The Research on Friction Characteristics of Non Smooth Bionic Mesoscopic Surface

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Abstract: *The application of using friction to transmit power and prevent slippage is very widely used, many animals have very strong adhesion climbing ability, and it has important theoretical significance and wide application prospect to research and the prepare bionic surface to increase transmission friction using the bionic technology. In recent years, the research of foot structure of climbing animals shows that their surface morphology has both macro and micro scale features, and only study from the macro to the micro scale surface structure can be better elucidate the mechanism of increasing-friction of climbing animal. This paper will study bionic surface structure on mesoscopic scale from micron to millimeter level, research the influence of foot structure of climbing animal under mesoscopic scale on characteristics of increasing friction using bionic technology, prepare the bionic non-smooth surface of convex or concave using bionic manufacturing technology, establish the friction model of non-smooth surface, investigate the increasing-friction mechanism of the bionic surface morphology on mesoscopic scales, reveals the influence of surface morphology, layout, size and material properties on the friction characteristics, provide the design of bionic friction surface and calculation method of friction coefficient and provide reliable theoretical basis for engineering application.*

Keywords: *Bionic, Tribology, Increasing-friction, Mesoscopic surface.*

Introduction

The bionic non-smooth surface tribology is one of the hottest issues in research of bionic engineering field [3, 5, 6, 10]. The application of using friction to transmit power and prevent slippage is very widely used, such as vehicle brake, friction wheel transmission and belt conveyor, etc. The preparation of the bionic non smooth surface increasing the friction by studying the foot structure and morphology of climbing animals with bionic technology, to increase the friction coefficient between the interfaces and increase the friction, provides a new research idea and design method for the friction drive and non-slip surface, in order to better meet the needs of industrial and agricultural production. Climbing animals feet possess the characteristics of adsorption and increasing-friction and adsorption is mainly relied on Van der waals interaction produced by bristles, but the increasing-friction is relied on the non smooth surface structure style of their feet, the two forms of climbing mechanism is completely different. Structure form of bristles adsorption is not applicable to friction drive, and imitating the animals non-smooth feet cushion can prepare the bionic non-smooth surface which is used to transmit power and prevent slippage. In recent years, the research whose goal is to improve friction or increase the drag using the bionic technology has made some progress [1, 2, 4, 7-9], mainly concentrated on the bionic macro surface. The research results show that the bionic increasing-friction surface need to be further studied from macro to micro. This paper mainly studies the increasing-friction mechanism of climbing animals in the mesoscopic scales on the basis of the research of macro increasing-friction surface to prepare bionic non smooth increasing-friction surface and reveal the influence on the increased friction of factors. It will provide reliable theoretical basis for engineering application.

Bionic increasing-friction mechanism

The domestic and foreign scholars have conducted a lot of research on the biological climbing and adsorption mechanism. The results showed that the main adsorption types of animals are bristles and epidermal pads, and the adsorption organ are smooth and deformable epidermal pads, adsorption bristles and viscous fluid [2, 8]. The adsorption mechanisms of different animals are not identical, some are bristle-based, some are mainly adhesive pads, and some of them mucus plays a dominant role, but more are combined effects. The structure of adsorption type of bristles is complicated and manufacture is difficult. At the present research status, it is more suitable for climbing robot, MEMS, and it difficult for mechanical friction drive and preventing slippage etc. The type of epidermal adsorption pads is more suitable for friction drive or non-slip surface.

Bionic increasing-friction technology which references bionics [6] is used to produce similar material surface morphology through research and analysis adsorption mechanism of epidermal adsorption pads of animals (such as tree frogs, katydids, ants and others) [3]. It is propitious to improve the friction coefficient between friction surfaces and increase the friction which helps to enhance the vehicle braking safety and friction transmission reliability.

