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Analytical predictive modeling of scuffing initiation in metallic materials in sliding contact ☆

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ABSTRACT

Scuffing, described as sudden catastrophic tribological failure of a sliding surface, is a complex phenomenon and consequently still poorly understood. Its occurrence is influenced by many factors such as material microstructure, lubricant chemistry, operating environment, and contact parameters. Over the years, numerous attempts have been made at predictive modeling of scuffing occurrence, often based on the assumption that adhesion and consequent welding between contacting asperities is the basic mechanism of the failure. These previous attempts at scuffing prediction have not been satisfactory. A mechanism of scuffing based on adiabatic shear instability in the near-surface material of sliding interface was recently proposed by the authors. As a follow on to that work, a predictive analytical model is developed for scuffing with adiabatic shear instability as the basic mechanism of failure is presented in the current paper. The model expresses susceptibility of a sliding contact interface to scuffing in terms of material properties and contact conditions. Preliminary correlation was established between the model prediction and scuffing test results with 4340 steel. As modifiers to the shear instability mechanism, the effect of lubricant chemistry and surface reactions and numerous other factors that are known to affect scuffing damage can be incorporated.

1. Introduction

Machine elements and components that are involved in sliding contacts are usually lubricated. Examples include gears and piston ring/cylinder liners. The lubricant is expected to not only reduce friction coefficients, but also to prevent or at least retard the rate of progression of various forms of surface damage and/or wear. Most of the gradual or progressive wear modes in such components are well enough understood to predict and assess their occurrence and progression over time. Besides, these gradual wear modes only affect the durability of the system or component. Ultimately, all mechanical systems wear out at some point in time. However, scuffing is one of the most problematic failure modes in lubricated surfaces engaged in sliding contact because it occurs suddenly (often in the early part of component life) and results in loss of surface integrity and component functionality. Hence, scuffing constitutes a major reliability problem, and no manufacturer of machine components wants to make unreliable products.

Because of its significance in tribological components and systems reliability, scuffing has been studied extensively for several decades. Unfortunately, it still remains one of the least understood mechanisms of lubricated surface failure, which is a reflection of the complexities of the phenomenon. Over the years, there have been many definitions, often confusing, of what constitutes scuffing. It has been defined as "gross damage characterized by formation of local welds between sliding surfaces" [1]; "surface roughening by plastic flow whether or not there is material loss or transfer" [2]; and "localized damage caused by solid-phase welding between sliding surfaces" [3]. Yet another definition is found in the ASTM G40, where scuffing is defined as a form of wear occurring in inadequately lubricated tribo-systems which is characterized by macroscopically observable changes in surface texture with features related to direction of relative motion.

In addition to these various definitions of scuffing, several other terms have often been used in the tribological literature seemingly describing the same failure phenomenon, terms such as "scoring", "galling", "seizure", and "adhesive wear". The only consensus point among the people conducting research on scuffing is that the basic mechanism is not, or at best very poorly, understood. For instance, three reviews by notable authorities on the subject over a quarter century time span all came to the same conclusion; mechanisms of scuffing are poorly or inadequately understood [1,2,4].

The definition of what constitute scuffing is confusing indeed! Hence, it is imperative that in papers that deal with subject,

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the authors should endeavor to define what is meant by the term scuffing in their work. For the present paper, we describe scuffing as a sudden catastrophic failure of a lubricated sliding surface; signified by a sudden and rapid increase in friction, contact temperature, noise/vibration resulting in surface roughening, and loss of surface integrity and functionality. Certainly, scuffing is a tribological failure mode to be avoided in machine elements and components. As a result, over the many years of study of scuffing phenomena, researchers have made numerous empirical observations, which have formed the basis for strategies to prevent scuffing in machine components and systems. Engineers and product designers have had to rely on these empirical strategies for scuffing prevention because of the absence of a satisfactory predictive model or methodology for the phenomena a priori. One of the essential goals of engineering is the development of predictive performance models that the product engineers and designers can use [5]. The lack of a satisfactory model for scuffing prediction is by no means due to lack of effort. Indeed, attempts at predicting the onset of scuffing failure date back to as early as 1937 when Blok [6] proposed a critical flash temperature for scuffing initiation. There have been numerous other attempts since then to predict scuffing occurrence a priori. Some of the previous attempts at scuffing prediction will be discussed in the next section. Unfortunately, these prior attempts at scuffing prediction have all proven to be inadequate for sufficient general correlation with experimental data.

