Multiscale Modeling of Friction Coefficients: A Review from Nanocontacts to Macroscopic Sliding

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Abstract. Friction, being a very ubiquitous form of energy dissipation and material wear in engineering systems, has a range of physical scales, including atomic interactions and bulk mechanical behaviour. Despite the continued use of the classical laws of Coulomb and Amontons in engineering practice, recent research has shown that the behaviour of friction is much more intricate than can be suggested by these linear relationships. The review gives an overall overview of the progress made in multiscale tribology, including macroscopic measurements of friction, surface roughness modelling, dynamics of stick-slip on the nanoscale, energy dissipation processes, and atomistic simulations. Special attention is given to the effects of surface topography, material structure, lubrication state, and environmental conditions on the value of the friction coefficient in various regimes. The critical roles of interfacial adhesion, third-body effects, and multiphysical coupling in regulating the frictional response are also explained. Additionally, we highlight the development of combined multiscale methods and predictive methods, such as machine learning-based parameter inference and experiment-simulation co-modelling. We discuss that friction has become a complicated interfacial phenomenon with statistically emergent behaviour, and its controlled regulation in detail is necessary through a synergistic framework that cuts across scales and disciplines. Such an approach offers a basis for the rational design of friction in future intelligent mechanical systems.

Keywords: Tribology; Multiscale modeling; Interfacial adhesion; Energy dissipation; Molecular dynamics.

1. Introduction

1.1 Background

Friction is a fundamental problem of interest in the mechanical efficiency, energy usage, and performance of engineered systems (ranging in scale between nanocontacts and large mechanical systems) [1]. In the context of microelectromechanical systems (MEMS), excessive friction causes wear and stiction, whereas in geophysics, friction is the mechanism that controls the nucleation of earthquakes and fault slipping. In essence, friction is a multiscale, multivariable phenomenon, which is concurrently controlled by a set of macroscopic variables (normal load, sliding velocity, and lubrication) and a set of interfacial forces, which are microscopic due to the interactions between atoms and molecules [2]. The systematisation of the macroscopic and nanoscopic coupling of these physical processes has become one of the fundamental and persistent problems in tribology.

The empirical laws of Amontons and Coulomb, which extend Leonardo da Vinci's initial observations, state that the frictional force is proportional to the normal load and independent of the apparent contact area [3]. These laws have proven to be incredibly stable over a range of six orders of magnitude in scale and have been reported to help explain macroscopic sliding phenomena. However, at the nanoscale, where atomic stick-slip perturbations and interfacial adhesion dominate, the coefficient of friction is no longer a constant value but is an emergent, statistically defined quantity [3], [4]. This inconsistency leads to the scale paradox: how can a simple empirical law be true in such a highly diverse set of regimes, where microscopic interactions are complex and varied?

1.2 Literature review

Early efforts to describe friction on a microscopic scale aimed to connect the behaviour of molecules to that on a macroscopic scale. The molecular theory of friction (1929) was proposed by

Tomlinson, who postulated that the irreversible occurrences of atomic repulsion during the sliding process transform mechanical work into heat [5]. Given this background, Bowden and Tabor (1950s) showed that the proportionality between friction and normal load is a result of the scaling of the actual contact area with load [3].

Later, evolutionary developments in experimental equipment transformed the field. In 1986, the atomic force microscope (AFM) was invented [4] , which made it possible to measure forces directly at nanonewton scales, allowing for the experimental study of atomic-scale stick-slip motion and energy dissipation. Similarly, the introduction of the surface forces apparatus (SFA) in the 1960s, along with its subsequent improvements, including the SFA-2000, enabled the conduct of meticulous studies on the adhesion, lubrication, and shear behaviour of molecularly smooth surfaces. These instruments revealed primary microscopic sources of friction, such as the influence of molecular layering, interfacial adhesion, and rate-dependent energy dissipation.