The micro scale adhesive contact theory

The non smooth characteristics of biological surface

Biological surface appears smooth on a macro-scale, but it displayed a surface morphology composed by many irregular peaks and valleys when viewed under a microscope. The micro geometry properties which consist of height and dense degree of tiny peak and valley are called surface roughness which is also known as surface micro irregularity. The surface roughness which is called surface finish before is the degree of the actual surface dimension deviated from the ideal surface within the error range on the micro geometry. As shown in Fig. 1, the average roughness R_a as general parameters of surface roughness represent the region of the unit length area ratio which is separated by the imaginary (midline) line whose length is l. The horizontal line of R_a is above the line after getting the absolute value:

$$R_a = \frac{1}{l}\int_{x=0}^{x=1} |z(x)| dx . \tag{1}$$

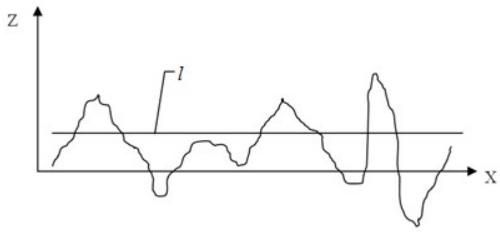


Fig. 1 Surface roughness

The roughness is the degree of uneven surface of component on micro and its micromorphology can be regular periodic fluctuation and it can also be a random fluctuation with no rules at all. Roughness R_a is micro geometry error which is relative to the datum and its distribution usually follows the $N(0, \sigma^2)$:

$$R_a = \frac{\int_0^1 |y| dx}{l}.$$

Many biological surfaces have different geometric non-smooth morphology, the surface characteristics of geometric non-smooth surface show the aspects of following:

1) The size and shape of non-smooth geometry are basically same.
2) Arrangement, density and direction of geometry are distribution regularity.
3) Roughness R_a of everywhere is consistent.

The animal foot pad adhesive contact theory on micro scale

The traditional theory of macroscopic contact only considers the role of the external forces when two parts contact with each other, and does not consider the effect of surface forces. The characteristic scale of subject investigated will appear many phenomenons which the traditional macroscopic contact theory can not explain when it reduces into limits. We attributed it to the effect of surface force between two objects, the surface energy and surface stress which is derived by surface energy are key factors which determine the adhesion, contact and deformation behavior of solid surface. In macro-contact theory, these surface forces are weak in comparison with elastic force and can be ignored. For the adhesion, contact and deformation micro-phenomena which are happened on the scope of atoms and molecules in the solid interface, the traditional method of continuum mechanics has been insufficient to resolve such problem. The theory of adhesion caused by surface force (or surface energy) is combined with classical mechanics theory and constitutes the microscale adhesion contacts theory.

Considering the influence of adhesive generated by free energy, surface energy of contact bodies on the contact behavior, the relationship between elastic ball contact and surface adhesion has been defined.

When the two elastic ball contacts without external loads, attractive interactions between two surfaces produces a limited contact circle with radius of *a* on interface. The energy balance characterized by which surface energy on interface is transformed into the elastic energy caused by surface deformation. The loss of surface energy U_s is:

$$U_s = -\pi a^2 \gamma, \qquad (2)$$

where γ is adhesion energy of contact surface.

It exists energy conversion between the contact interfaces under an external contact load F_0. The total energy UT is a function of contact area of A, which is consists of three parts, the external loads do the work to contact elastic bodies U_M (mechanical energy), the elastic potential energy UE converted by elastic deformation produced by two contact elastic bodies and the surface free energy U_s of two contact interface. To determine the equilibrium equation using the principle of minimum potential energy, and then obtain the relations between F (produce equivalent load of deformation of contact bodies when consider the adhesion energy) and the contact load F_0:

$$F = F_0 + 3\pi\gamma R + \sqrt{6\pi\gamma R F_0 + (3\pi\gamma R)^2}\ . \tag{3}$$

It achieves balance when $\frac{dU_T}{dA} = 0$, and we get the relationship between the contact area radius a and the elastic body compression δ after Hertz theory is revised:

$$\begin{cases} a^3 = \frac{R}{K}(F + 3\pi\gamma R + \sqrt{6\pi\gamma RF + (3\pi\gamma R)^2}) \\ \delta = \frac{a^2}{R} - \left(\frac{8\pi a\gamma}{3K}\right)^{1/2} \end{cases}. \tag{4}$$

