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Lubrication under charged conditions

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ABSTRACT

Understanding on the lubrication properties under charged conditions is not only one of the important fundamental research directions in the lubrication field, but also is of great significance in some newly-emerging applications. This paper presents a review of important research progresses on charged lubrication in recent years. First, the lubrication and friction behaviors in different lubrication states under charged conditions, as well as representative lubrication instabilities at charged interfaces are reviewed. Subsequently, two relevant applications, i.e., charged bearings and electric contact lubrication systems, are introduced. Finally, a brief summary and future outlook of the researches on charged lubrication are given.

1. Introduction

Lubrication is one of the oldest technologies in human history. When building the pyramids, the Egyptians applied water, animal fats and vegetable oils as lubricants to move large stones on a two-rail flat-bottom sledge across the flat ground [1]. During the Industrial Revolution in mid-eighteenth-century, many relevant researches on lubrication were aroused due to the needs of continuous lubrication of machinery parts [2]. At that moment, great attention was paid to the hydromechanics and Reynolds's equations for bearing design. Over the subsequent century, the lubrication researches have gained significant improvements, and gradually developed to an interdisciplinary science involving physics, chemistry, material science, fluid dynamics and contact mechanics, etc.

The impetus for moving lubrication forwards comes firstly from the demand of constantly improving and advancing the science and technology of lubrication. For lubrication theories, on the one hand, Reynolds proposed the basic lubrication equations in 1886, laying the foundation for the studies on fluid lubrication (FL) [3]. Afterwards, Hertz elastic contact theory was incorporated into the Reynolds fluid lubrication theory, and then elastohydrodynamic lubrication (EHL) theory was obtained [4]. Significant progresses on the EHL theories have been made by Grubin [5], Dowson [4], Cheng [6], as well as Wen and Yang [7,8]. On the other hand, Hardy proposed the concept of boundary lubrication (BL) in 1919 [9], and subsequently significant advancements were made to this theory. Many BL models were put forward successively, e.g., Bowden model [10], Adamson model [11], Kingsbury model [12] and Cobblestone model [13]. The viscous fluid film plays an important role in FL and EHL, obeying the laws of continuum mechanics, while the adsorbed film or chemical reaction film is predominant in BL. The effective viscosity of the lubricant oil under BL near metal surfaces was found to be exceptionally higher than the bulk value [14]. Furthermore, analysis of the lubricant film thickness and the physical characteristics of film suggests that an intermediate lubrication regime could exist between the EHL and the BL regimes [15]. Wedged spacer layer optical interferometery was used to study the thickness variations of thin oil films in concentrated contacts by Spikes and Johnston et al., and ultra-thin film lubrication was proposed [16,17]. Afterwards, generalized thin film lubrication (TFL) was put forward by Wen [18]. From then on, Luo and Wen have conducted a systematic work experimentally and numerically on TFL [19–24], which was defined as a lubrication state taking both the surface adsorption effect and the fluid flowing effect of lubricants into consideration. The physical model of TFL has been defined as [19]: One or two layers of lubricant molecules are firmly adsorbed (static adsorbed films) on the smooth surfaces of narrowly-spaced tribo-pairs; this static adsorbed film could induce the adsorption of several layers of ordered lubricant molecules, and the molecules farther away from the solid surface are less ordered; at high entraining speeds, the lubricant film thickness is large, being close to the calculated value on the basis of the EHL theory, and the fluid flowing effect is obvious; at low entraining speeds, the lubricant film thickness is relatively small, which is, however, larger than the calculated value on the basis of the EHL theory. In this case, the surface adsorption effect is obvious.

In principle, because the film thickness in the TFL and the BL regimes is in the range of ~1 to ~10 nm, it is reasonable to expect that the structure and conformation of the lubricant molecules near tribo-pair surfaces could be easily changed after being changed to charged conditions. In the FL regime, the rheology or interfacial properties of some special fluids could be potentially

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modified by external charges. In this sense, the theoretical studies on the film formation mechanism and the nature of friction at the lubricated interface under charged conditions could be helpful for the active control over friction/lubrication. Moreover, these studies could deepen and broaden the basic understandings on lubrication fundamentals as well as enrich the lubrication theory system.

The impetus for the study on lubrication under charged conditions also comes from industrial needs. For one thing, the high precision movable surfaces in micro/nano devices are frequently with charges, for instance, the head/disk interface in ultrahigh density magnetic storage system and the charged movable interfaces in some micro/nanoelectromechanical systems. For another thing, the asymmetric effect of unbalanced magnet winding in variable-frequency alternate-current (ac) motors, which have increased uses in many rotary machineries, could induce the generation of shaft voltage and the resultant current flow through the bearing system [25]. Moreover, currents often flow through bearings in electrified trains, wind turbine generators [26] and aircraft propulsion system [27]. The emergences of these new technologies and problems need the renewal and development of existing knowledge and understandings on the lubrication design for these special conditions. Under these circumstances, the study on the friction/lubrication under charged conditions is of great engineering significance.