Simultaneously, theoretical and computational techniques have undergone significant improvements. The stick-slip behaviour at the atomic level has been reproduced through molecular dynamics (MD) simulations, and it has been demonstrated that the law proposed by Amontons only appears after averaging over the varying interatomic forces [5]. Recent investigations also indicate that the energy dissipated is not solely due to a purely mechanical process, but rather to a thermodynamic process, specifically the irreversible compression-decompression cycles of asperity contacts.

Recent experimental and computational research is still in the process of perfecting and testing the classical concept of friction. Yu et al. (2024) have shown using MD simulations that the deformability of substrates and applied load are inherently coupled in such a way that they experience nontrivial transitions between friction regimes at the nanoscale [6]. Song et al. and Huang et al. documented nonmonotonic dependence on velocity and damping attributes in the year after, and demonstrated that the atomic level of friction is not always proportional to the velocity of sliding as predicted by Amontons and Coulomb [34], [35].

On larger scales, in 2025, Kalin reintroduced measurements of adhesion and real contact geometry into Amontons' law and demonstrated that deviations are found[7]. Further supporting publications in contact mechanics [8] and multiscale wear modeling [9] also point out that classical continuum modelling is unable to fully account for the combined effects of adhesion, surface roughness, and plasticity. Also, Weber et al. (2018) employed molecular probe methods to demonstrate that the dependence between actual contact area and load cannot be linear, confirming the interpretation of Amontons' law as a successful mean-field approximation [10].

Although these have been achieved, a single conceptual framework that can reliably connect the atomic level of interaction to the engineering level of friction coefficients has not been realised. Whereas condition-dependent and frequently scattered results are obtained in macroscopic tribometry, atomistic simulations have limited spatial and temporal scope. One of the most critical issues in contemporary tribology, therefore, is the development of a robust multiscale framework that combines these regimes.

1.3 Objectives

The review represents the synthesis of friction research at the macroscopic and microscopic scales. It elaborates on classical empirical laws and newer knowledge gained through experimental and computational investigations, aiming to explain the relationship between these scales and progress towards a unified understanding of tribological behaviour. Specifically, this work:

1) Summarises the historical and modern developments in the study of friction, between the macroscopic tribological experiments of Amontons and the laws of nanotribology in the modern world.

2) Breaks down the mapping relations between macroscopic friction coefficients and their microscopic origins and the ways that atomic-scale processes (e.g., stick-slip, adhesion, energy dissipation) can create macroscopic regularities.

3) Suggests a conceptual framework of cross-scale combining MD, surface science, and continuum contact mechanics, which determines when empirical laws of friction are or are not obtained.

4) Discusses the existing issues and future perspectives and highlights the necessity of predictive multiscale tribological models that could provide connections between nanoscale-level understanding and engineering-scale implementations.

The rest of the paper will follow the following structure: Section 2 will define the coefficient of friction and provide a summary of how the coefficient can be measured at each scale. Section 3 discusses the macroscopic aspects that influence the friction coefficient, including surface roughness, material properties, and lubrication effects. Section 4 discusses both microscopic and molecular processes of friction, based on interactions at the atomic scale, dissipation, and progress in simulation. The fifth section wraps up with significant conclusions, existing limitations, and future perspectives for predictive and data-driven tribology.

2. Definition and Measurement Methods of the Friction Coefficient

At the macroscopic level, the Coulomb–Amontons law traditionally defines the friction coefficient as the ratio of the friction force to the normal force exerted L:

$$\mu=\frac{F}{L} \tag{1}$$

This simple proportionality has been confirmed for a wide range of materials and geometries. It is routinely measured using standard tribometers such as pin-on-disk, ball-on-disk, reciprocating linear, or rolling setups [11].

