Discrete Element Simulation of Durability for Bionic Wheels of Mars Rover

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Abstract. Four kinds of bionic surfaces (convex, scale-like, ribbed and concave shape) for Mars rover wheels were designed to improve wheel durability. A discrete element wheel-soil simulation system was developed, and three-dimensional discrete element analysis and soil bin tests were conducted. The results show that the masses of the convex and scale-like forms increased by 5.4\% and 17\%, respectively, and that the tangential cumulative forces decreased by about 40\% and 70\%, respectively. The wear mass decreased by 53\% and 47\%, respectively, compared with a prototypical wheel. The simulation shows that the durability increased significantly. The average tangential cumulative forces of the concave and ribbed shapes increased by more than 50\%, and the wear mass decreased by 35\% and 32\%, respectively, compared with a prototypical wheel. The simulation shows that the results were not definitive. The analysis shows that the durability of the wheels can be improved via bionic optimization method. These results therefore provide a basis and reference for the design and optimization of the Mars rover’s wheel surface.

1. Introduction

Mars is covered by a layer of loose Martian soil and by many craters, volcanoes, sand dunes, and canyons \cite{1,2}. These poses a challenge to the motion and durability of the Mars rover’s wheel. The data shows that NASA used the experiences of the Opportunity rover and the Sojourner rover in the development of the Curiosity Rover’s wheel, but they ignored the influence of batholith pavement on the thin tread of the rover’s wheels \cite{3}. On October 2, 2013 (sol 411), considerable wears and many holes were discovered in the left front wheel of the Curiosity, which affected the normal development of the detection mission. Therefore, optimization of the rover wheels and a study of wheel durability are critical to ensure the mission.

In the 1960s, when NASA developed the lunar roving vehicle (LRV) wheel, they considered the friction and wear of the lunar soil and the tire surface \cite{4}, and carried out soil-bin and drum test under vacuum in high and low temperature environments. In recent years, to verify the service life of all-terrain hex-limbed extra-terrestrial explorer (ATHLETE) wheels, NASA and Clemson University designed a durability test device \cite{5} and tested the durability of different treads \cite{6}.The Japan Aerospace Agency tested the durability of the lunar rover in a vacuum environment, and found that the effect of air pressure on wear was not significant, but that wear appeared earlier in a vacuum environment \cite{7}. NASA studied the anti-wear characteristics of aluminum (Al), nickel (Ni) and
platinum (Pt) in the Sojourner Mars wheel abrasion experiment (WAE). It was concluded that Martian dust is harder than Al, similar to Pt and softer than Ni [8]. In response to the wear and tear problems encountered by the Curiosity, NASA developed a new type of spring tire for the Mars 2020 rover, in cooperation with Goodyear, to improve its durability and pass ability based primarily on the design of the Curiosity’s wheel [9].

Durability testing of rover wheels is a lengthy and expensive process. It is also difficult to quantitatively and qualitatively evaluate the effects of the microscopic tread and microgravity on durability. Therefore, simulation analysis is an ideal tool for evaluating the mobile performance of deep space exploration vehicles. Many researchers have studied the interaction of wheels with the Martian soil or the interaction of the human foot and Martian soil based on the finite element method and the discrete element method, and have achieved a series of important results [10-13]. However, few studies have used the discrete element method to examine the durability of the rover wheels.

According to the characteristics of anti-wear organisms, in this study, the bionics method was used to optimize the wheel surface of the rover, and a dynamic simulation system suitable for investigation of the wheel-soil interaction was established. The effectiveness of the simulation system was verified in soil-bin tests for durability under different slip ratios and loads. Also, the tangential cumulative forces of the bionic wheel and the prototype wheel were compared, and the influence of shape on the durability of the wheel was analyzed.

2. Bionic non-smooth Mars wheel model construction

2.1. Bionic prototype

Land animals in caves and aquatic mollusks often come into contact with soil or sea sand when they are in motion, and their surface has long suffered from erosion by soil or sea sand and abrasive wear. In the process of adapting to the environment, such organisms have developed anti-wear geometric surfaces [14-15], as shown in figure 1. Through bionic design, the convex and concave body surfaces of land animals, the overlapping scales of the pangolin body surface, and the ribbed surface of Chlamys farreri were applied to the surface design of the wheel of the rover.

