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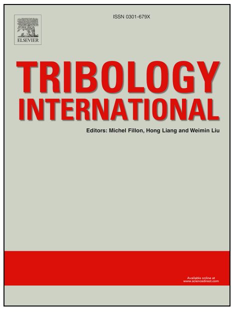


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# Effects of Substrate Surface Roughness and Nano/Micro Particle Additive Size on Friction and Wear in Lubricated Sliding

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**Abstract**

Macroscopic wear experiments were complemented by atomistic simulations to study the effect of nano- and micro-scale titanium dioxide particles as lubricant additives on friction and wear. The size of the particles and initial roughness of the sliding surfaces were varied to characterize the interrelated effects of these two properties. Results from both experiments and simulations suggest that there is an optimal particle size that will minimize friction and wear for a given surface roughness. Analyses support a previously-proposed mechanism for particle-based additives in which the particles fill in valleys on the sliding surfaces. In this context, particles that are smaller than the characteristic roughness of the surfaces are most likely to perform this function.

## 1. Introduction

Reducing friction and wear is essential for increasing energy efficiency and improving the reliability of mechanical systems. This is typically done by using liquid lubricants which form a thin film between the counterfaces to bear the load and avoid direct solid-solid contact. Liquid lubricants generally consist of base oil and additives, where the additives supplement the base oil functionality. Material particles, often with nano- to micro-scale dimensions, are one type of additive used to reduce friction and wear at sliding interfaces [1–4]. Various mechanisms have been proposed to explain how particles function as additives, including: acting as ball bearings that roll in the interface to minimize sliding contact [5,6]; filling in valleys on the surfaces, effectively mending them and resulting smoother surfaces [7–9]; and forming a protective tribofilm on one or both surfaces [10–13].

All of these mechanisms are affected by characteristics of the particles themselves and one of the most important properties of these additives is their size. Some studies have shown that filling of valleys on the sliding surfaces by particles is facilitated by smaller diameters [14,15]. A study of the anti-wear and load-carrying capacity of liquid paraffin with $SiO_2$ particles of different sizes (from 0.058-0.684 μm) showed that smaller particles provided better tribological properties [16]. Similar behavior was observed from measurements of $Zn_{0.92}Mg_{0.08}O$ particles in paraffin oil which showed smaller sizes provided better anti-wear properties [17]. Measurements of $MoS_2$ particles showed that particles with diameters between 0.15 and 0.35 μm yielded similar performance, but this improvement was not exhibited by larger micron sized particles [18]. These studied have shown that particle size can affect tribological performance and that, typically, smaller sizes are better. However, most of the proposed mechanisms rely upon the interaction of the particles and the sliding surfaces. Therefore, it is also important to understand the role of surface characteristics on additive performance.