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Numerical Simulation and Experimental Study on the Rolling Process of Polar Particles

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Abstract: The densification process of electrical paste particles during the process of battery pole piece rolling is studied. *The mechanism of the pole rolling is analyzed theoretical;the basic parameters of the electric slurry particles in the movement are described; the force equation is established; and the basic conditions for the stable rolling are analyzed. The dynamic simulation is carried out by using relevant parameters, and the results are verified by theoretical analysis, numerical simulation and experimental verification.* The results show that there is a certain relationship between the relative density of the electrode paste and the thickness of the electrode. The study verified the densification of the electric slurry particles during the whole rolling process. Theinfluence of the density uniformity and thickness uniformity on the battery quality was also investigated, which provided guidance for the battery production.

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极片颗粒轧制过程的数值模拟与试验研究

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摘要：对电池极片轧制过程中电性浆料颗粒的致密化过程进行研究。*对极片轧制机理进行了理论分析，并描述了电性浆料颗粒在运动中的基本参数，建立受力方程，分析出稳定轧制的基本条件；利用相关参数进行动态模拟仿真，采用理论分析与数值模拟以及试验验证相结合的方法得到结果验证。结果表明：电池极片电性浆料颗粒相对密度与极板厚度存在一定的关系。*该研究验证了电池极片在整个轧制过程中电性浆料颗粒的致密化规律，另一方面通过探究电池极片的密度均匀性和厚度一致性对电池品质的影响，为电池生产提供了指导。

关键词：电池极片；轧制机理；模拟仿真；试验研究

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Introduction

The battery pole rolling is the most important step in the process of compacting the compound slurry particles coated on the pole plate. The purpose of which is to increase the compaction density of the battery pole piece, so that the active material and the foil are combined in a denser and even thickness, and the thickness is suitable. The compacted density can increase the discharge capacity of the battery, reduce the internal resistance, and prolong the cycle life of

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the batter. So it is of great significance to study the compaction density of the battery pole piece.

Many scholars have conducted corresponding research on the rolling of battery pole pieces. By studying the roller after rolling, different pole ratios were obtained. The effect of different compaction ratios on the internal resistance and performance was analyzed[1]. Researched and discussed the influence of material particles on battery pole pieces, and studied the battery production process and electricity chemical performance[2]. The effect of different roll thickness positive plates on the internal resistance of lithium-ion batteries was studied. The results show that the rolled thickness of the positive plate affects the contact resistance between the active material and the current collector[3]. Based on the numerical simulation study of semi-solid slurry flow shape, the slurry particle flow during the battery pole piece rolling process was discussed[4]. The deformation of stainless steel under two different rolling conditions is studied. The results provide reference for the deformation of the stainless steel during the rolling process[5]. The relationship between deformation and microstructure of plate rolling process is analyzed by finite element method. The simulation results are compared with the results of actual rolling process, and good results are obtained. The research results have guiding significance for battery pole plate rolling[6].

This paper introduces the rolling mechanism of the battery pole piece mill; analyzes the necessary conditions for stabilizing the entire rolling process; deduces the mathematical model; builds the finite element model of the battery pole piece rolling through ABAQUS software and then simulates the entire process. It reveals the deformation, movement and particle densification of the electrical paste particles.

1 Pole piece rolling principle

1.1 Brief introduction of rolling principle

Pole piece rolling and steel rolling are quite different [7]. The purpose of rolling is to obtain an extension. In the course of rolling, the molecules extend in the longitudinal direction and spread transversely, and the thickness of the rolled piece becomes smaller, but the density does not change. The rolling of the pole piece is to compact the slurry particles on the pole plate so as to increase the compaction density of the battery pole piece. Before the rolling of the battery pole pieces, the electric slurry coating on the copper foil is a semi-flowing, semi-solid granular medium, and the particles and the particles are in a state of no connection or weak connection, and have a certain degree of dispersion. The electrical paste particles are attached to copper foil or aluminum foil, are constantly trapped into the roll gap by friction force. They are rolled into a battery pole piece with a certain density[8].The rolling principle is shown in Fig.1.

