Effects of Step Length to Failure Mode about Micro Penetration of Traction Batteries

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ABSTRACT: The internal short circuit of the traction battery is one of the typical failure behaviors that cause the thermal runaway and cause the thermal propagation of battery system. As an effective test method to reproduce the internal short circuit, test conditions need to be studied in depth based on internal short circuit behavior. The penetration step length is one of the important factors affecting the internal short circuit behavior. However, for different battery samples, there is no clear test procedure for how to choose the appropriate penetration step to better reproduce the internal short circuit behavior. In this paper, penetration test with thin nail with different penetration steps was carried out to analyze the evolution of electrical and thermal parameters, which provided data reference for the establishment of universal internal short circuit simulation test.

KEY WORDS: lithium-ion battery, nail penetration, internal short circuit, motor, damage study

1. INTRODUCTION

At present, the quantity of new energy vehicles in China has exceeded 10 million units, and the safety energy of traction battery, as a key component of new energy vehicles, has been a key research area for the industry and research institutions [1-2]. As an important support for the development and validation of traction battery, testing and evaluation technology has received great attention from the industry. Simulation of the possible damage of traction battery under actual working conditions of new energy vehicles with high degree of reproducibility on the experimental rig is an important direction for the current measurement and evaluation technology [3-5].On the other hand, thermal runaway and thermal diffusion caused by internal short circuit of traction battery has been one of the most important factors in the fire of new energy vehicles, and the study of damage and internal short circuit of traction battery has been a hot topic of interest [6-8].

The nail penetration test that has been widely used to examine whether the penetration of steel nails with a diameter of 6 mm-8 mm into the battery will lead to fire and explosion and other uncontrolled phenomena, and the steel nails penetrate into the battery while conducting through each layer of positive and negative plates to cause an internal short circuit of traction battery. Meanwhile, in the method for evaluation of thermal diffusion of traction battery in GB38031-2020 "Safety Requirements for traction battery for Electric Vehicles", the nail penetration method is also a recommended thermal runaway trigger scheme [9-11]. This nail penetration test is designed to directly verify the safety that the battery will not cause fire and explosion when suffering from penetrating injury. On the other hand, no common conclusion has been reached on how to establish a safety test method closer to the actual internal short circuit [12-15]. In enterprise or R&D test methods such as PV8450, as well as in literature studies, a method of using fine nail superficial penetrating for internal short circuit triggering is provided, i.e., using nail with a diameter of 1 mm at 0.1 mm/s to needle, so as to slowly trigger the battery internal short circuit, so as to analyze and judge the battery safety [16-18]. However, the above-mentioned methods still lack systematic and theoretical analysis, and the actual testing process with reference to these methods will have problems such as unclear test details and poor test consistency, which need further refinement and establishment of test details method to improve their universality and effectiveness. On the basis of such experiment, aiming at the important parameter of precipitation step, we thoroughly explored the change trend of precipitation step in fine nail superficial penetrating test on battery internal short circuit state, electrical signal and thermal signal.

2. EXPERIMENTAL

2.1 Experimental set-up

This experiment uses a high-precision needling table to complete the process of fine nail superficial penetrating of traction battery. After fixing the traction battery on the table, the battery was performed the nail penetration test with a 1 mm diameter stainless steel nail at a speed of 0.1 mm/s. Fig.1 illustrates the testing platform for fine nail superficial penetrating.

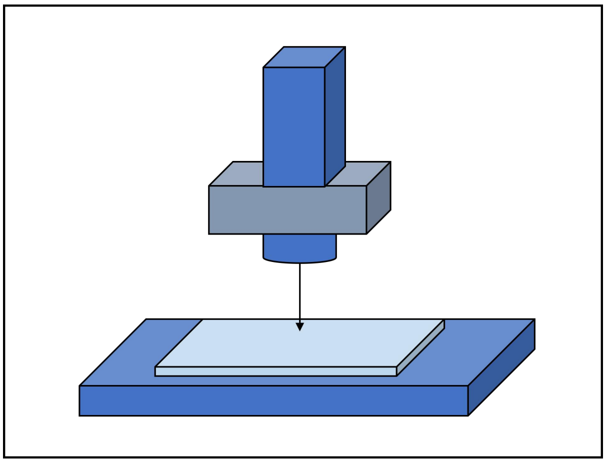

Fig. 1 Schematic of fine nail superficial penetrating platform

The experiment was carried out by using a fine nail superficial penetrating method, and the characteristics of superficial penetrating are: (a) using a fine nail with a diameter of not more than 1 mm; (b) adopting a phased penetration instead of a one-time penetration method. The superficial penetrating test allows the sample to maintain a certain voltage level after partial penetration and to continue the charging/discharging test to a certain extent. Fig. 2 shows samples used in this study of a longitudinal section of the battery after 50% depth superficial penetrating. As observed, the penetration marks are obvious, but the battery as a whole is not fatally damaged by the penetration. This method can be used to classify the traction battery into different layers and stages of superficial destructive analysis, which can better analyze the safety of the traction battery monomer.