At the microscopic level, Bowden and Tabor provided a physical basis for Amontons' law by relating friction to the *real* area of contact A, which is formed by plastically deformed asperities. They showed that the real contact area scales with load as

$$A\propto\frac{L}{H} \tag{2}$$

where H denotes the hardness of the softer material. The total friction force thus contains both adhesive and ploughing components:

$$F=\tau A+F_{plough} \tag{3}$$

in which τ is the interfacial shear strength. Failure to account for the ploughing contribution is an omission.

$$\mu\approx\frac{\tau}{H} \tag{4}$$

The Law of Friction and Lubrication of Solids, initially described in The Friction and Lubrication of Solids[1], is still the focus of microscopic theories of Amontons' law.

The definition of the friction coefficient is further extended to the atomic scale in modern MD simulations. In this model, the local coefficient of friction is the ratio of lateral to regular forces between atoms at the interfaces over time or in the short term. Energetically, it can just as well be given as the ratio of dissipated work W_{diss} to the mechanical work done by the normal load W_{load}:

$$\mu\approx\frac{W_{\mathrm{diss}}}{W_{\mathrm{load}}} \tag{5}$$

In this case, W_{diss} caused by atomic-level processes, such as stick-slip events, phonon excitations, and microplastic deformation [3].

Local measurements of friction coefficients have been made possible experimentally with surface-science instrumentation. Binnig, Quate, and Gerber introduced the AFM in 1986 [4], which is capable of detecting both regular and lateral forces with a sensitivity of sub-nanonewtons. The SFA, which was first invented in the 1960s and later improved to the SFA-2000, measures adhesion and shear forces of molecularly smooth surfaces over separations of 0.001 μm to 1 μm. Moreover, QCM methods can be used to measure interfacial energy loss in thin films and lubricated interfaces.

These nanoscale strategies demonstrate that the friction coefficient is not a fixed number, but a variable that changes in response to load, velocity, adhesion, surface chemistry, and environmental conditions.

The coefficient of friction is, therefore, defined differently at different scales:

1) Macroscopic scale: an empirical ratio $\mu=F/L$, which is determined by tribometers.

2) Microscopic scale: a relation based on the material $\mu\approx\tau/H$, based on the interfacial shear strength and hardness.

3) Nanoscale: A local ratio of shear to regular forces of atoms, or dissipated to applied work – available by AFM, SFA, and MD simulations.

This multiscale structure emphasises the fact that, although the law of Amontons is phenomenologically strong, a collective energy-dissipative phenomenon of atomic contacts renders it relevant. The concept of bridging these scales is a crucial step toward creating predictive tribological models that can be used to correlate molecular processes with performance at an engineering scale.

3. Macroscopic Factors Influencing the Friction Coefficient

3.1 Surface Roughness and Topography Effects on Macroscopic Friction

The coefficient of friction (μ) at the engineering scale is an emergent effect of the combined effect of the topography of the surfaces, material properties, lubrication regime, and environmental factors. Even though the law of Amontons presupposes the constant proportionality of the force of friction and the normal load, many tribological experiments indicate that the value of μ is highly dependent on test conditions and the parameters of operation.

To explain the macroscopic causes of these variations, this section surveys the prevailing causes of frictional behaviour. Also, it looks at the degree to which they conform or otherwise with the seeming universality suggested in the law of Amontons. The parameters of representative surface roughness as specified in ISO 25178 and their tribological significance are tabulated in Table 1, and the contributions made to the variation of μ by various characteristics of surface texture are also tabulated.

Table 1. Representative surface roughness parameters and their influence on friction behavior