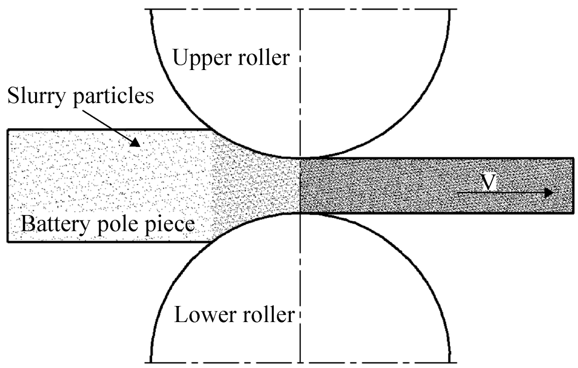

Fig. 1 Schematic diagram of rolling

According to the location of the battery pole piece in the rolling process, the slurry particles undergo displacement and deformation after being pressed, and the pole piece density changes, the

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entire process of pole piece rolling can be divided into three regions; zone-*I* slurry particles free flow, zone *II* - slurry particle connection , zone *III* - slurry particle formation . as shown in Fig.2.

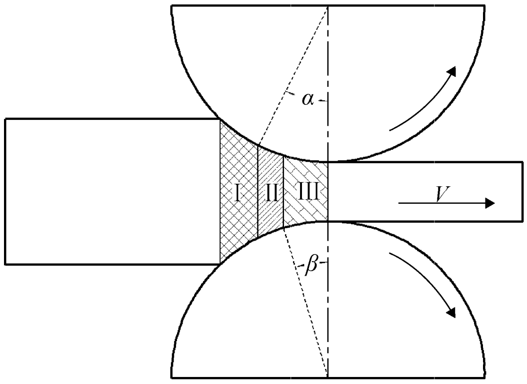


Fig. 2 Schematic diagram of pole piece rolling

1.2 Basic parameters of the rolling process

According to the analysis of the rolling process above, the relevant parameters can be used to describe the rolling process. The power-supplying slurry particles are used as the force-receiving unit, and the length, height are d_x d_y.

Where: ΔR is the radial pressure of the roller due to the electric slurry particles;

ΔQ is the lateral pressure generated by the surrounding slurry particles, and ΔT is the friction generated between the contact surfaces of the rollers.

Among them, the bite angle α ensures that the battery pole piece can smoothly enter the key parameters of the roll gap, which is the angle between the line connecting the center of the nip and the center of the roll and the vertical line. The parameter diagram is shown in Fig. 3.

1.3 Establishment of stable rolling conditions

Through the above description of the basic parameters of the battery pole piece in the rolling process, a corresponding mechanical equation can be established in the horizontal direction of the pole piece rolling. $\Delta T_X=\Delta T\cos\alpha$ is the component force of the frictional force between the slurry particles and the roller surface in the horizontal direction, which provides the pulling force for the pole piece rolling; $\Delta R_X=\Delta R\sin\alpha$ is the component force of the radial pressure of the roller on the slurry particles in the horizontal direction, which is the rolling resistance of the pole piece.the rolling.So the Force as shown Fig. 4.

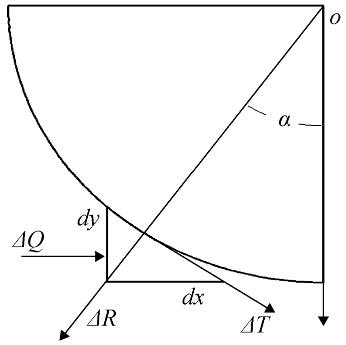


Fig. 3 Forced analysis of electrical slurry particles

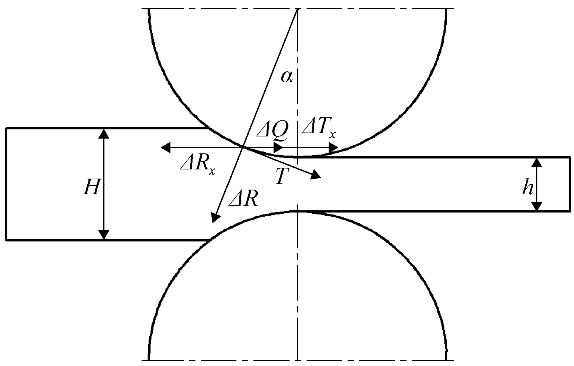


Fig. 4 Rolling force on pole piece during rolling

Therefore, from the perspective of mechanics, the basic conditions for bite-in of the pole piece are:

$$\Delta T\cos\alpha + \Delta Q > \Delta R\sin\alpha \qquad (1)$$

Where $\Delta T=\mu\bullet\Delta R$, μ is the friction coefficient between the electric slurry particles and the pole piece roll. Substituting this into (1), we have :

$$\tan\alpha < \mu + \frac{\Delta Q}{\Delta R\cos\alpha} \qquad (2)$$

Simplified, we obtain:

$$\tan\alpha < \mu + \xi \qquad (3)$$

Where: ξ is the lateral pressure coefficient.

Eq.(3) shows that when the sum of the coefficient of friction and the coefficient of side pressure is greater than the tangent of the bite angle, the electrical slurry particles are bitten by the pole piece roll.

Where: μ is the friction coefficient, which depends on the properties of the electrically conductive paste particles, the roughness of the pole piece roll and the rotation speed of the pole piece roll.

The ξ is the lateral pressure coefficient related to the physical composition of the electrical slurry particles, the material plasticity, the coating quality, the gap between the particles, and the stability of the rolling. In general, the coefficient of lateral pressure is much smaller than the coefficient of friction for electrically conductive slurry particles.

Therefore, the electric slurry particles are mainly due to the friction between the particles and the pole piece rolls. Through the action of the friction force, the electric slurry particles can be continuously bitten by the pole piece rolls, we have:

$$\Delta T_X > \Delta R_X \tag{4}$$

$$\Delta T\cos\alpha > \Delta R\sin\alpha \tag{5}$$

Where $\mu = \Delta T / \Delta R$, the boundary conditions can be written as:

$$\mu > \frac{\sin\alpha}{\cos\alpha} \tag{6}$$

Subsequently, we have:

$$\mu > \tan\alpha \tag{7}$$

Eq.(7) shows that when the pole piece is biting in, when the friction coefficient between the pole piece and the rolling surface is greater than the tangent value of the bite angle, the pole piece can naturally bite in. The larger the coefficient of friction μ, the smaller the biting angle α, and the more favorable the biting.

After entering the stable rolling, the force condition of the pole piece changes, and the acting points of the forces of the slurry particles ΔT and the ΔR gradually move to the middle of the roll gap, and the bite angle α gradually becomes smaller at this time. As the friction coefficient μ remains constant and the bite angle α gradually becomes smaller. Eq.(7) is established. So once the pole piece bites in the rolling process can be established.

When the rolling conditions are stable, the quality of the pole pieces passing through the section into the deformation zone per unit time is equal to the mass of the pole piece rolled per unit time due to the principle of equal mass before and after rolling. The thickness and width of the substrate before and after rolling are parameters no change, so the quality of the pole piece is ignored and the quality of the substrate is ignored; For the reason described above, we can write:

$$H \cdot B \cdot \rho_1 \cdot V_1 = h \cdot b \cdot \rho_2 \cdot V_2 \tag{8}$$

Where: H: thickness thickness of the pole piece before rolling; h: thickness of the pole piece after rolling; B: width of the pole piece before rolling; b: width of the pole piece after rolling; ρ_1: the density of the slurry particles before rolling the pole piece; ρ_2: the density of the slurry particles after rolling; V_1: feed rate of the pole piece; V_2: rolling speed of the pole piece.

The actual pole piece rolling is very small, thus, $B \approx b$.

Eq. (8) can be written as:

$$\frac{H}{h} = \frac{V_1}{V_2} \times \frac{\rho_1}{\rho_2} \tag{9}$$

Defining rolling deformation coefficient in the formula $\varepsilon = H/h$ is the suppression coefficient, $\lambda = V_1/V_2$ is the extension factor. This parameter is difficult to determine, it is related to the rotation speed of the roller and the deformation of the pole piece particles. Usually taken 1.00-3.02[9].