![Figure 1](image1)

**Figure 1.** Four Non-smooth Surfaces of Animals: (a) convex; (b) concave; (c) scales; (d) ribs.

2.2. Bionic prototype

The model wheel was 120 mm and 180 mm in diameter. According to the non-smooth surface structures and size parameters shown figure 1, four kinds of bionic non-smooth surfaces were designed. The height or depth of the bionic unit was 1 mm, and the ribs were sinusoidal. The four bionic non-smooth surfaces are shown in figure 2.
3. Construction of discrete element simulation model

3.1. Determination of bulk particles and wheel parameters

The soil groove particles were divided into two types: The bottom particles are set as single spheres. The top layer of particles were triple spheres to control the number of particles and improve the operation speed. At the same time, the mechanical properties of the particles were ensured to be consistent with the test. Through the virtual accumulation experiment, as shown in figure 3, the contact mechanics parameters of discrete element particles were constantly adjusted so that the physical parameters of the Martian simulated soil were consistent with those of quartz sand used in the soil trough test in figure 4. According to the quartz sand density, the experimental value was selected as the simulation parameter, and the collision recovery coefficients were 0.15, 0.35, and 0.75. The static friction coefficients were: 0.2 and 0.8 and the rolling friction coefficients were 0.2 and 0.3. The twelve groups of parameters were simulated and calibrated as described above, and the calibration results are shown in table 1.

Table 1. Certification Result of Repose Angle

| Sequence of simulation | Collision coefficient of restitution | Static friction coefficient | Coefficient of rolling friction | Stacking angle (°) |
|------------------------|--------------------------------------|----------------------------|---------------------------------|-------------------|
| 0                      | 0.5                                  | 0.50                       | 0.01                            | 30.5              |
| 1                      | 0.15                                 | 0.2                        | 0.2                             | 27.5              |
| 2                      | 0.15                                 | 0.2                        | 0.3                             | 27.2              |
| 3                      | 0.15                                 | 0.8                        | 0.2                             | 34.6              |
| 4                      | 0.15                                 | 0.8                        | 0.3                             | 38.4              |
| 5                      | 0.35                                 | 0.2                        | 0.2                             | 27.8              |
| 6                      | 0.35                                 | 0.2                        | 0.3                             | 28.3              |
The repose angle test results presented in table 1 show that when the particle collision response coefficient, the static friction coefficient and the rolling friction coefficient were 0.75, 0.2, and 0.2, respectively, the repose angle is 33.8°. The average experimental measured angle was close to 32.1°, which is an average angle deviation of 1.7°. Therefore, the collision recovery coefficient, the static friction coefficient and the rolling friction coefficient between particles were set as 0.75, 0.2, and 0.2, respectively.

![Figure 3. Result of repose angle.](image1)

![Figure 4. Measurement of repose angle.](image2)

The discrete element simulation used a Martian soil cohesion of 0.5 KPa, and the internal friction angle is 33.8°. The grain contact model used was that of Hertz Mindlin (no slip), and the wheel was defined as a stainless-steel material. Table 2 shows the contact mechanics model parameters of the bulk particles.

| Parameters                                  | Values                  |
|---------------------------------------------|-------------------------|
| Number of particles                         | 200000                  |
| Particle Poisson ratio                      | 0.3                     |
| Particle shear modulus /(Pa)                | 1.6×107                 |
| Particle density /(kg/m3)                   | 2000                    |
| Particle - wheel collision recovery factor  | 0.5                     |
| Particle - wheel static friction coefficient| 0.5                     |
| Particle - wheel rolling friction coefficient| 0.01                   |

3.2. Dynamic simulation system
The formation of the simulation system required four steps: (1) the formation of the bottom particle aggregation, which reached a steady state under the earth’s gravity field; (2) the formation of upper particle aggregation, which reaches a steady state under the earth’s gravity field; (3) the three-
dimensional model of the wheel, which was introduced at the specific position of the soil groove, whereupon contact of the wheel with the particles reached static balance; (4) setting the motion parameters of the wheel, including rotation angular velocity, load on the wheel and slip rate. Wheel subsidence only occurred under the action of gravity. Figure 5 shows the dynamic simulation system composed of a prototype wheel and a particle.