Parameter	Definition / Physical Meaning	Typical Range	Tribological Effect on μ	References
Sa	Arithmetic mean height – deviation of surface from mean plane	0.01–5 μm	Higher Sa increases asperity deformation → increases μ	[12], [13]
Sq	Root-mean-square height	0.02–10 μm	Higher Sq → greater ploughing/friction	[12], [15]
Ssk	Skewness – asymmetry of height distribution	−1 ~ +2	Ssk > 0 increases μ; Ssk < 0 lowers μ	[13], [16]
Sku	Kurtosis – peakedness of surface profile	2 ~ 8	High Sku > 3.5 increases μ; Sku ≈ 3 preferred	[13], [3]
Str	Texture aspect ratio – isotropy of surface pattern	0.1 ~ 1	Low Str (<0.3) promotes lubrication; high Str uniform μ	[12], [15]
φ	Texture coverage ratio	10–70%	Optimal φ ≈ 40–50% minimizes μ	[17]–[19]
h/d	Dimple depth-to-diameter ratio	0.02–0.2	Optimal h/d ≈ 0.05–0.1 lowers μ	[17], [18]
p/d	Pit-spacing ratio	2–6	Intermediate p/d ensures stable μ	[18], [19]
θ	Inclination angle of texture	0°–45°	Small θ reduces flow resistance	[17]
r	Feature radius (curvature)	1–100 μm	Larger r distributes stress → lower μ	[17], [18]

Caption: Summary of roughness and surface texturing parameters relevant to tribological performance. Ranges correspond to typical engineering surfaces under moderate loads and dry or mixed lubrication.

Numerous empirical models have been developed to correlate surface roughness parameters with the friction coefficient. For engineering surfaces, μ often correlates with the composite roughness ratio σ/λor the real contact fraction A_{real}/A_{app}. A simplified scaling can be expressed as:

$$\mu=\mu_0+k_1 Sa^{n_1}+k_2 Ssk^{n_2} \tag{6}$$

where μ_0 represents the ideal smooth-surface coefficient, and k_i, n_i are empirical constants fitted from tribometric data [20],[21].

Pettersson (2015) and Zhang (2020) reported that *Sa* accounts for up to 60 % of μ variation in mixed-lubrication regimes, whereas *Ssk* and *Str* primarily govern the transition between boundary and hydrodynamic friction.

3.2 Material and Mechanical Properties

Material composition and mechanical strength also play decisive roles. According to the Bowden–Tabor model (Formula 4), as *H* increases, the real contact area decreases, leading to lower μ. Metallic contacts, which exhibit high adhesion, generally yield large μ values (0.4–1.0), whereas ceramics, hard coatings (e.g., TiN, DLC), and polymers show smaller coefficients due to reduced plastic deformation and adhesion [3], [10].

Thermomechanical effects complicate this relationship. Asperity junctions may be softened by frictional heating, and adhesion promoted by frictional heating, while oxide or transfer films that form during sliding may be stabilising or destabilising to the friction, depending on their ductility [7], [9], [23]. The repeated sliding processes may create third-body debris and change the geometry of contacts and the load-bearing surface. As a result, μ is a dynamically evolving coupled mechanical, thermal, and chemical system.

3.3 Lubrication and Environmental Effects

Lubrication introduces additional governing parameters, including film thickness, viscosity, and contact pressure, which determine the transition between boundary, mixed, and elastohydrodynamic (EHL) lubrication regimes.

Boundary lubrication: In this case, friction is moderated mainly by the presence of adsorbed molecular films and chemical additives, which determine the interfacial shear strength depending on their polarity and molecular orientation [2], [17]. Polar additives, such as phosphates and fatty acids, have the capability of creating low-shear strength boundary layers, which brings the coefficient of friction down to less than 0.1. In the transition to the mixed regime, the contact surfaces partially separate, and the values of μ vary with film thickness, which decreases rapidly [20]. Viscous shear dominance occurs under EHL conditions, and μ can be less than 0.01, which is in agreement with the classical Stribeck curve [24].

Environmental conditions such as humidity, temperature, and reactive atmospheres also influence the frictional behaviour. Humidity on hydrophilic surfaces increases μ because of the formation of capillary bridges, whereas on hydrophobic surfaces, it may cause a decrease in μ [25]. The elevation of temperature reduces the viscosity of the lubricant, and it becomes more asperity-contacted. Oxidative reactions can generate protective or abrasive surface films that stabilise or destabilise friction [26]. Therefore, macroscopic friction is dominated by an extreme sensitivity to the state of lubrication as well as the environment in which it is present.