The adhesion force when separated is:

$$F_s = \frac{Ka^3}{R} - \sqrt{6K\pi a^3\gamma}\ . \tag{5}$$

After removing external contact load, contact circle radius produced by adhesive force is:

$$a_0 = \left(\frac{6\pi R^2\gamma}{K}\right)^{\frac{1}{3}}. \tag{6}$$

The minimum load F, that is the maximum force required as separating two contacts spherical, is:

$$F_{pull-off} = -\frac{3}{2}\pi\gamma R\ . \tag{7}$$

At the point, the contact radius and normal displacement are:

$$\begin{cases} a_p = 0.63a_0 \\ \delta_p = -0.21\frac{{a_0}^2}{R} \end{cases}. \tag{8}$$

According to the adhesion theory of elastic body friction, we can draw the adhesion friction coefficient μ_a is:

$$\mu_a = B\left(\frac{E}{P^\nu}\right)\tan\lambda = B\left(\frac{E}{P^\nu}\right)\frac{a_p}{\delta_p}, \tag{9}$$

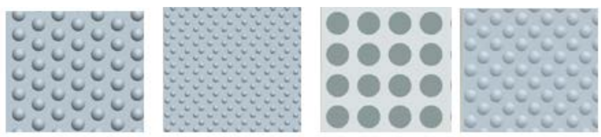
where B is a constant, E is elasticity modulus, P is pressure, ν is a function about the adhesion ability produced by surface, $\nu < 1$, λ is material loss angle whose tangent is the ratio of contact radius and direction of displacement.

The bionic model of surface structure of animal foot pad

We observed the foot pads of frogs, katydids, house lizard and bees and other animal through using super depth 3D digital microscope and scanning electron microscope experiments. Fig. 2 shows the micro non-smooth increasing-friction surface structure of the tree frogs and katydids and adhesive pads of non-smooth surface morphology of these animals were analyzed. The results suggest that adsorption mechanism plays a dominant role in all factors of friction driving force produced by insect. And the adsorption of tree frogs, katydids, house lizard and bees rely mainly on epidermal pad which rely on deformation of unevenness of the animal claw foot flexible skin to increases the contact force and the epidermal pad adsorption is suitable for friction drive and increasing- resistance and non-slip surface. A set of sample size of bionic non-smooth surface model has been designed according to the surface structure of tree frog and katydids as shown in Fig. 3.

(a) the frog's fore foot structure (b) the foot pad structure of katydids

Fig. 2 Micro non-smooth increasing-friction surface structure of the tree frogs and katydids



(a) sample 1; (b) sample 2; (c) sample 3; (d) sample 4

Fig. 3 The samples of bionic non smooth surface model

The preparation process of bionic non-smooth mesoscopic surface

Micro array of the rubber surface is formed using imprint technology and chemical corrosion method. Firstly, we can process multiple sets of templates in the macroscopic surface which has been prepared using the laser micro-nano processing technology and make templates possessing the micro array in which uniform silica particles. Align bionic materials with the templates and apply pressure and heat treatment, as shown in Fig. 4, and embed the silica particles into bionic materials. Then we get the two-dimensional monolayer microspheres with large area and highly ordered on the bionic material surface. Then use the HF acid corrosion solution to remove silica microspheres, and then we can obtain two-dimensional concave surface with large area and highly ordered on bionic materials surface. Bionic surface which has been prepared is shown in Fig. 5.

