Article

The Adhesion Characteristics and Aging Performance of Reversible Color-Changing Coatings for Self-Detection of Temperature by Power Equipment

Guanke Liu [1,*], Wanwei Wang [1], Xiliang Dai [1], Rongfu Zhong [1], Haipeng Zhang [1] and Bingbing Dong [2,*]

[1] Dongguan Power Supply Bureau of Guangdong Power Grid Co., Ltd., Dongguan 523120, China; wanww422@163.com (W.W.); dxl426153@163.com (X.D.); guank426153@163.com (R.Z.); haipz422@163.com (H.Z.)

[2] School of Electrical Engineering and Automation, Hefei University of Technology, Heifei 230009, China

* Correspondence: lgke426153@163.com (G.L.); bndong@126.com (B.D.)

Abstract: In order to detect abnormal heat generation in time, a reversible color-changing coating temperature measurement method is proposed for self-detection of temperature by power equipment, and its adhesion characteristics and aging performance were analyzed. The results showed that the reversible color-changing coating prepared with crystalline violet lactone as the colorant, bisphenol A as the color developer, octadecanol as the solvent, and RTV-II as the base paint can meet the requirements of self-detection of temperature by power equipment with its adhesion performance. The accelerated aging tests using high temperature, light and humidity were carried out in the laboratory, and we concluded that the deterioration degree of the color-changing coating was positively correlated with the temperature. Light can accelerate the aging rate of reversible color-changing coatings, and the degradation process of the coating was significantly accelerated under UV light. The effect of humidity on the coating was not significant. The degradation of the coating after aging for 288 h under indoor conditions was small, while it was accelerated under outdoor natural conditions. This research can provide a reference for the on-site application of reversible color-changing coatings for self-detection of temperature by power equipment.

Keywords: power equipment; temperature monitoring; color-changing coatings; adhesion; aging

1. Introduction

Power equipment withstands high voltages and high currents during operation, and needs a long period for fault repair, replacement and repair [1,2]. Once a malfunction occurs, it will threaten the safe and stable operation of the main network frame, leading to significant economic losses. Therefore, it is extremely important to ensure the safe operation of power equipment [3,4]. The high current flowing through the high-voltage conductor of the power equipment generates Joule heat. The long-term accumulation of heat leads to the superheating of the equipment. This may affect its service life, and even cause equipment damage or accidents [5]. Therefore, it is of great significance to carry out temperature detection and provide overheating warnings for power equipment [6].

At present, the temperature detection methods for power equipment mainly include infrared temperature measurements, fluorescence optical fiber temperature measurements and RTD temperature measurements. Infrared temperature measurements have a wide measurement range, high sensitivity, and simple operation, and is the most commonly used method for on-site operators to carry out thermal inspections of power equipment [7]. However, it is affected by environmental factors and its anti-interference ability needs to be improved; its real-time performance is also poor, and manual operation and maintenance costs are high and the workload is large. With the development needs of intelligent grid inspection, offline infrared detection technology for power equipment needs to be

combined with real-time monitoring and fast image-processing methods in substations, using big data technology to achieve real-time online monitoring of power equipment in substations. Fluorescent optical fiber temperature measurements are highly accurate, can be performed in real time, and are not easily affected by electromagnetic interference. However, optical fibers can easily fold and break and cannot resist high temperatures; thus, the equipment needs to be arranged in advance before use, and there are different relevant arrangement standards [8]. It is difficult to promote the application of a large area of multi-volume power equipment. RTD temperature measurements are based on the thermal effect of resistance to achieve temperature measurements of power equipment, with a wide range of measurement and other advantages; however, its electromagnetic interference resistance and temperature sensitivity need to be improved, and regular manual calibration is required, with the corresponding operation and maintenance workload [9].