3.4 Universality and Heterogeneity

Even without this constancy, μ tends to be found to remain approximately constant over large load ranges, which is sometimes called apparent universality. This is because in most contacts of rough surfaces, the actual contact area $A_{(real)}$ is almost proportional to the applied load L as a result of plastic asperity deformation, and that $F \propto L$ [1], [3], [7]. Therefore, the macroscopic coefficient of friction is an average of the heterogeneous microcontacts, which have varied shear strength and adhesion properties.

However, under smooth, clean, or nanostructured conditions, the preponderance of adhesion and elastic deformation prevails, breaking down the proportionality and resulting in load- or velocity-dependent μ [6], [10], [22]. As such, the law of Amontons should be viewed as a statistical emergent relationship that arises from collective asperity behaviour, rather than a universal constant.

3.5 Negative Effects and Failure Modes

Frictional stability is compromised when operational parameters go beyond the optimum levels. Overtextured surfaces ($\varphi > 70\ \%$ or $h/d > 0.2$) may trap debris, hinder lubricant flow, and increase μ [17], [18]. When the lubricant is used at high speed or temperature, it may cause thermal softening, oxidation, and stick-slip oscillations [27]. Further alterations to surface geometry are affected by fatigue wear, pitting, and microcrack propagation, which introduce nonlinear instabilities that break the Amontons law. These feedback mechanisms underscore the importance of combining mechanical design with thermal and chemical control to prevent tribological failure.

3.6 Summary

In short, the macroscopic coefficient of friction μ is not a material constant, but a systemic-level property that arises from the interaction between the roughness of the surfaces, material characteristics, the lubrication mode, and the environment. Although the law of Amontons is a good approximation to the heterogeneous reality of microcontacts in various engineering cases, it conceals the nonlinear effects of adhesion, deformation, and thermal-chemical interactions, as well as the heterogeneity of microcontacts. Bending of the linear scaling is evident in the presence of smooth or highly regulated surface conditions, or when operating parameters exceed the stability limits, resulting in frictional instabilities and failure. These macroscopic dependencies must therefore be fully understood to facilitate the reconciliation of experimental tribometry with the microscopic processes of friction.

4. Microscopic and Molecular Mechanisms of Friction

4.1 Atomic and Molecular Interactions

The molecular origin of friction is due to the atomic and molecular interactions between interfaces of contact. These are van der Waals, Coulombic, hydrogen-bond, and π–π stacking forces, which combine to form the corrugated interfacial potential-energy surface that controls shear resistance [3], [16], [29].

The interfacial interactions can be investigated with high precision in AFM and SFA experiments. AFM also has nanonewton force sensitivity and atomic resolution, which is especially useful in studies of adhesion, lattice commensurability, and local friction anisotropy [2], [4], [16]. Instead, the SFA is used to measure regular and shear forces between molecularly smooth surfaces over separations ranging from ångströms to micrometres, which allows molecular layering, squeeze-out behaviour, and shear-induced structural rearrangements to be directly observed [2], [30].

The MD simulations are an effective supplement to these experimental methods because they can scale the interaction potentials at the atomic scale into observable frictional responses at larger scales. In particular, the local shear strength (τ), adhesion energy, and actual contact area are determined by the amplitude and periodicity of the interfacial potential energy landscape. Averaging out such heterogeneous nanoscale interactions statistically to obtain the quasi-linear macroscopic dependence between the friction force and normal load is similar to the law of Amontons [3], [5], [6], [22].

One of the important lessons gained from the simulation and experiment is that the stronger the adhesive or electrostatic forces, the higher the stick-slip amplitudes, and the more sensitive the friction can be to load and sliding velocity. Additionally, surface chemistry, molecular orientation of terminal groups, and ambient humidity are other factors that significantly influence adhesion and energy dissipation pathways [16], [25], [26]. Such results indicate the multi-parameter and environment-specific nature of nanoscale friction.

