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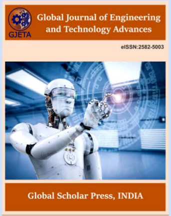

(Review Article)

Review on modern and future tribological directions of frictional-thermal sliding wear modeling

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Abstract

Mechanical wear is a tribological phenomenon that causes parts deterioration over time when they are in service. The wear causes enormous performance and economic burden on the mechanical applications, and the main aspects of mechanical designs should consider first. Mechanical wear is accelerated in the presence of high temperature that is caused by the frictional forces between the sliding surfaces. The generated temperature is classified into instantaneous (flash) and bulk. Both flash and bulk temperatures are modeled mathematically and verified experimentally. The models utilize different techniques and simplifications in order to obtain valid results. Future directions of the modeling techniques involve enhancing the collection of the experimental data as well as the incorporation of the chemical interactions.

Keywords: Sliding Wear; Frictional-thermal; Bulk temperature; Flash temperature

1. Introduction

Wear in components is classified into mechanical, chemical, or a combination of both. Mechanical wear is one of the main reasons for components failure during service, hence the relatively high economic losses associated with it. This loss is directly related to the mechanical consumption of the parts, as well as indirectly related to the lack of performance and energy burden that accompanies the mechanical wear. Furthermore, researchers have shown that the economic burden resulting from mechanical wear exists on all levels of mechanical components, macro, and micro, with different degrees of influence depending on the surrounding operational conditions [1–3].

By definition, mechanical wear is defined as the continuous loss of amounts of the contacting bodies' surfaces during service. This loss exists where relative motion and normal pressure exist between any two contacting surfaces. In the relative motion, surfaces experience ploughing of the micro asperities with the counter surface part, which involves plastic deformation. Furthermore, this process usually involves chemical reactions which get fueled by the elevated temperature resulting from the heat that is generated by the thermoelastic and thermoplastic of the asperities' interactions [4,5].

During contact between two (or more) surfaces, about 95% of the frictional mechanical energy is converted to heat and then dissipated into the involved bodies and their surroundings. Furthermore, this heat generation is the main reason behind the wear events that might lead to the eventual deterioration of the components [6]. In addition to the instant effect on the components, the elevated temperatures are often unwanted and would push the designers to take care of the heat in order to optimize the general operation during the service life. The mitigation of wear and heat usually involves adding lubricants to the surfaces in the form of liquids or materials in the components [7]. The temperature in

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a frictional system is usually classified into flash and bulk. The former is used to describe the instances at which the heat is generated at the exact contacting surfaces, which makes it the maximum [8], while the latter is used to express the energy that diffuses to the far masses of the bodies. Unlike the flash temperature, the bulk temperature is affected by many material and geometrical factors, such as the thermal diffusivity, thermal conductivity, heat capacity, convective heat transfer coefficient, and the shape of the geometry, i.e., the same parameters that affect the conventional conduction-convection heat transfer problem.

Despite the huge importance of this heat generation, the way this energy is distributed into the surroundings is highly disputed among researchers. In this context, some works considered an even heat partitioning between the contacting surfaces [9], while others took one side as the full dissipator of the heat energy [10]. The increase in temperature at the contacting surfaces is, naturally, at its highest at the close regions of the contacting surfaces. The modeling of the thermal distribution has taken significant parts of the literature.

2. Modeling of Frictional-Thermal Sliding

There have been several attempts with different assumptions on how to model the thermal interaction between the bodies. Some works assumed that the body is isolated with semi-infinite dimensions [11,12]. Others modified the model by including a few additional heat dissipators [13]. In comparison, other works considered what is known as a thermal coupling in the studies in order to include both of the contacting surfaces [14,15]. Additionally, several other works included the unbalanced factors of the contacting nature [16,17].

Frictional-thermal studies have utilized theoretical, experimental, and experimental-oriented modeling to investigate the nature of the thermal characterization of the contacting surfaces. In theory-based studies, researchers have derived their models from the governing equations of heat conduction in solids. The widely-used example for those studies is the Pin-on-Disk (PoD) experiment. The modeling of this experiment's disk considers transient conditions in which temperature is calculated as a function of time and position along radial and thickness directions. At the same time, variations with time are not included in steady-state studies. As for the pin, it is usually taken as a one-dimensional body in which the temperature variation is considered along the longitudinal direction only [18]. Typically, the theoretical solution involves simplifications and assumptions related to the way heat energy is partitioned, natural convection, and rotational velocity. These simplifications are necessary in order to approximate a closed-form solution [19].