$z = \rho_1 / \rho_2$ is the compaction factor, it is related to the rolling force of the rolling mill and the deformation ability of the slurry of the pole piece. Its solution can be written as:

$$\varepsilon = \lambda z \tag{10}$$

Set the roller diameter D, we have:

$$H = D(1-\cos\alpha) + h \tag{11}$$

Combined with the above formula, we can get:

$$h = \frac{D(1-\cos\alpha)}{\lambda Z - 1} \tag{12}$$

$$\rho_2 = \frac{\rho_1}{\lambda}[1 + \frac{D(1-\cos\alpha)}{h}] \tag{13}$$

According to the above equation, the density of the slurry particles after rolling is proportional to the density of the slurry particles before the rolling, and is inversely proportional to the elongation factor, and is related to the diameter of the roll, the bite angle, and the thickness of the rolled-out pole pieces. In this way, the density can be calculated according to the given pole piece thickness under a certain rolling process condition, or the thickness of the pole piece can be calculated according to the given density. In the following, the relationship between the pole piece density and the pole piece thickness is simulated.

2 Rolling model establishment and related conditions

2.1 Basic assumptions for model establishment

Based on the above theoretical analysis, the following assumptions can be made by combining the characteristics of the electric slurry particle during the rolling process of the battery pole piece and the assumptions necessary in contact analysis:

(1) Simplified the transient process of the battery pole rolling process. It is considered that during the rolling process, the non-linear strain of the electrical slurry particles occurs over time;

(2) During the rolling process, the rigidity of the slurry on the pole piece is much smaller than that of the roll, so the elastic deformation of the pole piece is considered to be ignored and it is set as a rigid body in the analysis process;

(3) Set Coulomb friction between the electric slurry particles and the pole piece rolls;

(4) Simplify the calculation procedure, the pole piece sets the density, but not the gravity;

(5) A given pole piece with an initial speed simulates the operating state of the pole piece before it is bitten;

(6) The electric slurry particles are simulated by the plastic model of porous metal.

2.2 Establishment of geometric model

Using ABAQUS software to establish a three-dimensional rolling model, it can also output contact force and contact pressure. The pole piece is set as a deformation body, and the upper and lower rollers are set as discrete rigid bodies [10].The center points of the upper and lower roll side circular surfaces are set as the center point of the roll rotation for the application of rotary load. The model is shown in Fig. 5.

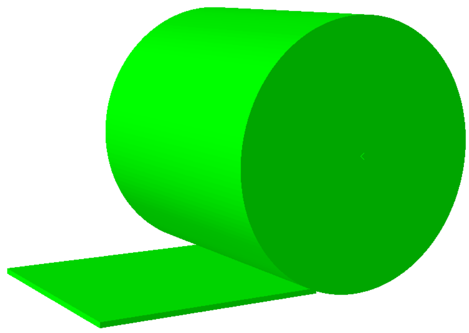


Fig. 5 Three-dimensional rolling model

2.3 Mesh division

In the mesh of the ABAQUS software, the material and mesh of the roll and the pole piece are separately divided. The properties of the roller

(9Cr2Mo) are as follows: the diameter of the roller body is 700mm, the mass density is 7700Kg/m^3, the elastic modulus is 2.36E11Pa, the Poisson's ratio is 0.3; the unit size is set to 10mm, and the upper roll model is divided into 12 729 Unit, 20 865 nodes.

The pole piece material properties are as follows: grain elastic modulus (1.91e11Pa), particle Poisson's ratio 0.224; the pole piece is meshed, the unit size is set to 5mm, the pole piece model is divided into a total of 29760 hexahedron units, and 35867 node.