4.2 Stick–Slip and Energy Dissipation

A primary characteristic of atomic-scale friction is the stick-slip motion, i.e., the periodically alternating pinning and rapid sliding between the phases [5], [31]. The Prandtl–Tomlinson (PT) model classically describes this behaviour, which occurs when a slider of stiffness k moved over a sinusoidal substrate potential:

$$U(x)=U_0 \sin\left(\frac{2\pi x}{a}\right) \tag{7}$$

The appearance of the stick-slip process depends on the dimensionless parameter

$$\eta=\frac{4\pi^2 U_0}{a^2 k} \tag{8}$$

where $\eta>1$ leads to multistable stick–slip dynamics and $\eta<1$yields smooth sliding. Due to the amplification of interfacial stiffness by the normal load U_0 ,the stick-slip transition k^* can be experimentally controlled by varying the applied normal load, tip geometry, or substrate compliance [3], [31].

On an atomic scale, the energy dissipated during one of the sliding events is due to several simultaneous processes. Shear energy is converted to lattice vibrations, or phonon excitation [3], [29], and into conduction electron or polar mode excitation, which results in velocity-dependent dissipation [16], [32]. Further irreversibility is achieved due to deformation of microplastics and reorganisation of structures at asperity junctions [6]. Moreover, non-equilibrium heat transport between localised temperature spikes and localised relaxation processes becomes coupled between frictional work and thermal fields [3], [9]. The sum of these channels determines the amount of energy lost, which in turn establishes the friction force.

Energetically, the coefficient of friction satisfies the exact proportionality as in the case of Section 2 (formula 5), and in this case, the coefficient of friction is roughly proportional to the ratio of total dissipated work to the mechanical work done by the driving force, i.e., $\mu\approx W_{\text{diss}}/W_{\text{load}}$. In this case, W_{diss} is the sum of all irreversible dissipation channels, such as phononic, electronic, plastic, or thermal contributions, and W_{load} s the mechanical work done by the normal loading [3]. This expression will be used to provide a microscopic explanation of the macroscopic coefficient of friction used above and to highlight that friction is caused by multichannel energy conversion, rather than solely by mechanical constraints.

4.3 Interfacial Films and Third-Body Effects

Practical tribological systems rarely have clean or ideal contacts; instead, they are mediated by interfacial films and third bodies, which have a prevailing influence on frictional behaviour [16], [17], [19], [26], [27]. According to the oxidation layer on metallic surfaces under load and temperature, it can improve surface hardness and decrease adhesion, which is recognised as a passivating effect. However, brittle oxides can fracture, producing debris and enhancing wear [26]. Polar additives, such as phosphates or fatty acids, can also form adsorbed layers on the surface, providing low-shear-strength films that reduce the interfacial shear stress and friction coefficient to values below 0.1, respectively [2], [17], [30]. Recurring sliding frequently creates transfer films or loose wear particles—a dynamically changing third body—capable of redistributing the load and either stabilising or destabilising the frictional response, depending on their compaction and mobility [27]. Moreover, the confined molecular films are stratified and orientationally ordered, and under critical stress, they undergo discrete slip events on their layers, resulting in shear weakening and velocity-dependent friction [2], [16], [33].

Throughout the change from boundary shear to mixed and ultimately EHL shear force, the interplay between interfacial shear strength τ and effective contact stiffness is what dictates the maintenance of the near-linear relation between friction and load rates as suggested by Amontons' law. This development is identical to the classical Stribeck curve, where an increased film thickness or reduced solid–solid contact suppresses the adhesive contribution to friction gradually [17], [24].

4.4 Advances in Simulation and Computation

Novel multiscale simulation schemes have become potent systems for connecting atomistic processes with continuum-scale tribological quantities [3], [6], [9], [22], [29]. Multiscale and coarse-grained MD methods take the spatial and temporal resolution to a higher level of simplified molecular models, allowing realistic load, speed, and temperature effects to be reproduced and the experimentally determined proportionality to be maintained $F \propto L$[3], [22]. Recent discoveries also indicate that the deformability of the substrate is a significant factor in determining frictional regimes. In a study article published by Yu et al. (2024) [6], the researchers showed that a combination of elasticity and applied force can trigger smooth sliding and the emergence of a stick-slip regime.

