Research on Motion Characteristics of Single Particle Third Body in Braking Process Based on W-M Fractal Feature

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Abstract. In order to explore the motion characteristics of the third body particle in the friction of the rough braking interface, based on W-M fractal theory and elastoplastic mechanics theory, the finite element model of the three body micro-extrusion shearing process of rough contact surface is established. The influence of the braking parameters on the motion characteristics of the single-particle third body is analyzed. The analysis results show that the three body contact steady state increases with the increase of brake pressure, and the shear speed affects the three body contact vibration. An increase in the friction factor accelerates the third body discharge friction gap to exacerbate the wear condition.

Key words: third body; rough surface; W-M fractal theory; motion characteristics

1. Introduction

In the process of friction and wear, a series of physical and chemical changes occur on the friction surface through the interaction of heat and force, which causing damage to the friction surface. The abrasive debris generated after the damage of the matrix remains in the friction surface and continues to participate in friction, which is called the third body. The formation of the third body transforms the ideal two-body friction system into a three body friction system. Many scholars have carried out fruitful research on the formation and evolution of the third body.

Godet[1] proposed the concept of a third body to describe the solid particle that existed between the two opposing moving frictional contact surfaces from the matrix. Greenwood[2] et al. proposed an elastic and elastoplastic hybrid contact model between rough surface and smooth surface on the basis of statistics, namely G-W contact model. Edouard[3] shown that the evolution of the vibrational behaviour and of the third-body layer are both gradual. Lin[4] studied plastic deformation zone grains lead to the shear deformation by means of friction stress. Wang[5] used a discrete parallel element method was used to construct a double parallel plate shear model to simulate the infinite shear motion, focusing on the expansion of the particle system under shear. Wang[6] built a caulking and coverage effect model based on the G-W model. Complete the transformation from rough surface contact to three dimensions. Yang J[7] established the 2-D granular matter parallel shearing cell models with different shape of micro-asperity surfaces by the explicit finite element method(FEM). These models were applied to analysing the influence of normal load and factor of friction of contact pairs on the gap. The above work is mainly aimed at the formation of the third body and the influence on the friction performance. However, the research on the existence state of the third body particle in the friction interface is not deep enough. In this paper, the finite element model of elastoplastic meso-three body
extrusion shearing process for rough braking interface is established by using ABAQUS. It mainly studies the influence of braking parameters on the deformation and motion of the third body particle, to provide a theoretical basis for understanding the three body friction mechanism.

2. Rough Surface Model Based on W-M Fractal Function
The W-M fractal function is a typical function used to represent random contours[8]. It has self-imitation and can accurately simulate and establish random surfaces with fractal characteristics, continuous and non-differentiable. The mathematical model expression is:

\[ Z(x) = G \sum_{n=1}^{\infty} \gamma^{(D-2)n} \cos(2\pi\gamma x) \quad (1 < D < 2, \gamma > 1) \]

Where, \(Z(x)\) is the height of the random surface topography; \(x\) is the position coordinate of the contour; \(D\) is the fractal dimension, which describes the irregularity of the function \(Z(x)\) at all scales; \(G\) is the characteristic scale coefficient, which reflects the magnitude of \(Z(x)\) and determines the specific size of \(Z(x)\); \(\gamma\) represents the spatial frequency of the contour and for random contours subject to normal distribution, it is suitable for the randomness of high frequency spectral density and phase, generally, \(\gamma=1.5\); \(n\) is a natural sequence number, \(n = 1, 2, 3, ..., 100\); \(G\) is the fixed parameter mesoscale factor; \(G=0.01\). Based on the W-M fractal theory, the simulation of the fractal curve under specific parameters is realized by MATLAB software programming. The fractal dimension of the main parameters can be obtained by measuring the roughness of the friction surface and then converting it. The fractal dimension is determined to be 1.9 and the fractal curve is simulated. Perform spline fitting and finally draw a two-dimensional rough surface profile as shown in Figure 1.

![Figure 1. 2D rough surface profile with \(D=1.9\).](image)

3. Establishment of Finite Element Model for Three Body Extrusion Shear of Single Particle
The rough braking surface is damaged by the braking shearing force. After the third body particle fall off the matrix, the third body in the free state exists in the two rough friction surfaces and directly participates in the friction. A single-particle three body extrusion shear finite element model was established using the ABAQUS/Explicit module. The third body particle in the model is considered as mixture particle falling off the matrix, and the size is uniform in the shape of round particle. The upper and lower friction surface topography models are obtained by introducing the Creo fitting with the obtained fractal curve. The model is imported into ABAQUS to complete the assembly as shown in Figure 2.