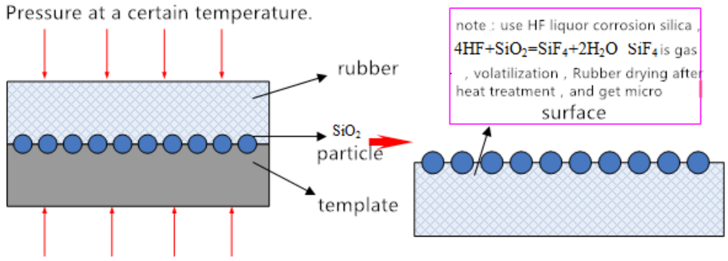
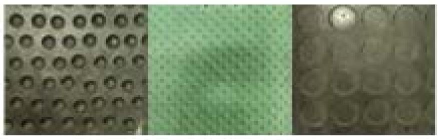


Fig. 4 The method of forming micro array of rubber surface using imprint technology and chemical corrosion



(a) sample 1; (b) sample 2; (c) sample 3

(d) sample 4; (e) sample 5; (f) sample 6

Fig. 5 Some preparing sample graphs

Experiments of friction characteristics of bionic surface

Control universal friction and wear testing machine to conduct friction performance experimentation of bionic surface using MMW-1A Microcomputer. Simulate the friction forms of rolling, sliding and complex motion of rolling and sliding under the constant pressure. Figure 6 is the principle and prototype of experimental system. Testing machine mainly consist of a panel, spindle drive system, spring loading system, the friction torque measurement system of test force, embedded computer control system (including LCD, host computer, data acquisition module, control board ,etc.), friction and special clamp.

The sample and size in experiment: the total samples of experiments are 6 groups and their materials are rubber. The laboratory projects are: effects of different pressure and sliding velocity on the friction coefficient, effect of bionic array form and density on the friction coefficient and effects of different interface media on the friction coefficient.

The analysis of friction characteristics of bionic surface

The effects of different pressure on the friction coefficient

The spindle speed of wear test machine is 40 r/min at room temperature and dry friction condition, the experimental sample is sample 1 and the different experimental positive pressures adopted are respectively 20N, 40N, 60N, 100N and 150N. Effects of different pressures on the adhesion friction coefficient are shown in Fig. 7.

As can be seen from Fig. 7, the friction coefficient decreases as the pressure increasing, and their relationship is nonlinear. The friction coefficient declines drastically at the beginning, and tends to standard last and it tends to be stable when the pressure increases to a certain value. The experimental results trend is consistent with that of theoretical results.