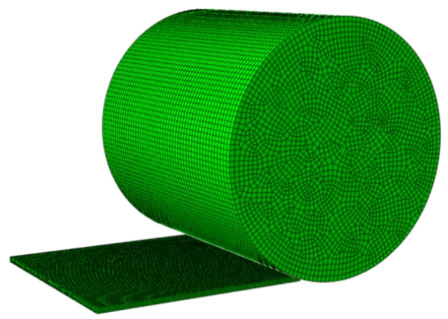


Fig. 6 Three-dimensional rolling model grid

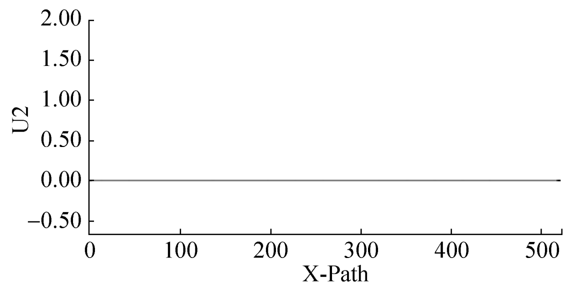
2.4 The battery pole piece rolling contact analysis

In the interaction module of ABAQUS software, select the Tangential Behavior in Mechanical, select the penalty function for Friction, and enter the friction factor to 0.3. Mass magnification factor here choose 10 000.

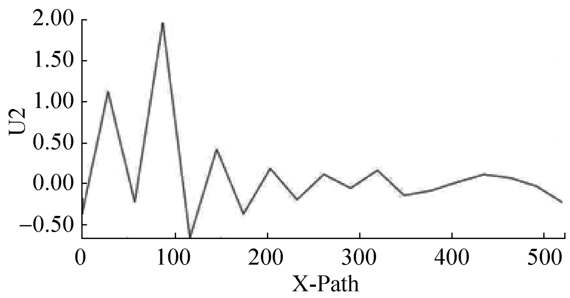
The loading module is selected to apply opposite angular velocity loads to the two rolls, limiting all degrees of freedom except the rotation center load, and giving the initial speed of the pole piece rolling model so that the pole pieces can be bitten into between the two rolls.

3 Flow law of the pole piece slurry in the deformation zone during rolling

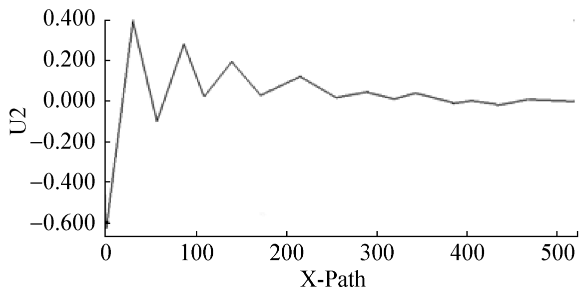
The following simulations verify the relationship between slurry particle density and pole piece thickness. The change of the pole piece in various directions during the rolling process is set. The thickness of the pole piece changes to the negative direction of the *Y* axis, the width of the pole piece is the *Z* axis direction, and the rolling direction is the positive direction of the *X* axis. The default numbers 1, 2, and 3 in the ABAQUS software are *X*, *Y*, and Z directions. By analyzing the thickness of the pole piece, the change in the relative density of the electrical paste particles is solved. So select 2 parameters, which is the displacement of the pole piece in the *Y*-axis direction.as shown in Fig. 7.



(a) t=0 s



(b) t=0.2 s



(c) t=0.4 s

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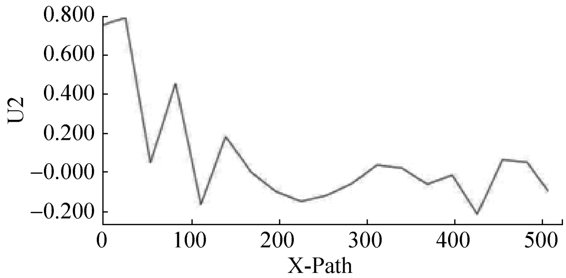
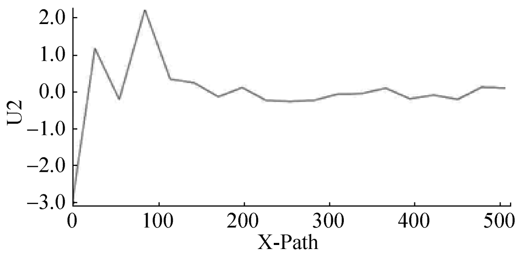
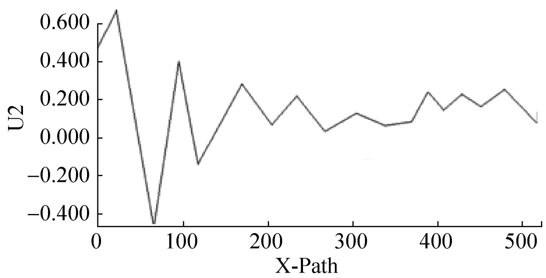