The main reason for lack of successful correlation of experimental data with predictions by the various previous models is that they were all based on an assumed mechanism of adhesion and cold-welding, once there is an asperity-to-asperity contact. The focus of these models is the condition for breakdown of the lubricant film or lack of adequate lubrication. Incidentally, many of the proponents of the various scuffing models often will state that the basic scuffing mechanism is not understood. Based on the authors' recent work on scuffing mechanisms [7–9], the current paper is part of a continuing effort at predictive modeling of scuffing initiation based on the proposed mechanism of adiabatic plastic shear instability.

2. Previous attempts at scuffing initiation predictive modeling

The oldest and perhaps the most familiar of scuffing predictive models are the various forms of thermally based models. Bouman and Stachowiak have provided a general review of some of the common scuffing models that have been developed over the years [10]. Only a brief overview or highlights of some models will be provided in this paper.

2.1. Thermally based models

The earliest attempt at scuffing prediction was by Blok, who suggested that scuffing occurs when the contact temperature reaches a critical value [6,11]. Blok's research was conducted in response to an epidemic of scuffing failure in gears as load and speeds were increased [11]. Block observed that in a series of gear tests with straight mineral oil, scuffing occurred at a constant total contact temperature of about 150 °C, with the total contact temperature being the sum of the bulk and flash temperatures. Since its introduction, the Blok postulate has been extensively tested experimentally by numerous investigators over many years. While some found correlation of their test results with Blok's constant temperature prediction, the vast majority did not [1,2,10]. Other variants of the critical temperature for scuffing have been proposed over the years. Over time, it became clear that, although temperature plays a crucial role in the occurrence of scuffing, constant critical temperature is inadequate as a predictive criterion.

Other thermally based criteria were suggested as an improvement over the Blok's critical temperature postulate. Perhaps, the most notable of these alternative criteria is the critical frictional power density. According to this criterion, scuffing occurs when the frictional power intensity (FPI), which is defined as the product of sliding velocity (V), friction coefficient (μ), and Hertzian contact pressure (P_H), exceeds a critical value, i.e., $\text{FPI}=\mu P_H V>$ critical value [12,13]. The FPI is the rate of frictional heating at the sliding contact interface. This criterion has also been found to be inadequate at predicting the occurrence of scuffing.

Another thermally based approach that has been suggested for scuffing prediction assumes that thermoelastic instability is the root cause of the failure [14,15]. In this approach, distortion in the contact pressure distribution produces a perturbation in frictional heating. The frictional heating causes thermoelastic deformation in asperities at the contact interface, which causes more distortion in pressure and heating until the system becomes unstable and scuffing failure becomes imminent. The contact condition for scuffing was also formulated. Experimental validation of the model prediction was again inadequate.

2.2. Ineffective lubrication base models

When there is adequate lubrication, sliding surfaces are completely separated from each other by a lubricant fluid film. This condition is obtained under hydrodynamic and elastohydrodynamic (EHD) lubrication regimes. As the severity of contact increases, mixed and finally boundary lubrication regimes can operate, in which various forms of chemical interactions can occur on the sliding surfaces. Effective lubrication of the surfaces thus involves both the fluid film and the surface chemical films. The scuffing predictive models based on ineffective lubrication are then based on the failure of either the fluid film or the surface chemical films.

2.2.1. EHD breakdown

The thickness of the lubricant fluid film can be calculated by the EHD equations for non-conformal contacts. A parameter commonly used to assess the adequacy of the lubricant fluid film is the so-called lambda ratio (λ), which is defined as the ratio of the minimum lubricant fluid film thickness (h_o) to the composite roughness of the contacting surfaces (σ), i.e., $\lambda=h_o/\sigma$. The EHD breakdown criterion approach suggests that scuffing will occur if λ is less than 1, and direct surface asperity-to-asperity contact occurs. The fluid film thickness, to a large extent, is determined by the entraining velocity and the lubricant viscosity. For components operating at a nearly constant velocity, the pathway for reducing the fluid-film thickness reduces the lubricant viscosity. Such viscosity reduction is expected with frictional heating of lubricated surfaces. The Cheng and Dyson model of the EHD film collapse model invokes a temperature that will result in enough viscosity reduction to allow metal-to-metal contact and consequent scuffing initiation [16]. However, in experiments and real-world applications, components are known to operate successfully without scuffing at very low λ values for extended periods of time, casting doubt on the validity of this EHD collapse model. Indeed, Lee and Ludema showed through experimental study that lubricated sliding contact can successfully operate with a λ value as low as 0.1 without the occurrence of scuffing [25].