Double Rough Surface Contact Model and Finite Element Simulation based on Fractal Theory

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Abstract. The contact between two rough surfaces is essentially the contact between micro-bulge of different shapes. In the process of interference fit, the distribution of contact area and contact stress at different positions of the two rough contact surfaces is uneven. In this paper, based on the test results of the morphology of machined surfaces with different surface roughness, a two-dimensional curve model of the contact surface is established according to the W-M fractal function and Matlab software. The contact area and contact load are analyzed with a two-dimensional finite element contact model of the double rough surface that established with Abaqus software. And the effect of surface roughness and surface displacement on the contact area and contact load is analyzed with the finite element contact model.

1. Introduction
The interference fit between the axle and the hub of a train wheel set is essentially the contact between two rough surfaces with different roughness. At present, the statistical method and fractal method are mainly used to analyze the contact problem of rough surfaces.

The earliest contact theory is the Hertz [1] elastic contact theory. As a classic contact theory, it is mainly used for the study of a single contact point. It uses the contact part as a quadric surface to analyze the elasticity and contact problems of the contact point. In recent years, there have also been many studies on the contact problem of rough surfaces based on fractal theory. Chandrasekar, S. [2] established the finite element model of the rough surface model and studied the normal contact problem between the rough surfaces. Chatterjee [3] used the W-M function to establish a three-dimensional rough surface model, and described the influence of varying elastic modulus in a non-adhesive frictionless bulk deformation contact between isotropic self-affine fractal surface and a rigid flat covering elastic, elastic-plastic and the plastic region. Jeng Haur Horng [4] proposed a fractal micro-contact model considering the elastoplastic transition process and the effect of adhesion. Jackson [5] established a three-dimensional elastoplastic contact model of fractal/multi-scale rough surfaces using analytical relations. Kuo Xu [6] established a normal contact stiffness model based on fractal theory, and obtained the relationship between normal contact stiffness and contact load. Based on the fractal theory, Yuan Y [7] developed a modified single-concave-convex elastoplastic contact model, and then established a three-dimensional fractal rough surface load-unload contact model [8]. Sun Jianjun [9] established a fractal contact model for rough surfaces, and studied the influence of the porosity and the actual contact area of the contact interface between rough surfaces on the rough surface morphology and load between
rough surfaces. Sun Juncheng [10] found that the contact performance of rough surface materials is mainly affected by the micro-bulge morphology. Wang Dong [11] established a normal contact model between two rough surfaces and studied the changing trends of contact load and contact deformation. Gan Li [12] proposed a modified elastoplastic contact model to study the relationship between the critical elastic contact area and the size of the micro-convex body.

In this paper, the microscopic topography of the turned axle surface and the two-dimensional contour curves under different roughness are obtained through experiments. Based on the fractal theory, the two-dimensional contact model between two rough surfaces is established using Abaqus software. The mechanical behavior and actual contact area between two rough surfaces were analyzed.

2. Measured value of micro-topography of rough surface

In the experiment, the roughness $R_a = 1.625 \mu m$ of the axle is measured by a surface topography measuring instrument. The surface topography measuring instrument can also measure the surface morphology of metals and non-metals. It can detect some parameters, such as arithmetic average roughness $R_a$, average peak-valley depth $R_z$ and root mean square roughness $R_q$. Through measurement, the true micro-morphology of the turning surface of the axle is obtained, as shown in Figure 1.

![Figure 1. Schematic diagram of experimentally measured real turning surface](image)

It can be found from Figure 1 that the surface of the axle obtained by turning is not smooth, and the surface is composed of micro-bulge of different sizes, and the micro-bulge in the processing direction are similar in shape. In addition, the surface roughness $R_a = 1.625 \mu m$ and $R_q = 3.924 \mu m$ were measured respectively to obtain two-dimensional contour curves under two different roughness, as shown in Figure 2.
It can be found from Figure 2 that as the surface roughness increases, the height difference of the micro-bulge on the turning surface becomes larger. When $R_a = 1.625 \mu m$, the height difference of the micro-bulge is about $4 \mu m$, and when $R_a = 3.924 \mu m$, the height difference is about $9 \mu m$.

3. Fractal contact model of rough surface
The contact between two rough surfaces with different roughness occurs on the higher micro-bulges, so the actual contact area of the two rough surfaces is much smaller than the ideal contact area. The results obtained by the two rough surfaces fractal contact model based on fractal theory are more objective and more realistic. The fractal contact model used in this paper is the M-B fractal contact model based on the W-M fractal function. According to the M-B fractal contact model, the W-M fractal function can be used to represent the two-dimensional curve of the rough surface. According to the W-M fractal function, Matlab programming is used to obtain the two-dimensional curve of the rough surface, and then extract the key point data from it, and import the key point data into Abaqus to establish a rough surface contact model, and then explore the contact properties of the rough surface. In the process of establishing the model, the roughness of the two rough surfaces is $R_a = 1.6 \mu m$, and the material properties are the same. The three-dimensional model established is shown in Figure 3.
4. Simulation and Analysis of Contact Behavior of Rough Surfaces

Establish a rough surfaces contact model in Abaqus, set the lower rough surface to be stationary, the upper rough surface is in a position just in contact with the lower rough surface, and gradually reduce the relative distance between the two rough surfaces, extracting data at different positions. When the distance between the two rough surfaces is $5\mu m$, select the output variable as PEEQ (equivalent plastic strain), and obtain the isoplastic strain cloud diagram, as shown in Figure 4.