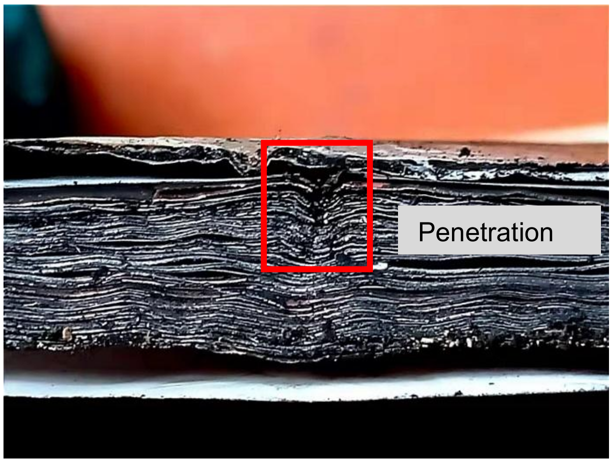

Fig. 2 Section after 50% depth superficial penetrating

2.2 Experimental scheme

The experiment conducted the penetrating phased superficial penetrating test on traction battery. In each stage, the penetration steps of 0.5, 0.75 and 1 mm were used to compare and analyze the overall safety of the traction battery under different degrees of internal short circuit caused by different penetration steps. The electrical and thermal parameters of battery voltage attenuation and temperature increase are mainly described and analyzed.

2.3 Sample treatment

The three-element battery system with high specific energy used in this study is one of the mainstream products of battery manufacturers in the industry. Table 1 lists parameters of this system. The standard charging/discharging cycle was performed before the experiment, and the charging/discharging curve was Fig. 3. The traction battery was activated and calibrated before the experiment started, and the battery capacity was adjusted to 100%.

Table 1. Experimental sample parameters

Category	Parameter
Battery system	Ternary soft pack
Rated capacity	10 Ah
Voltage range	2.8 V-4.2 V
Sample size	350 mm×260 mm×4.5 mm

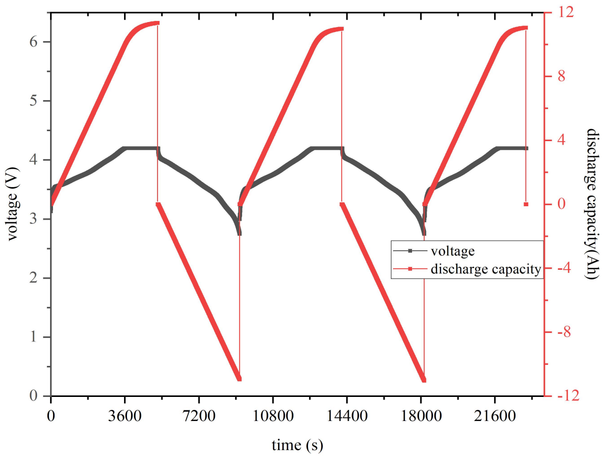

Fig. 3 traction battery pretreatment capacity curve

3. DATA AND PROCESSING

3.1 Procedures

Fix the prepared test object on the table and adjust the needle tip to the center of the sample, as shown in Fig. 4. The nail was controlled to penetrate the battery in stages of 0.5, 0.75 and 1 mm, respectively, at the speed of 0.1 mm/s. After each stage of penetration, the battery was left to stand for 1h to observe the voltage and temperature changes, and whether thermal runaway occurred. The temperature and voltage data were measured by temperature and voltage sensors during the superficial penetrating process and analyzed.

Fig. 4 Schematic of fine nail superficial penetrating of power batter

3.2 Data analysis

3.2.1 superficial penetrating at step of 0.5 mm

The superficial penetrating test was performed at reference step of 0.5 mm until all plates were penetrated. Fig. 5 shows the changes of temperature and voltage.