![Figure 5. Dynamic simulation system of a wheel and particles.](image)

4. Dynamic simulation and analysis of interaction of wheel and Martian soil
The simulation process is divided into two categories: The first kind of wheel does not slip and the wheels and Martian soil have rolling friction; The second kind of wheel skidding can realize rolling and sliding friction with the Martian soil at the same time. The two simulation conditions are shown in table 3.

| No. | Slip rate (%) | Load (N) |
|-----|---------------|----------|
| 1   | 0             | 80       |
| 2   | 10            | 80       |
| 3   | 30            | 80       |
| 4   | 0             | 100      |
| 5   | 0             | 160      |

4.1. Durability test stand
To verify the feasibility of the discrete element simulation, the durability test of the particle bed was carried out on an independently designed durability test bench. Figure 6 shows a schematic diagram of the durability test bench. Figure 6(a) shows that the durability test bench consisted of a frame, a soil groove, a control system and a drive system. The test time, mileage, speed and energy consumption were recorded by the data collector in the control system. Figure 6(b) shows the top view of the test bed. The diameter of the test bed was 1.7 m, and the test revolving radius could be adjusted by the drive system.
4.2. Evaluation index

In the durability tests, the quality loss increased with increasing time, and the quality loss was difficult to measure in a short time. The wheel was subjected to friction resistance during rolling, which is an instantaneous reflection of force. The work done by friction resistance during wheel rolling is energy loss, which reflects the accumulation of friction force with the energy loss per unit time. Therefore, the wear amount and energy loss per unit time, which were calculated by using equation (1) and (2), respectively, were used as evaluation indexes for the durability test.

$$\delta = \frac{m}{t}$$  \hspace{1cm} (1)

Here, $m$ is the mass loss, with units of milligrams (mg), and $t$ is the wear time, with units of hours (h).

$$p = \frac{W}{t}$$  \hspace{1cm} (2)

Here, $p$ is power consumption, with unit of watts (W), $w$ is the energy consumption over the wear time, with units of W, and $t$ is the wear time in hours (h).

In the process of wear, the vertical force acting on the contact point presses the hard particle into the material surface, whereas the horizontal force (the tangential force below) causes relative displacement between the hard particle and the surface. Under the joint action of various wear mechanisms, the motion of the abrasive particle against the surface of the material continuously produces furrows or grinding chips. After repeated plastic deformation, the surface of the material produces cracks and spalling, resulting in quality loss. Therefore, in discrete element simulations, the contact force of particles and contact objects is commonly used to characterize the degree of wear [16], and, it has been applied to evaluate the wear of working parts by using tangential and normal cumulative forces [17]. In this study, the normal force of the wheel during rolling was fixed, so it was not considered. However, the tangential force was the main factor of affecting wheel wear. Therefore, the net tangential force of the wheel in a single sampling step over the total sampling time was used-the cumulative tangential force represents relative wear.

The cumulative tangential force $F_t$ is the resultant force of the tangential force for a single sampling time $f_{\Delta t}$ within the total sampling time, as shown in equation (3).

$$F_t = \sum_{n} f_{\Delta t}$$  \hspace{1cm} (3)

Here, $\Delta t$ is the sampling time, $n$ is the sampling number, and $f_{\Delta t}$ is the tangential force of the wheel in a single sampling time.

4.3. Test verification

Figure 7(a) shows the durability test bench. The wheel, driven by the motor, rotated around the central axis, adding weight to the axle center of the wheel to realize wear. After a certain period of time, the
wheel was weighed on an electronic balance that had an accuracy of 0.01 g, as shown in figure 7(b). During the test, the speed of the wheel around the axle center of the test bed was 0.5 rad/s, and the load on the wheel was 8 N. The abrasive material was quartz sand with an average particle of 0.4 mm.