(d) t=0.6 s



(e) t=08s



(f) t=1 s

Fig. 7　Pole displacement with different rolling times

In order to describe this process in more detail, the variation of the density of the electric slurry particles at different rolling angles during the rolling process is selected, and the relative density between the electric slurry particles and the rolling angle is obtained. The relationship is as shown in Fig. 8.

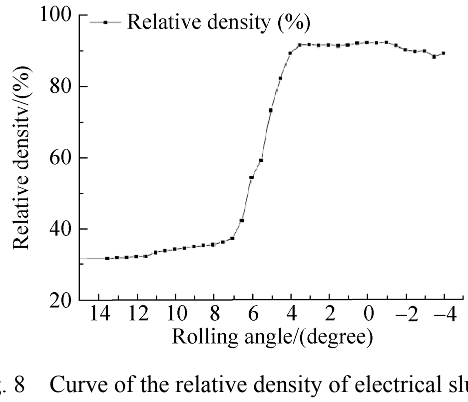


Fig. 8　Curve of the relative density of electrical slurry particles with rolling angle

The analysis of simulation results shows that as the time advances, the *Y*-axis negative direction displacement occurs on the upper surface of the pole piece after the pole piece enters the roller, and there is a slight extension in the *Z*-axis direction. When the electrical slurry particles enter the roll, the density of the electrical slurry increases and the relative density of the pole piece gradually increases. When the electric slurry particles are rolled out by the roll, the relative density reaches the maximum, and the displacement of the pole strip in the *Y*-axis direction slightly rebounds after it leaves the roll, causes a slight decrease in the relative density of the electrically conductive paste particles.

Through the above analysis, we can summarize the changes in the density of the electrically conductive paste in three different areas. In the case of an area *I* where the electrically conductive slurry particles enter the middle of the two rolls but do not reach the bite angle, the particles of the electrically conductive paste are generated. Displacement never fills the voids between particles, accompanied by a small amount of particle deformation; *II* area is the process of compaction after the electric slurry particles enter the bite angle, during which the density of the electric slurry particles is high. The amplitude increases. In this stage, the particles mainly undergo large deformation and compaction. The area *III* is the moment before the electric slurry particles come out of the two roller gaps. At this time, the roll angle is between 0-6 degrees. The particles of the electrically conductive slurry have been filled by the displacement of the first two stages and compacted by the roller compaction, and the density no longer changes. Battery pole strip density changes up to 90%. The validity and accuracy of this simulation content are proved, and it is consistent with the theoretical analysis. It also verifies that the model can accurately simulate the rolling process of electric slurry particles.

4 Research on battery electrode rolling test

Through the theoretical analysis and simulation of the entire rolling process of the battery pole piece, the battery pole piece rolling mill was used as the test platform and the battery pole piece rolling test was performed. The scanning electron microscope (Hitachi SU1510) was used during the entire rolling process. The battery pole piece was microscopically observed to show the uniformity of the rolled battery pole piece from the microscopic view, and the compression of the electrically conductive slurry particles on the longitudinal section of the battery pole piece was observed. This experiment was used to study the accuracy and reliability of the theoretical analysis and simulation content of the rolling process.

4.1 Test subject

The battery pole piece material of this test subject was a lithium iron phosphate pole piece coated with copper foil after coating, drying, and other procedures. The thickness was 0.200 (mm) and the width was 600 (mm).