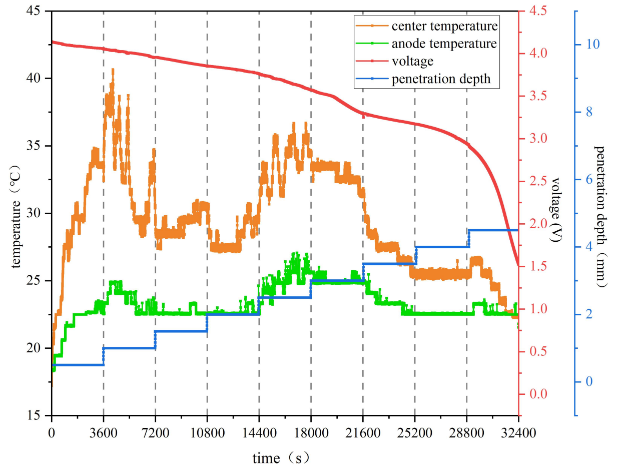

Fig. 5 Changes of temperature and voltage in superficial penetrating at a step of 0.5 mm

During the penetration process, neither explosion nor fire was observed for the battery, while voltage attenuation and temperature increase induced by internal short circuit were observed. Table 2 shows voltage attenuation at each stage of the penetration process.

Table 2. Attenuation in superficial penetrating at a step of 0.5 mm

depth (mm)	0.5	1.0	1.5	2.0	2.5
voltage attenuation (mV)	81	101	102	88	192
Stage attenuation rate (%)	1.96	2.49	2.60	2.29	5.10
Progressive attenuation rate (%)	1.83	4.40	6.87	9.00	13.65
depth (mm)	3.0	3.5	4.0	4.5	
voltage attenuation (mV)	280	122	244	1504	
Stage attenuation rate (%)	7.85	3.70	7.70	51.32	
Progressive attenuation rate (%)	20.42	23.35	29.28	65.61	

According to voltage attenuation, at the initial stage of the superficial penetrating, the deep penetration of the needles led to a smooth attenuation of the battery voltage, and when the penetration depth reached 2.5 mm, the battery voltage attenuation rate started to increase from 80 mV-100 mV to 192 mV, and then continued to reach 280 mV. After the penetration depth reached 4 mm, the voltage decayed rapidly, and the battery voltage was 2.8 V lower than the lower limit of normal voltage.

For the temperature analysis, the battery central temperature was used as the reference, and a temperature monitoring point was added near the negative pole as a reference for the temperature trend change.

From the temperature change analysis, the battery showed two significant temperature increase peaks during the whole needling process. The battery was pierced into the cell at the beginning of the needling stage, causing an internal short circuit in the superficial layer of the cell and a rapid increase in battery temperature, with the central temperature reaching 40.6 ℃ at the second stage of penetration depth 1 mm. The second peak occurred at the penetration depth of 2.0-2.5 mm, where the battery central temperature reached 36.7 °C. Since the internal short circuit caused by needling in the first two stages had already released part of the battery energy, and the internal short circuit had been carried out for 4 h before the start of needling, the second stage did not cause any dramatic temperature increase and heat change. After the penetration depth exceeded 3 mm, the battery temperature increase dropped back significantly, the battery energy had been released for a period of time, the voltage level dropped to the lower limit of the normal working voltage platform, the battery internal residual energy was greatly reduced, not causing excessive temperature increase.

3.2.2 Superficial penetrating at a step of 0.75 mm

A reference step of 0.75 mm was used to perform a superficial penetrating test until all plates were penetrated. Fig. 6 shows the changes of temperature and voltage.

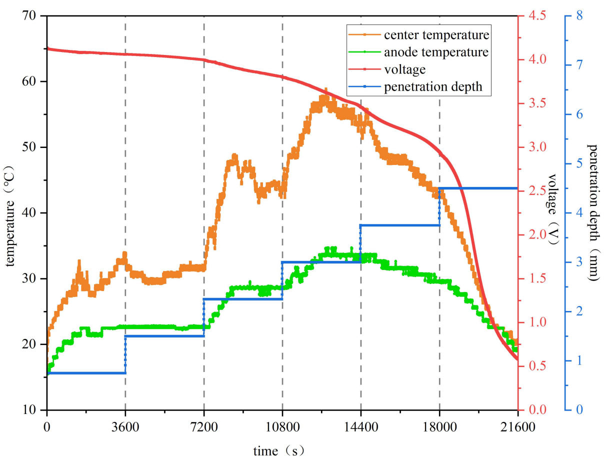

Fig. 6 changes of temperature and voltage in superficial penetrating at a step of 0.75 mm

During the penetration process, neither explosion nor fire was observed for the battery, while voltage attenuation and temperature increase induced by internal short circuit were observed. Table 3 shows the voltage attenuation at each stage of the superficial penetration process with a step of 0.75 mm.