Durability verification does not consider the influence of wheel materials on wear, only the influence of the bionic design microstructure. The model wheel was obtained by using imported photosensitive resin of UTR9000 through three-dimensional (3D) printing technology. The parameters of the five model wheels are shown in table 4.

**Table 4. Parameters of Model Wheels.**

| Shape     | Wheel diameter(mm) | Width(mm) | Thickness(mm) | Initial mass(mm) |
|-----------|--------------------|-----------|---------------|------------------|
| Prototype | 180                | 120       | 1             | 95.92            |
| Ribbed    | 180                | 120       | 1             | 101.39           |
| Concave   | 180                | 120       | 1.5           | 100.57           |
| Convex    | 180                | 120       | 1             | 103.53           |
| Scale-like| 180                | 120       | 1             | 112.65           |

Figure 8 shows the curve of wheel wear and wear time of the five models.

**Figure 8.** Wearing capacity vs. wearing time.

The wear data shown in figure 8 are the average values of three tests. It can be seen from the figure that the wear amount of the ribbed wheel before the test was 19.8 mg, slightly lower than the 20.2 mg of the concave wheel. After 45 h, the wear amount of the ribbed wheel was higher than that of the concave wheel, and both wear amounts were higher than that of the prototype wheel. The wear amount of the scale-like shape of 8 mg per unit time was slightly higher than that of the convex wheel at 7 mg.
and lower than that of the prototype wheel at 15 mg. The durability test therefore shows that, compared with the prototype wheel, the concave shape and the ribbed shape had no anti-wear characteristics, whereas the convex and scale-like shapes had obvious anti-wear advantages.

Figure 9 shows a schematic diagram of the energy consumption of the five wheels within 40 h of wear. A linear positive correlation can be seen between energy consumption and test time. The power consumption values of the ribbed wheel and the concave wheel were 3.1 W and 2.6 W, respectively, values that were higher than the 2.2 W of the prototype wheel. The power consumption values of the scale-like and convex wheels were lower than that of the prototype wheel, 2 W and 1.8 W, respectively. In general, the ribbed and concave structures consumed more energy than the prototype wheel and they had no drag reduction characteristics. However, the convex and scale-like structures had better resistance reduction characteristics.

![Figure 9. Energy consumption vs. wearing time.](image)

It was determined that the speed of the model wheel around its axis was 2 rad/s, the slip rate was 0, and the simulation time was 3s. In the test, wear quality increased over time, so the durability test took a long time. However, during the simulation, the wheel would sink under its own gravity. The external conditions (load, speed, and wheel type) changed little, and the rolling and sliding friction were almost unchanged. Therefore, it was believed that the tangential force did not change with time. Therefore, setting the simulation time to 3s could illustrate the change trend of the tangential force.

By setting the motion parameters of the wheel to ensure the same motion state, the load of the model wheel was represented by an output model wheel normal force. Under the premise of ensuring that the motion and force of the model wheels were consistent, the tangential accumulated force of the five model wheels was analyzed. figure 10 shows the original data of the wheel load.

![Figure 10. Original load data.](image)
As can be seen from the load data in figure 10, within 0-1 s, the load of each model wheel increased from 0 N to a dynamic stable state. The wheel load of 1 -3 s tended to be dynamically balanced, so an average load of 1 -3 s was taken as the load for a single simulation. The average load and load standard deviation of each wheel are presented in table 5.

| Shape       | Prototype | Ribbed | Concave | Convex | Scale-like |
|-------------|-----------|--------|---------|--------|------------|
| Load/N      | 78.5      | 80.4   | 78.5    | 81.6   | 85.0       |
| Standard Deviation | 5.3      | 5.8    | 5.5     | 6.7    | 5.3        |

As can be seen from table 5, the average loads of each wheels ranged from 78.5 N to 85.0 N, and the maximum fluctuation error of 80N required was 6.25%. Therefore, within the range of soil mechanics error, it is considered that the load of each model wheel was 80 N.