![Figure 2. Shear contact model of three body extrusion with single particle.](image)
accuracy of the result, and an independent force layer is provided on the upper surface for applying pressure. The material properties of the force layer are set to be extremely dense and rigid, it is not easily deformed, so that the upper plate can be uniformly stressed. Since the force layer is not directly involved in friction, its material properties have little effect on the simulation results.

Downward braking load is applied on the upper surface and the X-direction displacement of the upper surface is limited; the speed is applied to the right on the lower surface and the displacement of the lower boundary is limited in the Y direction. The influence of braking parameters on the stress and strain distribution and motion process of the third body during shearing is studied. The braking parameters are given in Table 1. The loading time is 0.4ms in the first step of simulation. After the steady contact of the three bodies, the speed is applied in the second step of simulation analysis for 2ms. In the shearing process of three body friction interface, there is contact friction behavior between particle and surface. The penalty function friction model of elastic slip is adopted. In the model, the particle and upper plate materials are copper-based powder metallurgy materials, and the lower plate materials are Q345B. Specific material parameters are shown in Table 2 and Table 3.

4. Simulation results and analysis

4.1 Analysis of extrusion shear process

Figure 3 shows the stress distribution of the three body contact model when the braking pressure is 4.5MPa and the speed is 1000mm/s and the braking process is 0.4ms, 0.8ms, 1.2ms and 2.4ms.
The upper plate moves downward with the application of the stress, and the particle are squeezed to the pits of the upper and lower plates. The positions of the particle and the lower plate are constantly adjusted until they reach a stable state. From 0ms to 0.8ms, in the process, the particle remains basically round before reaching the yield limit, and they roll counterclockwise to the right under the action of friction, accompanied by slippage. Because the loading speed from 0.8ms to 2.4ms reaches the maximum value, the particle is affected by the forces of the upper and lower plates. Contact with the lower plate micro-convex body is the cause of stress concentration. During this process, the third body particle are increased in plastic strain region due to the continuous impact of the micro-protrusions, and the particle are elliptical. At this time, the friction force is not enough to cause the elliptical particle to continue to roll, the particle is tightly embedded in the dimples, and a "filling" phenomenon occurs, the plastic deformation occurs in the lower plate due to the scratching action of particles, which results in the ploughing effect. Until the particle slides to encounter a micro-convex body that can produce enough impact force to overcome friction and release it from the pit. When the upper and lower plates are in contact with the particle. Residual stress is generated at the contact position after the two plates are stressed. The larger the residual stress value generated by the contact of the micro-convex with small curvature, the stress is more concentrated.

4.2 Effect of load on the motion characteristics of third body particle

Figure 4 shows the time when the particle reaches the maximum yield stress when the braking pressure is changed. Figure 5 shows that the particle reaches the maximum equivalent plastic deformation when braking pressure is changed. Third body particle can produce plastic deformation, there is only difference in the degree of deformation, so the time to reach the maximum yield stress of the material is the same as the time to start producing plastic deformation. Furthermore, the stress and strain changes of the third body particle in the extrusion shearing process are analyzed.

Figure 4. Chart of time with different pressure. Figure 5. Chart of PEEQ with different pressure.

Brake pressure increased from 1.5MPa to 4.5MPa, the time of maximum stress from 0.9ms gradually reduced to 0.2ms, the maximum stress of the time will not change along with the change of brake pressure as the pressure continues to increase, it remains at 0.2ms, because of the change of the brake pressure directly affect the contact stress, it can make the third body particle quickly reach the yield stress, the stress and the speed of loading takes time, so the brake pressure to add after 4.5MPa, the maximum stress in great changes of time no longer. When the braking pressure is 1.5MPa, it is difficult to reach the yield limit of the material and the plastic shape variable is small. When the braking pressure increases to 4.5MPa, the equivalent plastic strain rapidly increases to 0.4. When the braking pressure increases to 6MPa, the equivalent plastic strain value generated by the third body slowly increases to 1.2, and still shows a trend of increasing with the increase of braking pressure. In addition, the upper plate is lifted due to the contact between the micro-convex body and the particle of the third body in the process, and the plate spacing changes at any time with the contact between the micro-convex body and the third body. In the whole three body extrusion shearing process, when the pressure is 1.5MPa, the fluctuation is the most obvious. The three body contact stability is poor at this time. With the increase of brake pressure, brake pressure makes the three body contact close enough. The stability of three-body contact increases at this time, the fluctuation degree of plate spacing decreases, and the plastic deformation degree of the third body particle increases.
4.3 Effect of motion speed on the motion characteristics of third body particle