In recent years, reversible color-changing coatings have become a technical hotspot for researchers [10,11]. As a new type of temperature measurement technology, they have been widely used in energy-saving buildings, and the fields of aerospace, medicine, and printing and dyeing [12,13]. Reversible color-changing coatings directly show the temperature variation of power equipment after their surface is superheated. It has the advantages of a strong anti-magnetic interference ability, low cost, no maintenance, and high reliability. Through a substation monitoring system, the real-time online detection of power equipment temperatures can be easily achieved. Currently, scholars are focusing on the development and application of reversible color-changing coatings for the self-testing of temperature by power equipment. In [14], a color-changing coating for temperature detection of transmission line fittings was prepared, which provides reference value for the on-site application of color-changing coatings for temperature detection of power equipment. However, the color changing process of the prepared coating was not reversible, which means that the coating needs to be replaced after an overheating fault occurs, increasing the field operation and maintenance costs. In [15], three types of temperature-indicating coatings were developed according to the requirements for different types of power equipment heating faults, and their color-changing properties and mechanical properties were analyzed. However, the temperatures at which the prepared temperature-indicating coatings changed color were mainly concentrated in the range of 300–900 °C, which is higher than the temperatures of common power equipment thermal fault defects. Ref [16] proposed a reversible thermochromic coating preparation method for thermally induced defect detection in electric power equipment, with a color-changing temperature of 80 °C. This further enriches the temperature measurement range of reversible color-changing materials, providing a reference for the development of reversible color-changing coatings in this paper. However, this study did not carry out research on adhesion, aging and other properties that are critical for the on-site application of the coatings, and thus, there is still some time before the field application of the coatings. Currently, the study of reversible color-changing coatings for self-testing of the temperature of power equipment is still in its initial stage [17], and scholars around the world are mainly focusing on the color-changing performance of the coating, but have not yet studied the key issues in field applications of the coatings such as the adhesion effect and aging performance. The study of the coatings' aging performance is still at the stage of laboratory research, which has a low degree of compatibility with practical applications [18]. Therefore, the research on reversible color-changing coatings for self-detection of temperature by power equipment is still insufficient, and it is important to research the adhesion and aging properties of the coatings, which have an engineering application value.

In this paper, reversible color-changing materials were prepared by the melt method, using crystalline violet lactone as the color-generating agent, bisphenol A as the color-developing agent, and octadecanol as the solvent to develop reversible color-changing materials to detect thermally induced defects of typical power equipment (e.g., transformer casing posts, etc.), with a thermally induced defect temperature of 55 °C. The reversible color-changing coating for power equipment temperature detection was prepared by using

a room-temperature vulcanized silicon rubber anti-pollution coating for insulations (RTV-II) as the base paint. The study focused on the adhesion and aging properties of the coating and carried out experimental research to analyze the adhesion performance on different substrates and the aging of the coating under different environmental conditions. The research results can provide a reference for the field application of reversible color-changing coatings for self-detection of temperature by power equipment.

2. Materials and Method
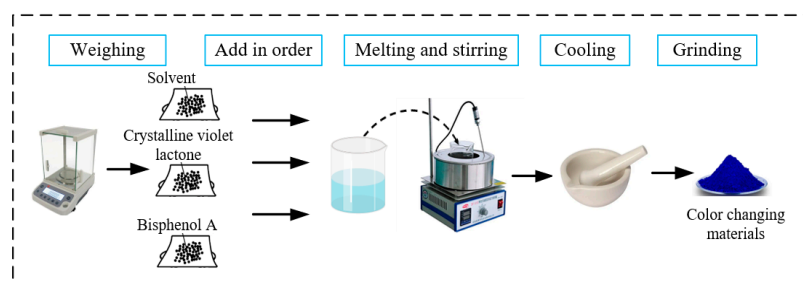
2.1. Materials and Instruments

The materials used in the preparation of reversible color-changing coating mainly included a chromogenic agent (crystalline violet lactone), chromogenic agent (bisphenol A), solvent (octadecanol), and base paint (RTV-II). The crystalline violet lactone (CVL) used in the preparation of the reversible color-changing coating was produced by Guangzhou Ruishi Bio-technology Co., Guangzhou, China. The room-temperature vulcanized silicon rubber anti-pollution coating for insulations (RTV-II) was produced by Hebei Zhonglian Huayu Electric Power Technology Co., Handan, China.