On the premise of determining the simulation conditions, the tangential accumulated force of each simulation model wheel was compared and analyzed. The tangential cumulative force is the accumulation of the tangential force on the surface of the model wheel caused by particles in contact with the wheel. The simulation took a time step and recorded the sum of tangential forces of the previous total time step. Up to the end of the simulation, the tangential force recorded by the last time step was the sum of the tangential accumulated forces of the total time step. The tangential cumulative force curve is shown in figure 11.

![Figure 11. Tangential cumulative force.](image)

It can be seen from figure 11 that the tangential cumulative forces on the surfaces of the concave, ribbed, prototype, scale-like and convex wheels are 240.1 N, 257.8 N, 122.2 N, 66.7 N and 33.9 N, respectively, and that the tangential cumulative forces are basically positively correlated with time. Compared with the prototype wheel, the tangential cumulative forces of the concave and ribbed shapes increased more than two times, whereas that of the scale-like and the convex shapes decreased by 45% and 72.2% respectively. The durability test wear corresponded to the tangential cumulative force in the simulation, and the comparison between figure 11 and figure 8 shows that the wear amount and tangential cumulative forces of the four bionic non-smooth surfaces have the same change trend compared with the prototype wheel, and that the same change trend exists between any two types of surfaces. Similarly, the comparison between figure 11 and figure 9 shows that the frictional force on the wheel surface during the test and the tangential accumulated force on the wheel surface during the simulation also have the same change trend. Therefore, the test shows that the simulation analysis is reliable. Figure 12 shows the tangential cumulative force cloud maps of the five -wheel surfaces.
The effect of non-smooth structures on wear performance was analyzed, and the tangential cumulative force cloud maps of each wheel surface were compared and analyzed. Figure 12 shows the tangential cumulative force cloud maps of each model wheel surface. It can be seen from the figure that a significant tangential cumulative force is present on the surfaces of the five-wheel spines, which indicates that the wheels rotate with the action of the soil. The wheel lug increases horizontal thrust and causes greater wear on the soil shear process. The accumulative force of the wheel surface on the outside of the soil-bin is significantly greater than that on the inside. Because the outside of the wheel rolls a greater distance than the inside, causing more wear.

In addition, significant differences were found in the tangential cumulative forces of the five wheels. The cumulative force on the surface of the prototype, concave, and ribbed wheels are significantly greater than those of the scale-like and convex wheels. Also, the tangential cumulative forces of the first three wheels are uniformly distributed on the surfaces of the wheels, and no obvious cumulative force distribution is seen on the latter two wheels. The accumulative force on the surface of the concave wheel is mainly distributed around the wheel surface of the concave, but there is no accumulation in the concave. This finding indicates that the existence of concave features reduces the contact area between the wheel surface and the particles, increases the force on the unit area of the wheel surface, and thus increases the wear on the wheel surface. The ribs are distributed on the entire wheel surface along the axle of the car wheel. In the process of wheel rolling, the particles are prevented from rolling, resulting in hilling and increasing wear. The convex and the scale-like structures are arc transition structures, which increases the rolling effect of particles, disperse the tangential force accumulation and reduces the wear on the wheel surface. This is explained at the microscale level in that the surface structures of scale-like and convex shapes can reduce the tangential force accumulation.

It can be seen from the above simulation that concave wheels and ribbed wheels have no anti-wear characteristic compared with the prototype wheels. Therefore, only the two non-smooth structures, convex wheels and scale-like wheels were investigated in the subsequent simulation.

4.4. Effect of load on wear of wheel surface
To explore the anti-wear characteristics of the non-smooth convex and scale-like wheels under different loading conditions, simulation analysis was carried out under three different loading
conditions. To explain the influence of load on the tangential cumulative force more clearly, the sampling number was reduced and the simulation efficiency improved, so that sampling intervals with different gradients were adopted. The three loads were 80 N, 100 N and 160 N. During the simulation, the slip rate was 0% and the simulation parameters are presented in table 3. Figure 13 shows the tangential accumulated force of wheels under different loads after 3s of simulation.

