Modeling Running-In Process of Engine Bearings with Roughness Evolution and Tribo-Film Effects

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This study proposes a numerical framework to quantitatively predict the running-in process of engine plain bearings by coupling rough-surface contact, tribo-film formation, and wear evolution. Frictional losses remain a major source of energy dissipation in both internal combustion engines and electrified powertrains. Under boundary lubrication, friction and wear characteristics change with operating history through running-in. Because this process involves coupled changes in surface topography, contact state, and tribo-film formation over multiple scales, it has been difficult to model systematically.

In the present study, the running-in process is modeled as the coupled evolution of rough-surface contact, tribo-film growth and removal, and substrate wear. Rough-surface contact is solved deterministically using the boundary element method (BEM). Surface topographies are generated from a prescribed power spectral density. This enables spatially resolved evaluation of contact pressure, deformation, and contact state with reasonable computational efficiency. The tribo-film thickness $h(x,t)$ is expressed as the balance between growth and removal:

$$\frac{\partial h(\mathbf{x},t)}{\partial t} = \dot{h}_{\mathrm{g}}(\mathbf{x},t) - \dot{h}_{\mathrm{r}}(\mathbf{x},t)$$

Film growth is modeled as a stress-assisted thermally activated process driven by the subsurface stress field generated by asperity contact, whereas film removal is treated as a mechanically driven process governed by normal stress and excess film thickness. Substrate wear is described using a film-thickness-dependent wear coefficient so that thicker tribo-films suppress substrate wear. In addition, tribo-film formation is assumed to modify the effective yield stress, introducing two-way coupling between tribo-film evolution and contact response.

To validate the proposed framework, bearing friction and wear experiments were conducted using a custom test rig that enables non-destructive, time-resolved wear evaluation. A dissipation-based wear indicator, ΔW, was defined based on the asymmetry between forward and reverse operations after separating the solid-contact component from the measured torque. The cumulative value of ΔW showed a clear proportional relationship with the measured wear area under different loading conditions.

The numerical model reproduced the main experimental trends, including large initial wear followed by gradual stabilization as running-in progressed, as well as changes in wear evolution associated with load variation. A point-by-point comparison between the experimental wear indicator and the simulated wear amount also showed a clear proportional relationship (Fig. 1). Although the correlation became slightly lower than that obtained using only final values when intermediate running-in states were included, the overall proportionality remained clear. Time-series comparisons further showed that the model captured the main evolution of wear under different loading histories.

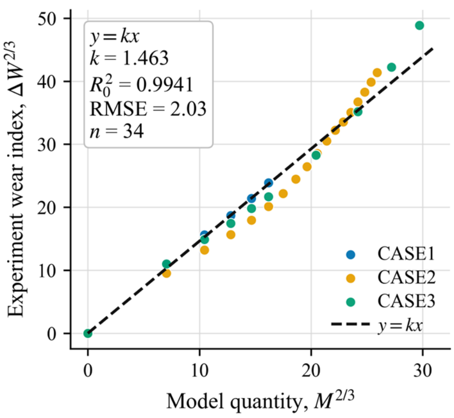

Fig. 1 Relationship between model quantity and experimental wear index

The simulations also indicated that wear preferentially occurs at surface asperities, while tribo-films form in similar regions and suppress excessive substrate wear through a balance between growth and removal (Fig. 2). These results demonstrate that the proposed framework captures the essential mechanisms governing running-in and provides a physically interpretable and predictive tool for evaluating and designing low-friction and high-reliability sliding surfaces in engine plain bearings under boundary lubrication.

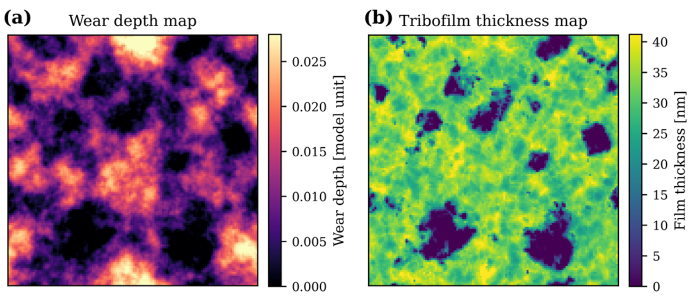

Fig. 2 Distributions of (a) wear depth and (b) tribo-film thickness after repeated contact