The present paper provides a review on important research progresses on the charged lubrication in the past decades, and a general framework of the present review is schematically given in Fig. 1. The review is organized into four sections: Section 1 discusses the basic researches on the lubrication properties under charged conditions. In this part, the lubrication and friction behaviors in different lubrication states, e.g., dry friction, boundary lubrication, thin film lubrication and fluid film lubrication, under charged conditions are discussed; Section 2 reviews some representative lubrication instabilities at charged interfaces, e.g., discharge, emergence of microbubbles, electrowetting/spreading and stability of lubricant film flow. Sections 3 and 4 introduce two typical applications relevant to charged lubrication, i.e., charged bearings and electric contact lubrication systems. Lubrication failure and damages, as well as reliability and durability of these lubrication systems have been discussed. Section 5 gives a short summary and brief future outlook in the direction of the researches on charged lubrication.

2. Basic researches on lubrication under charged conditions

As mentioned above, the fundamental researches on the possibility of utilizing external potentials/currents to change and control friction/lubrication properties, as well as the basic understanding on the underlying physico-chemical mechanisms, are the prerequisites of successful applications of charged lubrication and seeking effective solutions to engineering problems encountered in practice. In the past decades, extensive efforts have been made by researchers towards this research direction, and many interesting results have demonstrated that the lubrication/friction properties could be changed to varying degrees after external charges were applied. Nevertheless, the explanations and mechanisms of these phenomena differ greatly. As shown in Fig. 2, no simple and direct correlation between each specific mechanism and the experimental result can be made. In some cases, several mechanisms need to be used collectively to explain a specific result. In order to get a clear understanding on these phenomena and relevant mechanisms, comparisons and analyses of the tribological behaviors in different lubrication states under charged conditions will be reviewed in the following parts.

2.1. *Dry friction under charged conditions*

On the basis of whether surface films form on tribo-pair surfaces or not, dry friction under charged conditions can be generally classified as two categories: (i) electrostatic interaction or self-generated potential, and (ii) formation and transfer of surface films.

- For the case (i), electrostatic interaction can be imposed to normal load and then affect friction. At the macroscopic scale, for carbon black rubber/aluminum tribo-pair, the electrostatic attraction around the contacting surface asperities increases normal load and friction [28]. However, electrostatic interaction could substantially affect macroscopic friction when the potential is relatively high, and hence its effect on friction is more obvious at the microscopic scale. For instance, the electronic contribution to friction at semiconductor surfaces (e.g., silicon and GaAs) was investigated by using atomic force microscope (AFM) [29,30]. Charge accumulation or depletion could be induced by doping [29] or external potential [30], and then the tip-sample friction

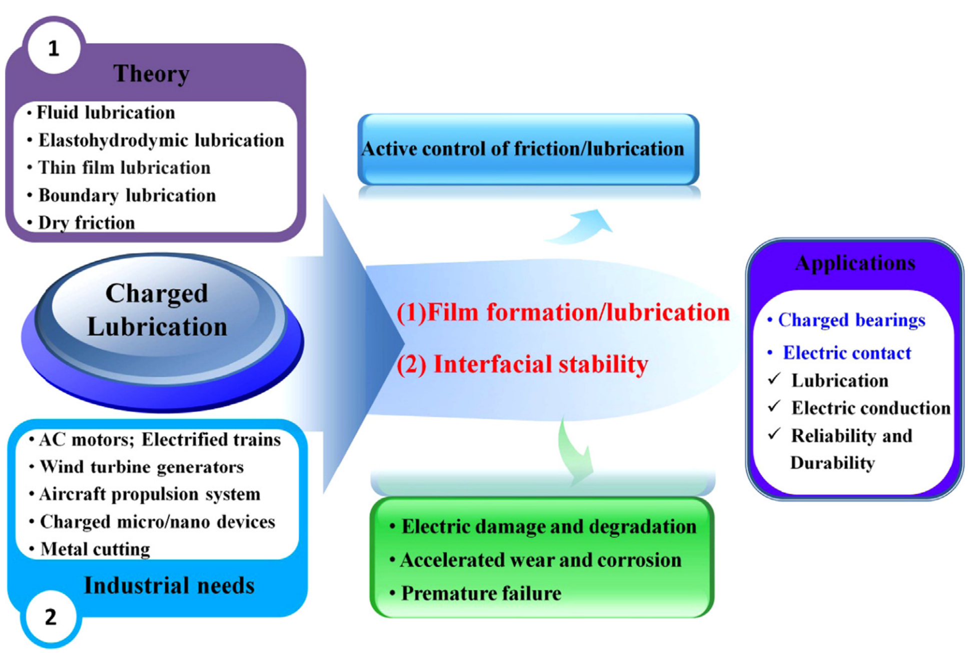

Fig. 1. Framework of this review: background (left part), basic research (middle part) and applications (right part).