Take pole pieces with six pole pieces on the same width of the longitudinal section from the center of the rolling center at –20 mm, –15 mm, –10 mm, –5 mm, 0 mm, and 5 mm. Each pole piece contains 5 pole pieces. After the samples were measured for thickness and averaged, relative density calculations were performed.

4.2 Analysis of polar strip density change during rolling

The pole pieces are now taken on 6 strips of the same width of the longitudinal section respectively from the rolling center position of –20 mm, –15 mm, –10 mm, –5 mm, 0 mm, and 5 mm.

It includes the whole process of the battery pole before rolling, rolling and rolling, and observing its micro structure under scanning electron microscope, the magnification is 3K times, the working voltage is 10 KV, the working distance is about 12 mm. as shown in Fig. 9.

Fig.9 reveals the deformation of the lithium iron phosphate particles coated on the pole piece of the battery during the entire rolling process. In order to more clearly reveal the changes in the density of lithium iron phosphate during rolling, the thickness of the pole piece of the battery during the rolling process is measured relative to the initial density, and the relative density of the pole piece is plotted against the distance from the rolling center point. In the case of changes, the rolling direction is the positive direction of the *X* axis and the vertical direction of the *Y* axis, as shown in Fig. 10.

A comprehensive analysis of Figures 9 and 10 shows that during the entire rolling process, the battery pole piece is located at a distance of -20mm to -13mm from the rolling center point, and its relative density gradually increases. The main reason is that it is close to the rolling center point. Part of the particles are subjected to squeezing flow to interact with the particles at the rear end, forcing the relative displacement of the part of the particles, filling the gaps between them, resulting in an increase in density, but due to the small interaction forces between the particles, the relative density increases. Relatively slow, about 3% to 5%; at a distance of -13 mm to 0mm from the rolling center point, the relative density of the battery pole pieces increases rapidly, mainly due to the large-scale displacement between the particles and the particles themselves produce

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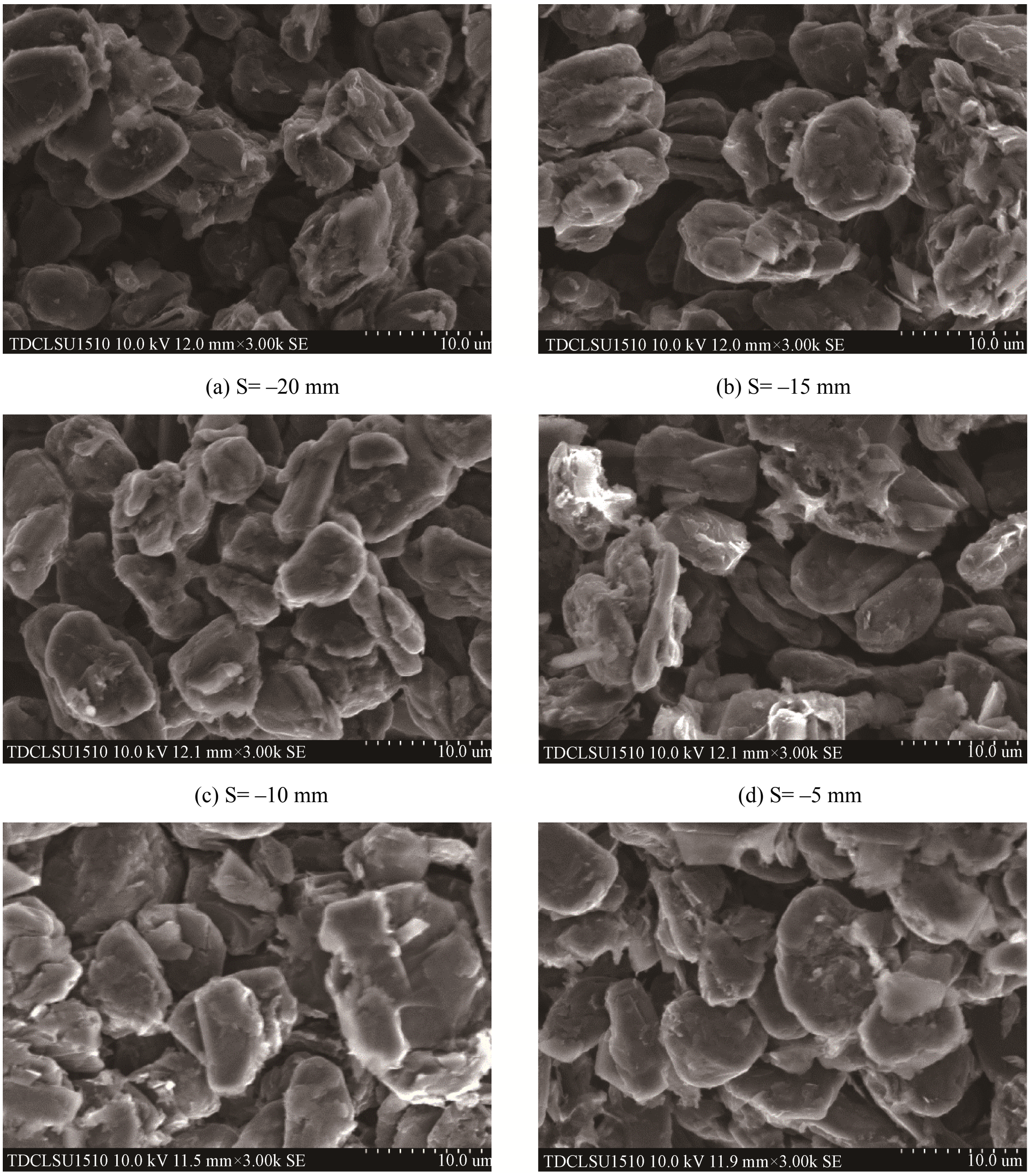
more Large deformation results in a substantial increase in density, which increases to about 90%; after the final pole piece passes through the rolling center point, its relative density slightly decreases, which is mainly due to the fact that the grain undergoes roll deformation after a large rolling force. However, some of the particles did not reach the yield limit. Therefore, the phenomenon of stress rebound occurred, resulting in a slight decrease in the relative density of the battery pole piece. Comparing the results of the test data with the simulation results, it is found that the overall trend of the simulation data of the battery pole piece with relative density changes is roughly in line with the actual change trend, which verifies the accuracy of the simulation content in this paper.