It can be seen from Figure 4 that the contact between the two rough surfaces is achieved by the contact of the micro-bulges on the two surfaces, the height distribution of the micro-bulge on the two rough surfaces is irregular. The higher the pair of micro-bulges, the greater the degree of deformation. Since the pairing of the micro-bulges on the two rough surfaces is irregular, the micro-bulges may undergo elastic deformation, elastoplastic deformation or plastic deformation. If the relative distance between the two rough surfaces continues to decrease, the micro-bulges that were not in contact will contact and deform. The micro-bulges that only undergo elastic deformation may undergo plastic deformation, and the number of micro-bulges that undergo pure plastic deformation will increase. The actual contact area between the two rough surfaces will also increase. Choose the output as CPRESS to get the contact stress distribution map, as shown in Figure 5. Compared with Fig. 4, it can be found that the deformation of the contact point is consistent with the distribution of the contact stress. The greater the deformation, the greater the contact stress.
After the simulation is completed, the contact area of each contact point is extracted, and the cumulative calculation is performed using Excel to obtain the actual contact area of the two rough surfaces, which is compared with the ideal contact area obtained by mathematical calculation. The ratio is shown in Figure 6.

![Figure 6](image)

**Figure 6.** The relationship between the ratio of the contact area and the distance between the contact surfaces

From Figure 6, at the beginning of the contact between the two rough surfaces, as the relative distance between the two rough planes decreases, the non-contact micro-bulges start to contact, and the elastic deformation micro-bulges begin to plastically deform. The ratio of the actual contact area to the ideal contact area increases linearly. When the relative distance reaches a certain value, the plastic deformation of the micro-bulge becomes larger, and the ratio between the two tends to be flat. When the roughness of both rough surfaces is $R_a = 1.6 \mu m$, in the process of the upper surface gradually approaching the lower surface, the normal load and tangential load of the contact surface are extracted. The relationship curve between the normal load of the contact surface and the distance between the two contact surfaces is shown in Figure 7, and the relationship curve between the tangential load of the contact surface and the distance between the two contact surfaces is shown in Figure 8.

![Figure 7](image)

**Figure 7.** The relationship between normal load and the distance between the two contact surfaces
Comparing Figure 7 with Figure 6, it is found that the law of normal load change with the distance between the two contacts and the ratio of the actual contact area to the ideal contact area with the spacing change tend to be consistent. Both of the law increase linearly at the initial stage, and when the relative distance reaches a certain value, the ratio tends to be flat. Comparing Figure 8 with Figure 7, it is found that the fluctuation of the tangential load between the two contact surfaces is large. While keeping the roughness of the lower rough surface unchanged at 1.6 $\mu m$, change the roughness of the upper rough surface, and take 1.6 $\mu m$, 3.2 $\mu m$, 6.3 $\mu m$ respectively for simulation experiments to obtain the relationship between the ratio of the actual contact area to the ideal contact area and the distance between the two contact surfaces, as shown in Figure 9, the relationship between the normal load between two contact surfaces and the distance between the two contact surfaces, as shown in Figure 10, and the relationship between the tangential load between the two contact surfaces and the distance between the two contact surfaces, as shown in Figure 11.
Figure 10. Normal load on surfaces with different roughness

Figure 11. Tangential load on surfaces with different roughness

From Fig. 9, as the roughness increases, the ratio of the actual contact area to the ideal contact area decreases, the ratio of the actual contact area to the ideal contact area and the relationship between the distance between the two contact surfaces tend to be consistent. As the micro-bulges on the softer contact surface are destroyed, there will be an increasing trend in the ratio after the flat area\textsuperscript{[12]}. In short, it increases linearly first, and the change trend becomes slower after the spacing reaches a certain value. From Figure 10 and Figure 11, when the distance between the two contact surfaces is the same, the greater the roughness, the smaller the normal load and tangential load, but the load change trend under each roughness is generally the same.

5. Conclusion

As the distance between the two rough surfaces decreases, the number of plastic deformation micro-bulges increases, the actual contact length of the two rough planes also increases with the decrease of the distance. The greater the difference in the roughness of the two contact surfaces, the slower the actual contact length increases with the increase in the distance between the rough surfaces. The normal load and tangential load between two rough surfaces will also increase as the distance between rough surfaces decreases. The greater the difference between the roughness values of the two contact surfaces, the smaller the normal load increase and tangential load increase as the distance between the rough surfaces decreases.

6. References

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