Other modeling works have utilized the advantages of numerical methods, especially finite element analysis [10,19–21]. In such scenarios, the domain is discretized into elements, and the differential equation of conduction is applied over each element for the whole domain. The numerical methods offer versatility in terms of the involved parameters and their limiting ranges. Therefore, they are often used to compare and verify the results obtained from analytical solutions. Additionally, the numerical tools have assisted in the determination of the temperature distribution for transient and steady-state frictional-thermal problems [22]. In order to obtain representative answers from the numerical tools, the proper boundary conditions have to be selected. The contacting surfaces usually have higher element density than the rest of their respective bodies in order to capture the gradients of the temperature and, if required, the stresses. Furthermore, for the PoD studies, the advantage of symmetry is taken in account in order to reduce the problem size and minimize the computational time. Although it facilitates several assumptions, still the heat generation splitting ratio has to be decided in order to convert the frictional energy into the contacting surfaces.

For both analytical and numerical methods, some of the parameters have to be obtained from experimental work, such as the coefficient of wear and the coefficient of friction. These two parameters represent the characterization of the contacting surfaces, and they involve significant mechanical and chemical complexity if attempted to be calculated analytically. As mentioned previously, heat energy partitioning has to be selected between the body-contacting bodies [15]. In the studies on the PoD experiment, some works considered equal energy partitioning, while others had the rotating body to have full energy dissipation. However, some studies have shown that it might be possible to calculate the ratio of energy partitioning analytically by equating the temperature at the center of the contacting surfaces [6]. The frictional energy is calculated from the following equation:

$$Q=\mu*P*V \;\ldots\ldots\;(1)$$

Where μ is the coefficient of friction, P is the normal pressure, and V is the relative sliding velocity of the two surfaces.

The flux of the energy of equation 1 results in generating what is known as the bulk temperature of the body for steady-state and transient cases. However, the exact mechanism through which this temperature is generated is believed to be through the flash temperature mechanism. The flash temperature is the instantaneous temperature that is generated due to the plastic deformation and bending of the contacting micro-asperities, the same asperities that give the frictional surfaces their resistive properties [23]. The flash temperature is not affected by the convection coefficient; however, it is highly impacted by the conduction coefficient. Also, this temperature could reach several folds higher than the bulk temperature [5]. The third type of modeling is the experimental-oriented modeling of the temperature of the frictional bodies [24]. In the experimental works, the temperature is measured via different techniques such as thermocouples, infrared sensors (IR), or a pyrometer (radiation thermometer) [25,26]. The setup is arranged such that; first, it represents an application of the frictional-thermal sliding, and second, there should be a valid way to measure the temperature. For the steady-state bulk temperature, thermocouples are used since they have inherited properties that suit the relatively-slower response. For the flash temperature, pyrometry is often used since the flash temperature happens almost instantaneously during relatively short times. The obtained temperatures are correlated against material and geometric properties with different curve fitting techniques applied. After the relationships are obtained, the models are derived based on the experimental data. Those models are usually normalized such that the problem is more generalized. However, the models that come out of this method provide the best conclusions for the case of the experimental data obtained.

3. Challenges and Future Directions

There are several challenges associated with the frictional-thermal studies of sliding wear, the most obvious of which would be the generalization of the models and the incorporation of other effects, such as chemical interactions. On the one hand, generalizing the models means that there should be models for differential parts of the sliding surfaces in which the bulk and flash temperatures are calculated. Then such parts can be expanded into the whole region. This is typically challenging as it does not only need the domain differential equations but also the proper boundary conditions. On the other hand, the incorporation of chemical interactions can help in the inclusion of the direct feedback loop of the changes in the heated surfaces. This is not easy as it requires dealing with the molecular level and connecting it with the forces applied on the surfaces.

4. Conclusion

- The frictional-thermal sliding wear is a phenomenon that should be included in the design process of the contacting parts that are expected to have those effects.
- The temperature rises because of the frictional forces, and it accelerates the wear rate. With the increased wear rate, the economic burden on the parts becomes high.
- The theoretical models show important characteristics of the temperature distribution in relation to the heat generation in the contacting parts.
- More experimental data are needed for the transient and steady-state temperature distribution.
- For future directions, the incorporation of the chemical interactions might shed some light on more details of the frictional-thermal wear.

Compliance with ethical standards

Disclosure of conflict of interest

We have no conflicts of interest to disclose.

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