The test apparatus mainly included an electronic analytical balance (Kunshan Youkeweite Electronic Technology Co., Ltd, Kunshan, China) for weighing the components of the test specimen with an accuracy of 0.1 mg; a collector-type constant-temperature heating magnetic stirrer (Shanghai Lichen Bangxi Instrument Technology Co., Ltd, Shanghai, China), which has both stirring and heating functions and was used for the preparation of the reversible color-changing materials; a paint brush (width: 23.5 mm, Leqing Yilaike Electric Co., Ltd., Leqing, China) for coating the surface of the substrate with the reversible color-changing coating; a constant temperature heating table (Jinfeng Electronic Tool Factory, Dongguan, China), which was used to test the reversibility of the color change of the coating; a roughness measuring instrument (TR200, Beijing Saibo Ruixin Technology Co., Ltd., Beijing, China), which was used to measure the roughness of the surface of the substrate; an adhesion tester, which was used to measure the adhesion level of the reversible color-changing coating; a constant-temperature accelerated aging test chamber (GHX-150, Hefei Anke Environmental Testing Equipment Co., Ltd., Hefei, China), which was used for the thermal aging test of the reversible color-changing coating; an incandescent lamp (Taigesi Lighting Co., Ltd., Foshan, China), which was used for the white light aging test of the reversible color-changing coating; a UV light, which was used for the white light aging test of the reversible color-changing coating; a UV lamp (Juheda Optoelectronics Co., Ltd., Shenzhen, China) for the reversible color-changing coating UV aging test; a humidifier (Ningbo Juyi Electrical Appliance Co., Ltd., Ningbo, China), which was used to regulate the humidity of the test chamber to study the effect of humidity on the characteristics of the reversible discoloration of the coating; and a humidity meter (Yunchuang IoT Co., Ltd., Suzhou, China), which was used to measure the humidity of the test chamber.

2.2. Reversible Color-Changing Coating Preparation Method

2.2.1. Preparation Method for Reversible Color-Changing Materials
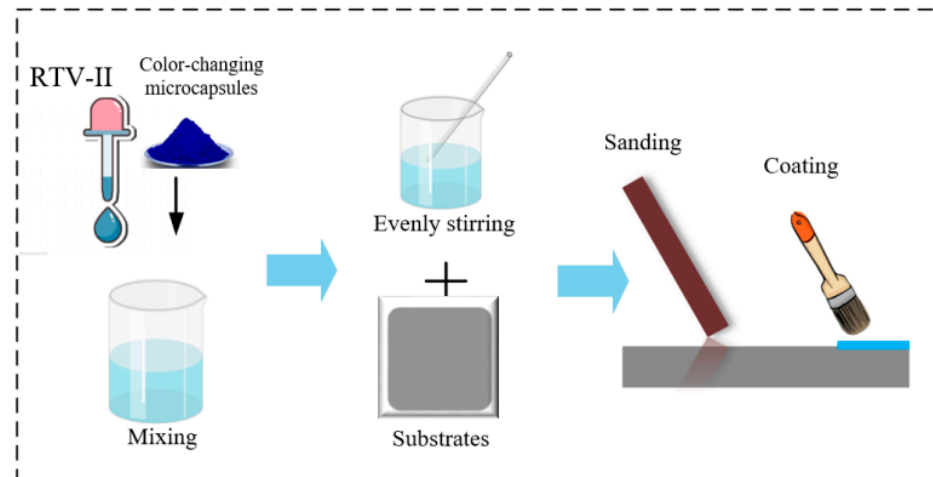
The reversible color-changing materials were prepared by the melting method, and the preparation process is shown in Figure 1 and consisted of the following steps:

Figure 1. Flow chart of preparation of reversible color-changing materials.

2.2.2. Preparation Method for Reversible Color-Changing Coating

The reversible color-changing material itself does not have adhesion; in order to facilitate its actual application in the field, the reversible color-changing coating was prepared by a mixing and stirring method, and the preparation process is shown in Figure 2. Mix the reversible color change material and base paint RTV-II at 300 r/min until a uniform, non-layered blue coating is formed, and then apply it to the surface of the substrate by a brushing method and cure it at room temperature for 24 h.

Figure 2. Flow chart of preparation of reversible color-changing coating.