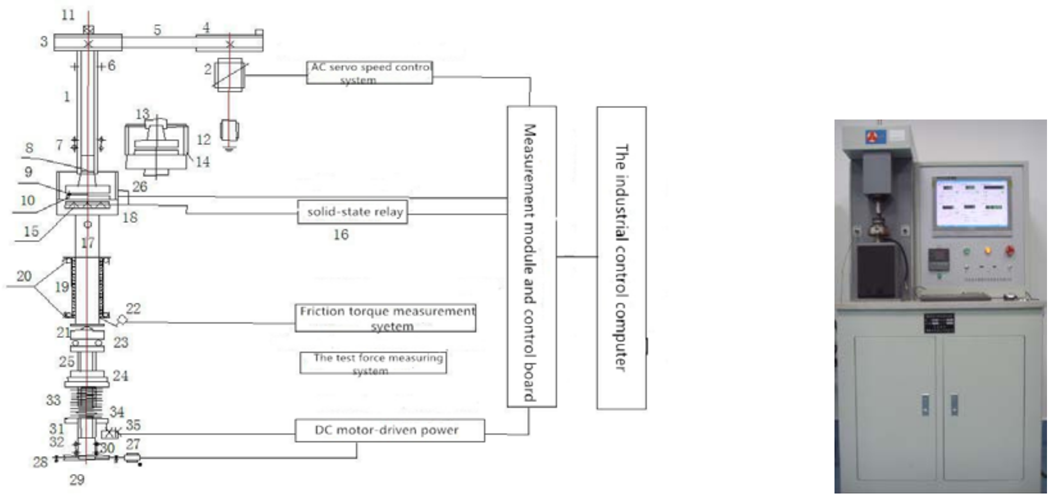


Fig. 6 The principle and prototype of experimental system

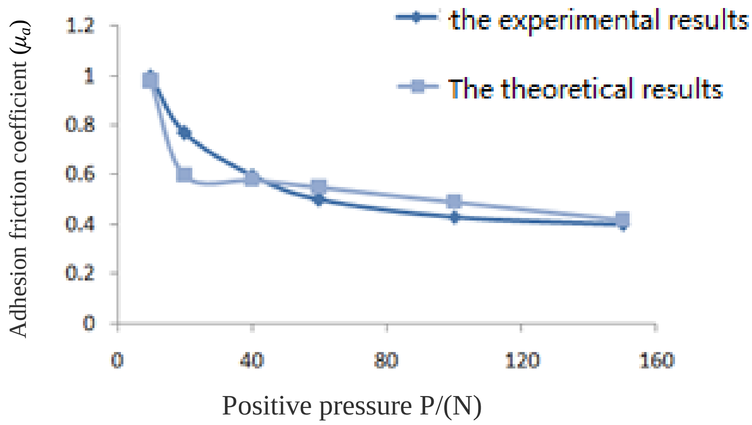


Fig. 7 Changing curve graph of the friction coefficient with the press

Effects of different temperatures on the friction coefficient

Under the dry friction conditions, the spindle speed of wear testing machine is 40 r/min and the experimental sample is sample 1. The positive pressure is 40N. The temperatures adopted in the friction performance experiment respectively are 0°C, room temperature 20°C and higher temperature 100°C. Effects of different temperatures on the adhesion friction coefficient are shown in Fig. 8.

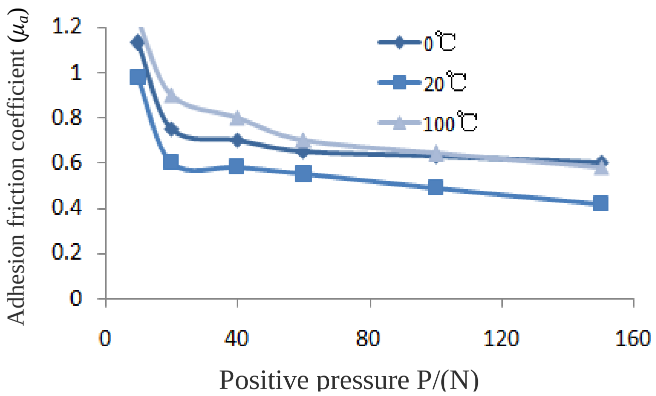


Fig. 8 Changing curve graph of the friction coefficient with the temperature

As can be seen from the Fig. 8, the adhesion friction coefficient decreases a little when temperature changes from 0°C to 20°C, but the adhesion friction coefficient will increase when temperature increase continually to 100°C which is bigger than that of 0°C.

Influence of sliding speed on the friction coefficient

At the room temperature and dry friction conditions, the experimental samples is sample 1 and positive pressure is 40N. Experiment adopts different wear test machine and their spindle speeds respectively are 0.5 r/min, 1 r/min, 40 r/min and 50 r/min. The influence of different sliding speeds on the adhesion friction coefficient is shown in Fig. 9.

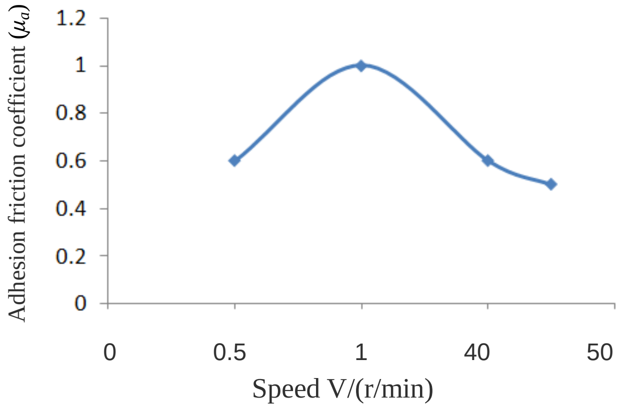


Fig. 9 Changing curve graph of the friction coefficient with the speed velocity

As can be seen from Fig. 9, the adhesion friction coefficient changes with sliding velocity in parabola, and friction coefficient is up to maximum when the spindle speed of experiment machine reach 1 r/min and descending to the slow and fast two party.

