

The Influence of Velocity, Load, and Temperature on Dry Nanoscale Friction

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The friction phenomenon is considered one of the most complex in nature. The present understanding of friction indicates that there are many variables and parameters that affect friction force directly or indirectly in relation to specific friction systems and their environments. The most important are the velocity, load, and temperature, but also the physical scale of the frictional contact. For dry nanofriction measurements, because of the high surface-volume ratio, there is a need to consider adhesive interactions that influence friction under certain velocity and load conditions. Research into the impact of different physical variables on friction and the study of different friction mechanisms not only gain basic knowledge, but also helps to better understand how to prevent the negative wear effects in modern miniaturized devices.

The atomic force microscope (AFM), which operates in lateral force (LFM) and force spectroscopy contact modes by means of the soft microcantilever with the tip at the end, has over the years become the most versatile instrument for studying friction and adhesion across the microscale to the atomic level. LFM enables direct measurement of the lateral force at the nanocontact in a range of physical variables, but due to many technical details, the determination of the resultant friction force is not an easy task. Furthermore, taking into account the number of parameters and large statistics necessary to describe friction phenomenon, the LFM output becomes a large data set with hundreds of thousands of individual data points per single friction point displayed on the graph. This makes data analysis and interpretation challenging.

Our previous work related to the topic shows that such friction experiments with the output in a form of average friction force versus sliding velocity and normal load help to identify the main dry friction mechanisms. They regulate the total energy dispersion of the system, in particular adhesive friction and stick-slip [1, 2]. These mechanisms mark their existence and domination under certain conditions. The first mechanism, adhesive friction, dominates in low load conditions, almost regardless of the velocity, and generally leads to a relatively low friction force. On the other hand, the energy dissipative stick-slip is dependent on the load and velocity, making relative movement less efficient. The latter mechanism is most probable at moderate and high loads as well as at low and moderate velocities. We have shown that the effect of velocity and load on friction force and the probability of the appearance of friction mechanisms in dry nanocontacts can be understood using a universal framework [1]. In addition, a precise calibration of the normal and lateral bending of the AFM cantilever allows for quantitative analysis of friction mechanisms using the models of thermally activated escape from the potential well. An important tool for supporting experiments is also the non-equilibrium molecular dynamics simulation.

Controlling the temperature of the nanocontact during sliding is also an interesting strategy that provides valuable insights into the nature of friction. This process is understood to be an addition of energy from outside the system that affects the friction force as a result of the increase in the probability of breaking the adhesive contacts.

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[1] Weiss, M., Majchrzycki, Ł., Borkowska, E., Cichomski, M., Ptak, A. (2021), *Tribology International*, 162, 107133.

[2] Weiss, M., Majchrzycki, Ł., Skonieczny, R., Florjan, D., Ptak, A. (2025), *Tribology International*, 201, 110203.