 1 exhibits localized large errors in high tangential energy regions, Model 2 maintains smaller and more uniformly distributed errors across the entire energy range. These results confirm that incorporating the nonlinear contribution of tangential energy dissipation enables more accurate prediction of wear behavior under combined impact-sliding conditions.

Table I: Main parameters of models

Models	Wear coefficient ($\mu m^3/mJ$)			n	R^2
	K	K_s	K_i		
Model 1	34.5				0.46
Model 2		262.3	6.4	2.4	0.90

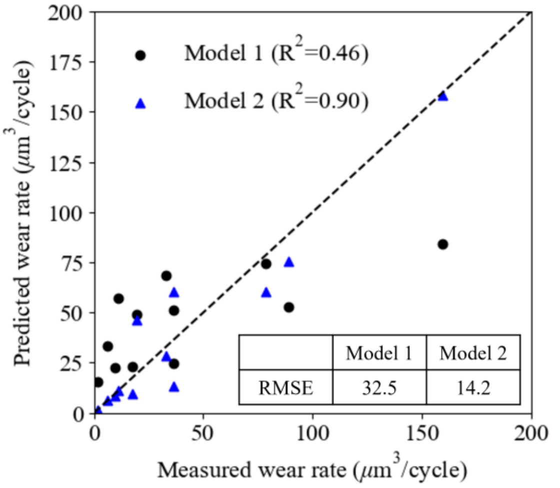


Fig. 2. Comparison of predicted and measured wear rates for Model 1 and Model 2.

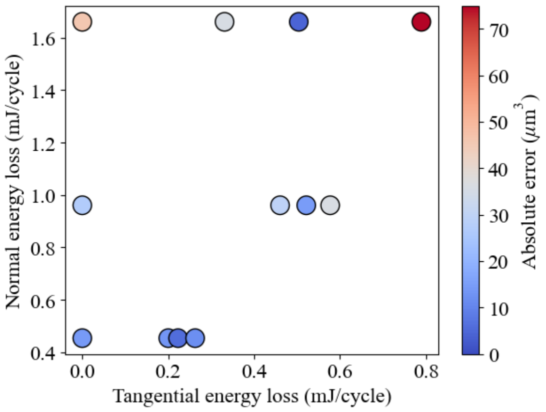
4. Conclusions

In this study, a component-separated energy-based wear model was proposed to describe the impact-sliding fretting wear behavior of SG tubes by independently accounting for tangential and normal energy loss components. The main conclusions are summarized as follows.

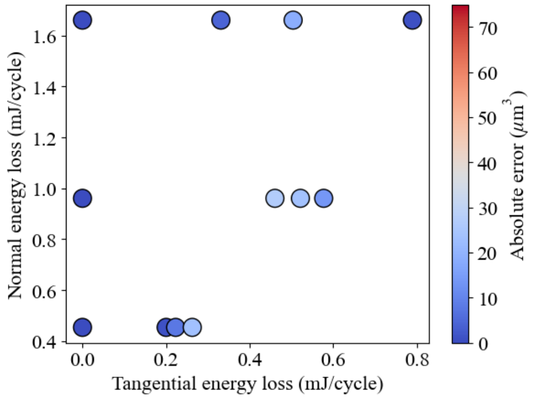
(1) By separating the tangential and normal energy components, the proposed model provides a more rational description of wear behavior under combined impact-sliding conditions.

(2) Model fitting results show that the proposed nonlinear component-separated model significantly improves the predictive accuracy than the linear total energy model, with clear improvements in both the coefficient of determination and error distribution.

(3) The fitted parameters indicate that the sliding wear coefficient is larger than the impact wear coefficient, and the tangential exponent exceeds unity. This confirms that fretting wear of SG tubes is shear-dominated and exhibits nonlinear wear growth characteristics.



(a) Model 1



(b) Model 2

Fig. 3. Absolute error distributions of wear rate prediction as a function of energy loss components: (a) Model 1, (b) Model 2.

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REFERENCES

[1] J.F. Archard, Contact and Rubbing of Flat Surfaces, Journal of Applied Physics 24 (1953) 981–988. https://doi.org/10.1063/1.1721448.

[2] H. Ming, X. Liu, J. Lai, J. Wang, L. Gao, E.-H. Han, Fretting wear between Alloy 690 and 405 stainless steel in high temperature pressurized water with different normal force and displacement, Journal of Nuclear Materials 529 (2020) 151930. https://doi.org/10.1016/j.jnucmat.2019.151930.

[3] Y. Sun, Z. Cai, Z. Chen, H. Qian, L. Tang, Y. Xie, Z. Zhou, M. Zhu, Impact fretting wear of Inconel 690 tube with different supporting structure under cycling low kinetic energy, Wear 376–377 (2017) 625–633. https://doi.org/10.1016/j.wear.2017.01.011.

[4] M. Yin, Z. Cai, Z. Zhang, W. Yue, Effect of ultrasonic surface rolling process on impact-sliding wear behavior of the 690 alloy, Tribology International 147 (2020) 105600. https://doi.org/10.1016/j.triboint.2019.02.008.