![Figure 13. Tangential cumulative force vs. load](image)

Figure 13 shows that, the tangential cumulative force increases as the load increases. Under the same loading conditions, the accumulated tangential force on the surface of the prototype wheel is the greatest and the convex is the least. Upon increasing from load 1 to load 3, the tangential cumulative force of the prototype wheel increased from 122 N to 254 N, an increase of 132 N, that of the convex increased from 34 N to 71 N, an increase of 38 N, and that of the scale-like wheel increased from 67 N to 132 N, an increase of 65 N.

When the load was increased by 25%, from 80 N to 100 N, the tangential accumulated force of the three wheels increased by nearly 25%. When the load increased by 60%, from 100 N to 160 N, the tangential cumulative force increases by nearly 60%. Thus, we can deduce that the tangential cumulative force is linearly positive relative to the load. With the increase of load, the anti-wear of the convex and scale-like shapes is more prominent and the convex has optimum anti-wear.

Figure 14 shows the tangential cumulative force maps of the wheel surfaces when the load is 160 N, compared with figure 11 when the load is 80 N.

![Figure 14. Cloud maps of tangential cumulative force: (a)the prototype; (b)the scale; (c)the convex.](image)

Figure 13 shows that different degrees of tangential cumulative forces can be found on the surfaces of the three wheels. During the process of wheel rolling, the rolling and sliding friction between the wheel surface and the particles are mainly rolling and sliding friction, whereas the wheel spines have shear effect on the particles to overcome the particle resistance and provide the power of the wheel rolling, so the cumulative force of wheel spines is more than that of the wheel surface. The distribution of tangential force on the three kinds of wheel surfaces is quite different: the prototype wheel surface is covered with a tangential force, whereas the scale-like shape and convex shape have no obvious large area coverage, which proves the conclusion of the initial simulation cloud map analysis.
4.5. Influence of slip rate on wear
Under a load is 80 N, with the other simulation parameters remaining unchanged, the rotation speed was adjusted so that the wheel had sliding speeds of 10% and 30%. The tangential cumulative force distribution under different sliding speeds was analyzed, and the results are shown in figure 15.

![Figure 15. Tangential cumulative force vs. slip](image)

Figure 15 shows that under the same loading conditions, the tangential cumulative force increases gradually with increasing slip rate. Under the same slip rate, the accumulated tangential force on the surface of the prototype wheel is the highest and the convex is the lowest. When the slip rate was increased from 10% to 30%, the tangential cumulative force on the surface of the prototype wheel increased from 122 to 521 N, an increase of 399 N, whereas the hat of the convex wheel increased from 34 to 208 N, an increase of 166 N. The tangential cumulative f scale shape increased from 67N to 314N, increasing by 247N. The greater the slip rate, the greater the increase of tangential cumulative force. Under the condition of high slip rate, the convex has the lowest tangential force accumulation, the lowest increase and the best anti-wear compared with the prototype wheel and the scale.

The tangential cumulative force cloud chart of wheel surface under the condition of 30% slip rate and no slip rate is compared and analyzed. Figure 16 shows the tangential cumulative force cloud chart of wheel under the condition of 30% slip rate.

![Figure 16. Cloud maps of tangential cumulative force: (a) prototype; (b) scale-like; (c) convex.](image)

Compared with figure 9, which shows the tangential cumulative force without slip rate, the tangential cumulative force on the surfaces of the three wheels increased to a certain extent. The tangential force covered a wide area on the surface of the prototype wheel and presented a continuous distribution, whereas the convex and the scale-like wheels surface did not have continuous coverage. The non-smooth structures disperse the tangential force accumulation, avoiding excessive wear in certain areas and thus avoiding damage.
5. Analysis and Discussion
For non-smooth surface under the action of an abrasive, their structural units have the a "rolling effect" and a "guiding effect" on abrasive particles. That is, the bionic geometric structure on the surface can change the contact state between the surface and the abrasive. Guided by the biomimetic geometric structure, the movement direction of particles changes, which causes the abrasive particles to roll and the particles that were primarily sliding on the surface of the wheel increase their own rolling. Some abrasive particles, mainly in the form of sliding contact, are transformed into a rolling-sliding combination contact, which reduces the wear on the surface. Because of the rolling of particles, the phenomenon of milling caused by abrasive particles is weakened, which reduces the rolling resistance of wheels. The ribbed surface increases the milling phenomenon caused by the abrasive and the concave shape part of concave limits the rolling of abrasive particles, so these two forms are not durable. However, the convex surface and the scale-like surface, because of the transition of the smooth surface, guide the particles to roll, thus reducing the phenomenon of milling, thus showing the anti-wear characteristic.

