PROSPECTIVE STUDY ON MOLECULAR FRICTION
Opportunities, Challenges, and Applications

by

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This paper dives deep into the fascinating world of friction on a molecular scale. It applies the geometric potential theory to reveal some hidden secrets from the incredible mechanical properties of spider silk to the fascinating agglomeration of graphene. A new and promising concept is proposed: that friction can accumulate energy. This has the potential to revolutionize many fields in the future. When coupled with fractal theory, the molecular tribology offers a whole new window to design molecule-scale devices.

Key words: *molecular friction, spider silk, Coulomb friction law, fractal theory, geometric potential*

Introduction

God made the bulk; the surface was invented by the devil.
Wolfgang Pauli (Nobel Prize Laureate in 1945)

Friction is everywhere, and it is an amazing thing! It is the main reason for energy consumption in the world [1-3], and it is also the reason why we can use mathematics to create non-conservation forms of governing equations [4, 5]. In thermodynamics, it makes thermal processes irreversible, which has been attracting much attention to explain it physically [6], and in fluid mechanics, it makes the turbulence model unsolved. But here is the best part: it can also be used in advanced applications like triboelectric generators [7-9] and molecule electrical junctions [10-13].

Friction is an amazing phenomenon that arises when two faces are in contact with each other, or more accurately, when two atoms or molecules are approaching each other. The Coulomb's law of friction has been widely used in engineering, which makes a simple but ineffective assumption: that the contacted area does not affect the friction. Kong and He [14] disputed this assumption and overturned it, suggesting a total new friction law that can unify Newton's viscosity force into the new law. This is an amazing development in the field of the friction theory, and a high-precision numerical verification [15] is still needed.

Some natural phenomena can be explained by the friction theory in a really reasonable way! For example, agglomeration is pretty common in nature and can be considered as a frictional phenomenon. When point-like materials come together, friction at the molecular scale is formed. After the material agglomerates, it is difficult to disperse because of the

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strong friction and close adhesion to each other. Agglomeration of added particles greatly affects the properties of printed objects [16-18], concretes [19, 20], and nanofibers [21-24].

Molecular friction

Tomlinson gave a molecular theory to explain friction in 1929 [25], and now molecular-originated friction [26, 27] or atom-originated friction [28] has been studied extensively. To illustrate molecular friction, we first consider two 0-D points, the point can be a molecule, sand, or even a plant. A dune in a desert is formed according to the properties of the sand and environmental factors [29, 30]. Water molecules can be agglomerated into a liquid or a solid or a gas, depending on the agglomerated distance between the molecules, furthermore, plants and the sun are agglomerated into our solar system [31], these phenomena are called as 0-D agglomeration.

The 1-D agglomeration can explain the mechanism of nanofiber membrane formation [32, 33] in the electrospinning process by the geometric potential theory [34-37]. The electrospinning or bubble electrospinning produces nanofibers, and in the receiver, nanofiber membranes can be formed [38-41] due to the 1-D agglomeration.

The 2-D agglomeration occurs in graphene, a 2-D nanomaterial [42, 43]. When two pieces of graphene come together, they are difficult to separate. According to the molecular friction, the interaction force between graphene sheets is very large, which can be explained by the Casimir force, which is generated when two pieces of planes are close to a few nanometers [44, 45].

If the two pieces of graphene are to be separated under the Casimir force, we can apply the lubrication theory [46]. This is a new idea for graphene separation. How do you separate? You fill the two plates with some oil or water, and you push the two graphene plates up. This is similar to the sliding bearing theory in tribology.

Molecular friction and spider silk

The reason why a spider silk has such an amazing mechanical property in strength and flexibility can be explained by molecular friction. The spider silk is actually a fiber aggregate composed of thousands of nanofibers with a diameter of about 20 nanometers [47, 48]. The spider silk is a dimensional agglomeration, so the friction between the nanofibers is extremely high. Wang, *et al.* [49] used this friction phenomenon to design a stab-proof fabric and the puncture resistance of nanofiber membrane, Qian, *et al.* [50] used the spider spinning method to design a long-tube spinning system to arrange the internal structure of macromolecules in a nanofiber. Zuo and Liu [51] concluded that the spider spinning process can be extended to 3-D printing technology.

Have you ever wondered how can spider silk be so strong? This paper presents a simple experiment that illustrates the incredible hidden secret of spider silk. Take two books and stack their pages on top of each other, fig. 1. It is hard to pull them apart, isn't it? The reason is that the strength of the paper is very weak. A tear will break, but if you put a page with a page interspersed with each other, the great friction will prevent the pages from being broken. Amazing, isn't it? This is because there is a lot of energy between the pages of the book, and the book will be torn only after the energy is overcome, so friction is a type of energy. When the pages of two books are stacked on top of each other, the strength increases, and the accumulated energy increases. It takes a lot of energy to pull the two books apart, and the books accumulate a lot of energy through friction. This has the potential to be used in the future in some really exciting ways! Let us think of friction as a kind of energy! Just like it takes energy to move water away, it takes energy to pull apart two books that are rubbing against each other. This means that energy is accumulated by friction. Collecting energy by friction is a very good, modern idea, much better than the traditional energy harvesting technologies [52, 53].

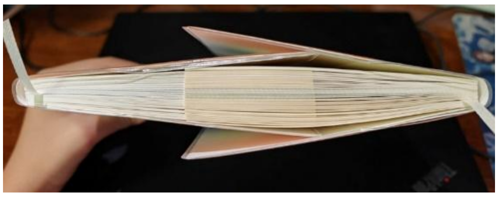

Figure. 1. Two books with pages stacking on top of each other

Now, we can finally explain the groundbreaking puncture prevention experiment by Wang *et al.* [49]. Through experimental analysis, they created incredibly thin and strong nanofiber membranes that can concentrate a tremendous amount of energy, such as bullets kinetic energy. A nanofiber membrane is an amazing material that can store a lot of friction energy. Imagine a knife, gun, or any other object hitting the membrane, and the energy is stored in the nanomembrane, which plays a crucial role in stab prevention. The nanofiber membrane is incredibly thin and has many intertwined fibers that can *eat* the extra energy, which is fantastic! If we want to break the fiber, we must first overcome its friction energy, which is equivalent to saying that the energy *eaten* is stored in the nanofilm. This is incredible! The nanofilm has the function of energy accumulation and puncture prevention, and the energy is stored by friction.

Discussion and conclusions

When studying friction from the molecular scale, we find that the traditional friction theory has been greatly challenged, which is really exciting! From the molecular scale, friction is related to the molecules interaction, so the most important thing is to introduce fractal geometry into nanofriction. The combination of fractal geometry and nanotribology can be explored and applied theoretically or experimentally in the future, which is really promising!

We are thrilled to introduce fractals into the fascinating field of molecular tribology, inspired by the incredible gecko effect [54, 55], which is a fantastic source of inspiration for the study of flexible molecular tribology or fractal tribology. The incredible hierarchical structure of the gecko foot has all the hallmarks of a fractal, and it performs like a dream! We are on the cusp of a revolution in tribology thanks to fractal theory. In the next few years, we will see fractal tribology theory applied in ways we never thought possible.

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