Table 3. Voltage attenuation in superficial penetrating at a step of 0.75 mm

depth（mm）	0.75	1.5	2.25	3.00	3.75	4.5
voltage attenuation (mV)	76	62	194	341	516	2379
Stage attenuation rate（%）	1.83	1.50	4.86	8.98	14.90	80.76
Progressive attenuation rate（%）	1.83	3.38	8.03	16.28	28.76	86.30

During superficial penetrating, the voltage attenuation rate increased with increasing penetrating depth. At a penetration depth of 1.5 mm (33% battery thickness), the voltage attenuation was in a uniform and stable state. In this state, the voltage attenuation rate remained below 2 %. When the penetration depth was between 1.5 mm and 3.75 mm, the voltage attenuation started to increase significantly, and the increasing trend was positively correlated with the penetration depth, and the voltage stage attenuation rate increased about 5 % per section in this state, which is uniformly accelerated. When the penetration depth reached the battery thickness, the whole battery plates were penetrated, and the voltage attenuation reached the maximum at this stage, the stage attenuation rate reached 80.76 %, and the battery voltage dropped to below 1 V rapidly.

From the temperature perspective, each needle penetration brought an increase in battery temperature. The first section of needling, battery surface was destroyed, nail piercing triggered the internal short circuit, there was a more obvious temperature increase; the second section of needling battery temperature increase was more moderate, temperature maintained above 30 ℃; In the third and fourth stage, the battery showed a higher rate of temperature increase, with the maximum temperature reaching 60 ℃. The biggest difference between the overall trend of the above experimental phenomena and the 0.5 mm step fine nail superficial penetrating test was the temperature increase at each stage. Specifically, an internal short circuit occurred during the first superficial penetrating stage of the battery causing a rapid increase in temperature. Then, the battery temperature continued to rise. As the penetrating step increased, the degree of internal short circuit caused by each stage of the battery increased, i.e., the battery exhibited a superposition of internal short circuit exotherm continuously, which is evident in the penetration depth 2.25-3 mm, eventually resulting in a maximum central temperature of battery of 58.5 ℃. After the penetration step exceeded 3 mm, the battery temperature gradually decreased as the battery energy was released, and finally returned to normal temperature.

3.2.3 Superficial penetrating at a step of 1 mm

A superficial penetrating test was performed with a reference step of 1 mm until all plates were penetrated. Fig. 7 illustrates the changes of temperature and voltage.

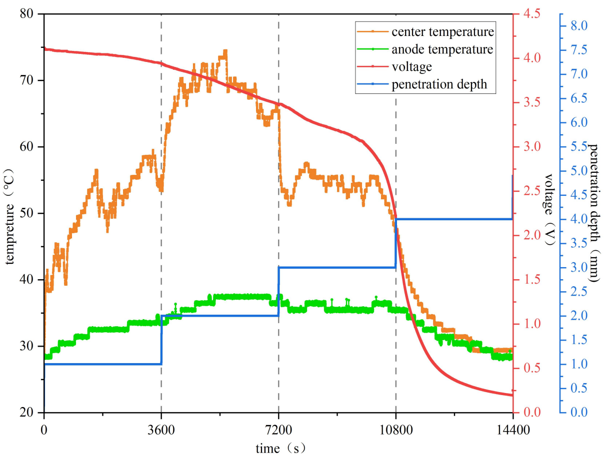

Fig. 7 Damage depth and temperature increase in superficial penetrating at a step of 1 mm

In the test with a penetration step of 1 mm, both voltage attenuation and temperature increase exhibited drastic changes compared with those at penetration steps of 0.5 and 0.75 mm. Before the nail had fully penetrated the battery, the voltage had dropped to 0.2 V, and the temperature had returned to near the initial temperature. Table 4 shows the voltage attenuation in superficial penetrating at a step of 1 mm.