Figure 6 shows the time when the particle reaches the maximum yield stress when the shear speed is changed. Figure 7 shows that when the shear speed is changed, the particle reaches the maximum equivalent plastic deformation. It can be seen from Figure 6 that with the speed increases, the plastic deformation time of the third body particle decreases. It means that faster speed will make the third body contact with more micro-convex bodies at the same time. The time for the third body to reach the maximum equivalent plastic deformation is also gradually shortened.

![Figure 6. Chart of time with different speed.](image)

![Figure 7. Chart of PEEQ with different speed.](image)

The third body maximum equivalent plastic shape variable showing a downward trend with speed increases from 400mm/s to 1200mm/s. The equivalent plastic shape variable is 1.20 when the speed is 400mm/s, and increases from 1200mm/s to 2000mm/s. The maximum value gradually decreases to around 0.95 and then tends to be stable. Because when the speed is small, the third body particle with two rough contact surface contact state is better, in the process of extrusion shear, the third body particle can be closely contact with each micro-convex body, the contact for a long time, make rough contact surface particle pass more energy to the third body, the third body particle equivalent plastic deformation; the third body particle and two rough contact surface contact state is not stable with speed increase, there is radial runout phenomenon. The contact time between the third-body particle and the micro-convex body becomes shorter in extrusion shear process. At this time, the rough contact surface only transfers limited energy to the third-body particle. The degree of grain deformation in the third body is reduced, and it fluctuates in a smooth range.

4.4 Effect of friction factor on the motion characteristics of third body particle

The force acting on the upper and lower plates acts on the third body particle through the form of extrusion and shear of friction force. In this process, the friction factor has a direct impact on the effect of the third body. Figure 8 shows the time when the particle reaches the maximum yield stress when the friction factor is changed. With the increase of friction factor from 0.1 to 0.5, the time when the third body particle reaches the maximum equivalent plastic deformation fluctuates between 0.2ms and 0.3ms. Removing the influence of random contact surface on simulation results, it can be considered that the friction factor has little effect on the time to reach the maximum stress of the third body.

![Figure 8. Chart of time with different friction factor.](image)

![Figure 9. Chart of PEEQ with different friction factor.](image)
Figure 9 shows the maximum equivalent plastic deformation of particle when the friction factor is changed. It can be seen from the fitting curve that the maximum equivalent plastic deformation of the third body particle increases gradually with the increase of friction factor from 0.1 to 0.3, and the minimum equivalent plastic deformation is 0.57 when the friction factor is 0.1. The maximum equivalent plastic deformation is 1.06 when the friction factor is 0.3. The third body particle are rolled to the right under the action of friction force during this process, with a little slip. When passing through the larger pit on the upper plate, the friction force given by the lower plate is not enough to make it get rid of the pit. The micro-convex body on the lower plate continuously impacts the third body particle that falls into the pit. The friction force of the third body particles increases with the increase of friction coefficient, the force concentration in the contact area between the particle and the lower plate micro-convex body increases, and the deformation degree of the third body increases. In the process of increasing friction factor from 0.3 to 0.5, when the particle falls into the pit on the upper plate, the micro-convex body of the lower plate gives enough force to the particle to get rid of the pit and continue to roll to the right. At this time, the force point of the particle is relatively uniform, and the equivalent plastic deformation of the third body decreases to about 0.85.

5. Conclusions
In this paper, the three body micro-extrusion shear process of brake interface is simulated, the finite element model is established and the dynamic characteristics of single-particle third-body of rough brake interface are analyzed. The results show that the braking conditions have a direct impact on the stress and strain of the third body particle. After the third body is loaded, the particle is embedded in the pit, the lower plate is plastically deformed by particle sliding action, resulting in the "ploughing effect". The increase of brake pressure can effectively improve the stability of three-body contact, and the shear speed mainly affects the vibration of three-body contact. The increase of friction coefficient can shorten the removal time of the third body from the friction surface clearance and increase the wear condition.

Acknowledgments
The authors gratefully acknowledge the financial support of National Natural Science Foundation of China (No.51675075) and Innovative Talents Program of Colleges and Universities in Liaoning Province (No. LR2018048).

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