Effect of bionic array form and density on the friction coefficient

Sample 5 and Sample 6 which are based on sample 1 remove a row of convex hull along different directions that is distribution density decrease. The difference between the sample 5 and 6 is the array form. Array mode of sample 6 is same as the motion direction and array mode of sample 5 and motion direction are 45 degree angle.

At room temperature and the dry friction conditions, spindle speed of wear test machine is 40 r/min and the experimental samples are sample 1, sample 5 and sample 6. Use different experimental positive pressures *P* and they are respectively 20N, 40N, 60N, 100N and 150N. The influence of different array mode and density on the adhesion friction coefficient is shown in Fig. 10.

Fig. 10 shows that the friction coefficients of sample 5 and sample 6 are smaller than that sample 1 under the same conditions, and distribute density of sample 5 and sample 6 decreases compared to that sample 1. It can be concluded that when the distribute density decreases, the friction coefficient decreases. The reason of decreasing is that contact surface reduces the number of convex hull and effect of mosaic caused by the convex hull decreases, so the friction coefficient decreased.

Compare with the curve of friction coefficient of sample 5 and sample 6 whose arrangement is different, we can find that the arrangement also has effect on the friction coefficient. When the direction of movement and the arrangement of convex hull are uniformly, the friction coefficient is smaller, namely sample 6 has smaller friction coefficient. The reason is the convex hull and the contact surface form a mosaic effect and will produce the plowing effect when move. The number of plowing effect of sample 5 should be higher than that of the sample 6.

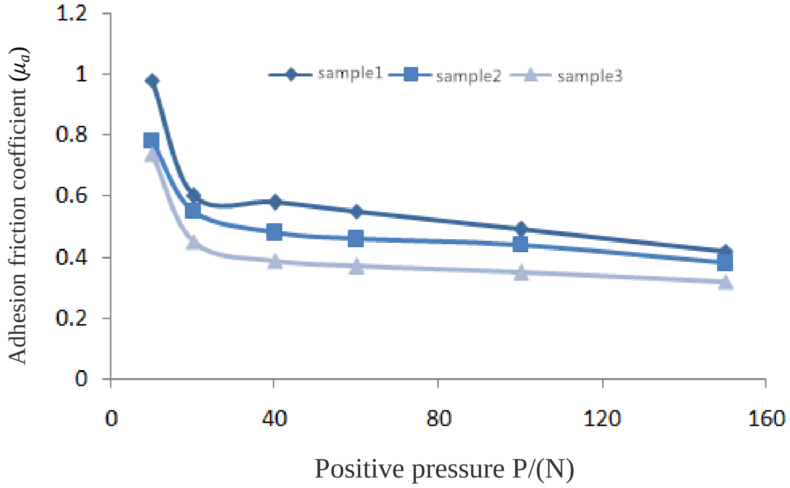


Fig. 10 Changing curve graph of the friction coefficient with the arrange way and distribution density

Effects of bionic array pattern on the friction coefficient

Spindle speed of wear test machine is 40 r/min and the experimental samples are sample 1, sample 2, sample 3 and sample 4 at room temperature and the dry friction conditions. Use different experimental positive pressures *P* and they are respectively 20N, 40N, 60N, 100N and 150N. The influence of different array patterns on the adhesion friction coefficient is shown in Fig. 11.