Table 4. voltage attenuation in superficial penetrating at a step of 1 mm

depth（mm）	1	2	3	4
voltage attenuation (mV)	177	459	1258	1971
Stage attenuation rate（%）	4.30	11.65	36.17	9.50
Progressive attenuation rate（%）	4.30	15.45	46.01	93.89

In terms of voltage attenuation, at the beginning of the superficial penetrating process the voltage decreased in a relatively rapid trend, with the most significant attenuation at the 2-3 mm penetration, and at the final stage the voltage dropped rapidly to below 0.2 V and the voltage attenuation process was completed.

In terms of temperature increase, the battery rose rapidly from the beginning of needling at a step of 1 mm, and the maximum central temperature reached 74.4 °C at the penetration depth of 1-2 mm. Compared with the cases at steps of 0.5 and 0.75 mm, both temperature increase and maximum temperature exhibited significant increase at a step of 1 mm. Then, the battery temperature stabilized between 50 °C and 55 °C and then dropped rapidly after the penetration step of more than 3 mm, and then dropped to below 30 °C in the fourth stage.

3.3 Results at different penetration steps

Fig. 8 shows voltage attenuation and temperature increase at different penetration steps.

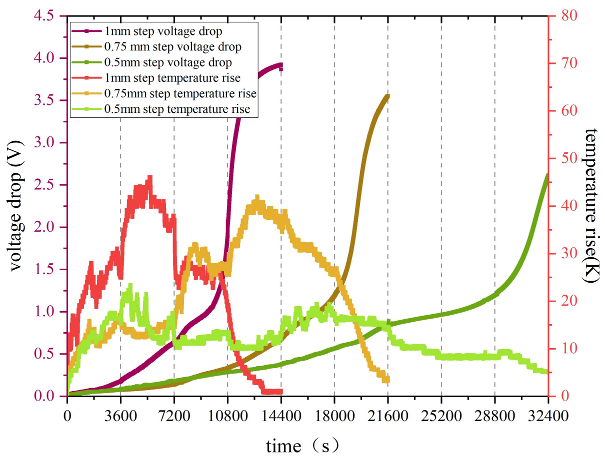

Fig. 8 Voltage attenuation and temperature increase at different steps

1) At a penetration step of 0.5, 0.75 or 1 mm, the linear fitting slope of voltage attenuation rate in normal discharging area was 0.42: 0.65: 1.23, indicating that the increase of traction battery voltage attenuation rate and temperature triggered by internal short circuit caused by traction battery superficial penetrating was positively correlated with the penetration step, and the discharging rate increased with the increase of penetration step;

2) At a penetration step of 0.5, 0.75 or 1 mm, the residual voltage after penetration was 1.52, 0.58 and 0.19 V, respectively. In other words, the penetration step is negatively related to the residual voltage, indicating that a complete internal short circuit

can be triggered by a large penetration step to accelerate battery discharging.

3) At a penetration step of 0.5, 0.75 or 1 mm, the maximum temperature increase was 23.4, 41.8 and 46.0 K, respectively. In other words, the maximum temperature increase is positively related to the penetration step. This can be attributed to the fact that a large penetration step can lead to a violent internal short circuit discharging, resulting in large short-term current in the internal short circuit, thus rapid temperature increase.

4) The temperature increase induced by superficial penetrating reached a high peak at 1.5-3 mm (33%-67%). On the one hand, this part is the central part of battery, and the heat dissipation effect is worse than that near the surface of the battery. At the same time, the internal short circuit effect reached a peak in this area, which was often accompanied by rapid discharging in the normal working voltage area. After exceeding this area, most of the battery energy had been released, and the degree of internal short circuit had decreased.

4. CONCLUSIONS

In this study, a traction battery fine nail superficial penetrating test bench was established, and based on a high specific energy three-element 811 system cell, the internal short circuit damage caused by different endurance steps was compared and analyzed in the monitored parameters such as battery voltage attenuation and temperature increase. The results showed that a large penetration step would cause a rapid and serious internal short circuit effect on the battery, which was directly reflected in the drastic voltage attention and large temperature increase. In this study, different penetration step tests on samples showed that when the penetration depth was in the middle 1/3 (33%-67%) of cell thickness, the internal short circuit effect of traction battery will reach the most serious level, which was specifically reflected in the rapid rise of voltage attenuation rate and the peak of temperature increase. Beyond this penetration depth, the battery will quickly enter the stage of rapid drop in voltage, and the temperature increase will also decrease. A large penetration step will no longer have a significant impact on the battery internal short circuit. This study can effectively analyze the electrical and thermal characteristics of cells at different stages of internal short circuit, thus providing data reference and technical support for establishment of a universal internal short circuit simulation experiment method.

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