Complementary information, however, is provided by the synergy between experiment and simulation: where AFM and SFA can directly measure interfacial shear strength, molecular spacing, and localised dissipation, MD simulations can resolve instantaneous fluctuations in forces and energy dissipation pathways at the atomic scale. The inherent gaps in temporal (milliseconds–seconds vs. nanoseconds–microseconds) and spatial (multi-asperity vs. single-asperity) resolution between these methods are reconciled through continuum contact mechanics, creating a unified multiscale description [9], [22]. In parallel, hybrid elasto-plastic–thermal models that couple mechanical deformation, lubrication, and frictional heat generation have been applied to predict the evolution of the friction coefficient in engineering components such as gears and rolling bearings, thereby advancing predictive, system-level tribological design [9], [33].

Fundamentally, atomic and molecular forces dictate the corrugation of interfacial potential energy surfaces and define the shear thresholds for sliding. Stick–slip motion converts external mechanical work into phononic, electronic, and microplastic dissipation, while interfacial films and third-body layers modify both local shear strength and real contact geometry. Through hierarchical upscaling, upscale to validate the apparent observation of Amontons' law across scales. These multiphysics, strongly coupled processes are the theoretical building blocks of the predictive framework developed in Section 5.

5. Conclusions

This review has discussed phenomena of friction at various scales, ranging from tribometric behaviour on a macroscopic scale to atomic and energy loss processes at the atomic scale. The discussion reveals that, despite the Coulomb–Amontons laws remaining impressively accurate on the engineering scale, they are best viewed as statistical emergent relations due to microscopic stick-slip physics, adhesion between interfaces, and dissipation under thermodynamic conditions. Experimental developments, such as the combination of AFM and SFA with high-resolution tribometers, along with MD simulations and continuum-scale modelling, have brought the distinction between atomic and macroscopic regimes closer. These experiments demonstrate that friction is not a material-fixed value, but rather a multivariate, multiscale, and complex response.

Although these were accomplished, several problems remain. The macroscopic tribological testing lacks standardisation, which remains one of the persistent problems. Differences in surface preparation, roughness parameters, environmental humidity, and load calibration often cause discrepancies from laboratory to laboratory, negatively affecting reproducibility and restricting the validity of comparative analysis. Moreover, the multiscale validation of the microscale results is not enough. Present-day nanoscale simulations and AFM experiments are usually restricted in their range to single-asperity contacts and nanosecond timescales, so their results cannot be easily generalised to tribology at the bulk scale or to component-level applications.

The future development of tribology will involve combining data-driven approaches with cross-scale experimental and computational systems. The opportunity to couple AFM or SFA to macroscopic tribometers by creating multiscale experimental platforms is one possible direction. In this way, real-time correlations between atomic friction and bulk wear behaviour can be made. There is also great potential in the use of machine learning methodologies for data fusion, as they can uncover unseen correlations and predict friction coefficients in complex operating conditions, thereby accelerating the identification of new tribological materials and surface treatments. Another crucial point is the creation of a set of standard testing procedures and publicly available databases, which would significantly enhance reproducibility and aid in validating predictive models.

The rational design of friction—between minimising energy loss, improving grip, or suppressing vibrations—will eventually become a possibility in the long run, due to coordinated efforts in surface texturing, material engineering, and adaptive lubrication. The tribology of the future will be multiscale, interdisciplinary, and intelligent by nature. Due to the convergence of experimental precision, computational abilities, and machine learning systems, it will become feasible not only to predict but also to program frictional behaviour based on atomic interactions, all the way down to the macroscopic level. It requires very tight interactions between physics, materials science, mechanical engineering, and data science to bring this vision to reality, thereby transforming friction from an empirical limit to a parameter that can be fine-tuned in advanced mechanical and energy systems.

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