6. Conclusion
According to the scale-like structure of a pangolin body, the convex shape of a dung beetle body surface, the concave and ribbed structures of Chlamys farreri, and a squamelli form, convex, concave and ribbed bionic rover wheels were designed.

The 3D simulations of the discrete elements were consistent with the test results of particle bed abrasion resistance, and the anti-wear effects of the four bionic wheel surfaces were: convex, scale-like, concave and ribbed.

The simulation results showed that compared with the prototype wheel, the quality of the convex and the scale-like bionic non-smooth wheels increased by 5.4% and 17%, respectively, and the tangential cumulative force decreased by about 70% and 40%, respectively.

Under the condition of increasing load and slip rate, the tangential cumulative forces on the surfaces of the wheels increased significantly; the cumulative force on the outside of the wheel surface was significantly higher than that on the inside, and the cumulative force at the lug part was the highest. The convex wheel has the best anti-wear property under high load and high slip rate.

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References
[1] Richter L, Ellery A, Gao Y, et al. 2006 A predictive wheel-soil interaction model for planetary rovers validated in testbeds and against MER mars rover performance data. 10th European Conference of the International Society for Terrain-Vehicle Systems, Berlin, Germany, September
[2] Blake D, Morris R, et al. 2013 Curiosity at Gale Crater, Mars: Characterization and Analysis of the Rocknest Sand Shadow Science 341 1-7
[3] Ono M, Fuchs T, Steffy A, et al. 2015 Risk-aware planetary rover operation: Autonomous terrain classification and path planning. Aerospace conference IEEE March
[4] Orr M, Stowe D, Thoe S, et al. 2009 Design of a scaled off-vehicle wheel testing device for textile tread wear SAE Technical Paper
[5] Morkos B, Summers J, Mathieson J, et al. 2010 Development of endurance testing apparatus simulating wheel dynamics and environment on lunar terrain. SAE Technical Paper, April,
[6] Satterfield Z, Shields S, Moylan J, et al. Off-Vehicle tire traction and endurance testing system: system upgrade design. ASME 2014 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. New York USA August 17-20
[7] Masataku S, Sachiko W, Takeshi H. 2016 Traveling and abrasion characteristics of wheels for lunar exploration rover in vacuum. *Journal of Terramechanics* 68 37-49

[8] Ferguson D, David M. Aloysius W. 2001 The Mars pathfinder wheel abrasion experiment. *Materials and Design* 7 555-64

[9] Creager C. 2016 The Development of High-Performance compliant tires for Mars Rovers. *8th Americas Regional Conference*, Detroit, September 12-14

[10] Weili D, Li L, Sida Z, et al. 2014 *Journal of Astronautics* 35(4) 388-96

[11] Haibao G. 2013 Longitudinal skid terramechanics for wheels of planetary exploration rovers. *Harbin: Harbin Institute of Technology*

[12] Rui Z, Sihua Z, Fang L, et al. 2013 *Journal of Jilin University* 43(4) 976-82

[13] Nakashima H, Fujii H, Oida A, et al. 2007 *Journal of Terramechanics* 44 153-62

[14] Luquan R, Zhiwu H. 2005 *Transaction of the Chinese Society for Agricultural Machinery* 36(7) 144-7

[15] Rong B. Biomimetic geometrical structure surfaces with anti-abrasion function and their abrasive wear against soil *Changchun: Jilin University* 2008

[16] Yuanqiang T, Junhua S, Hao Z, et al. 2014 *China Mechanical Engineering* 25(15) 3091-7

[17] Manoj K, Rob M. 2009 *Particulate Science and Technology* 27(1) 68-76