(a) S= –20 mm (b) S= –15 mm

(c) S= –10 mm (d) S= –5 mm

(e) S=0 mm (f) S=5 m

Fig. 9 Microscopy image of the pole piece with different positions in the same width

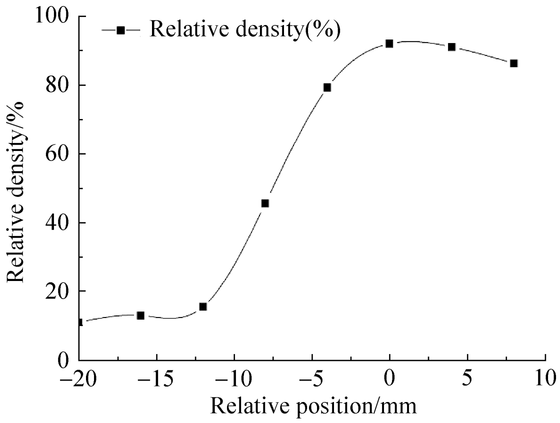


Fig. 10 Curves of the relative density of pole pieces at different positions

5 Conclusion

In this paper, the theoretical analysis, simulation study and the final test results show that:

(1) Through the exploration of the whole process of rolling the battery pole piece, the conditions for the stable rolling of the pole piece are obtained, and the working mechanism and mathematical model of the pole piece during the rolling process are analyzed and studied, which is the rolling process. Dynamic analysis lays a theoretical foundation.

(2) The relationship between the thickness of the pole piece and the relative density was analyzed by simulation, and the densification of the battery pole piece during the rolling process was revealed. The simulation results are similar to the theoretical analysis results.

(3) By scanning the test sample for analysis, it reveals the change of the relative density of the slurry particles with the change of thickness, and the correctness of the theoretical analysis and simulation results is verified through the test results, providing guidance and recommendations to the battery pole piece manufacturers.

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