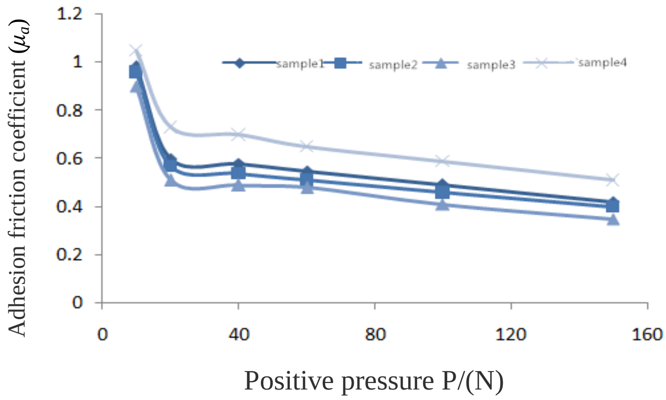


Fig. 11 Changing curve graph of the friction coefficient with the arrange style

As can be seen from Fig. 11, under the same conditions, the friction coefficient of sample 4 is greater than sample 1, due to the array density of sample 4 is larger than sample 1. The friction coefficient of sample 2 is smaller than sample 1 because the convex hull size of sample 2 is too small, the mosaic effect between the convex hull and the contact surface is not obvious. Instead, the existence of the convex hull reduces the contact area. This kind of surface morphology reduces the friction force instead of increasing friction, which is also one of the principles of bionics non adhesive. Friction coefficient of sample 3 is smaller than sample 1, due to the surface of the sample 3 is a dimple and the surface area is larger, the density is smaller. When the bionic rubber surface contacts with the metal surface, they can not form a mosaic, so its friction coefficient is minimum.

The effect of different interface media on the friction coefficient

At room temperature, the spindle speed of wear testing machine is 40 r/min, the experimental sample is sample 1 and the positive pressure is 40N. Experimental samples are sample 1, sample 2 and sample 4. Use the different lubrication which are respectively dry and clean without any lubrication, water lubrication and oil lubrication. The influence of different interface media on the adhesion friction coefficient is shown in Fig. 12.

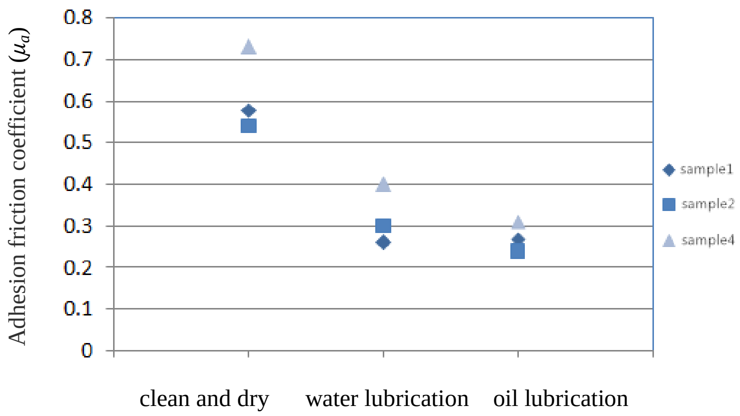


Fig. 12 The influence of different interface media on the adhesion friction coefficient

As can be seen from Fig. 12, the friction coefficient under the dry cleaning media is maximum in 3 samples, followed by water lubrication and oil lubrication minimum.

Conclusions

The main conclusions of the presented research could be summarized as:

- The friction coefficient decrease as the pressure increasing, and their relationship is nonlinear.
- The friction coefficient decreases as the temperature increasing before rubber softened, and the friction coefficient will increase when reached the certain temperature.
- The friction coefficient changes with sliding velocity in parabola, and friction coefficient is up to maximum when the spindle speed of experiment machine reach 1 r/min.
- The friction coefficient decreases when the distribution density of bionic array decreases.
- The arrangement also has effect on the friction coefficient, when the direction of movement and the arrangement of convex hull are uniformly, the friction coefficient is smaller.

Also, the friction coefficients are different when bionic array style is different. The friction coefficients of sample 1, sample 5 and sample 6 designed by using bionic technology are larger than that of ordinary surface. It shows that simulating the foot structure and morphology of climbing animals and preparing bionic non-smooth increasing-friction surface to increase the friction coefficient between friction interfaces and to enhance the friction is feasible.

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