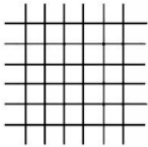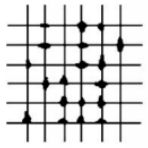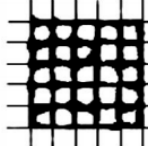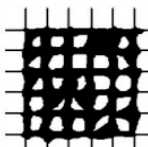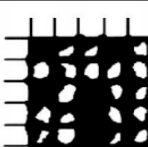*2.3. Reversible Color-Changing Coating Adhesion Performance Test*

The GB/T 9286-2021 was used to test the adhesion performance of the color-changing coating [19]. The experimental steps were as follows: use a baguette knife with a blade spacing of 3 mm, as shown in Figure 3, to apply a uniform force to the surface of the coating until it is scratched through, draw a "well"-shaped grid, use a brush to sweep along the diagonal to clean up the cutting line, and then evaluate the adhesion level of the coating according to the graded reference for the test results shown in Table 1.

Figure 3. Cross-cut tester.

First, the prepared reversible color-changing coating was uniformly coated on the surface of commonly used substrates for electric power equipment, which were represented by copper sheets, aluminum sheets, epoxy resin glass plates, and silicone rubber in this paper, and the adhesion performance was tested to analyze the adhesion performance of the color-changing coating on different substrates. Then, the roughness of the substrate surface was changed by sandpaper sanding, and the roughness of the substrate surface with different sanding degrees was measured using a roughness measuring instrument; each group was measured five times and the average value was taken. Finally, the reversible color-changing coating was coated onto the surface of substrates with different degrees of roughness, and the adhesion level was determined by the grid method to obtain the adhesion performance of the color-changing coating under different substrate roughness conditions.

Table 1. Comparison table of grading results of grading test.

Grade	Clarification	Surface Appearance of Cross-Cut Areas Where Detachment Occurs
0	Cutting edges are completely smooth, no shedding in the grid.	
1	A small amount of coating is peeling off at the intersection of the cuts, but not more than 5% of the cross-cut area is affected.	
2	Coating loss at kerf intersections and/or along kerf edges, with greater than 5%, but not greater than 15%, of the cross-cut area affected.	
3	The coating is partially or completely removed in large fragments along the cut edges and/or partially or completely removed on the different parts of the lattice, with more than 15%, but not more than 35%, of the cross-cut area affected.	
4	Coating is partially or completely peeling off in large fragments along the cut edges and/or some squares, affecting more than 35%, but not more than 65%, of the cross-cut area.	
5	Degree of detachment exceeding grade 4.	-

2.4. Reversible Color-Changing Coating DSC Test

Weigh a small amount of a reversible color-changing coating sample and prepare it in a crucible. Use a blank crucible as a reference sample and test the sample using a differential scanning calorimeter (DSC). The temperature ranged from 0 to 200 °C and the heating rate was 10 °C/min.

2.5. Reversible Color-Changing Coating Aging Test and Performance Test

2.5.1. Laboratory Accelerated Aging Test

In order to clarify the effect of a change in a single environmental factor (temperature, light, humidity) on the aging of the color-changing coating, a simulated accelerated aging test was carried out in the laboratory to study the performance of the color-changing coating under different aging conditions in order to obtain the aging characteristics of the color-changing coating.

Thermal Aging Test

A thermal aging test was conducted to study the effect of temperature changes on the characteristics of the color-changing coating, i.e., the change in the performance of the color-changing coating under prolonged high-temperature conditions. A constant temperature accelerated aging test chamber is used to study the thermal aging characteristics of the color-changing coating. Experimental steps: According to the requirements of

thermal aging test to adjust the aging chamber temperature, time and other parameters, the reversible color-changing coating samples placed in the aging chamber, and Nikon D750 (Nikon Imaging Instrument Sales (China) Co., Ltd. Beijing Branch, Beijing, China) camera to capture the surface discoloration of the coating before and after the thermal aging, to get the effect of temperature on the aging characteristics of the coating.

Light Aging Test

The light aging test was mainly performed to study the performance changes exhibited by the color-changing coating under long-term light exposure. This study mainly carried out incandescent lamp and ultraviolet radiation aging performance tests. The test steps were as follows: the coating samples were aged in a room temperature (25 °C) environment under incandescent lamps and ultraviolet lights, and a camera was used to photograph the coating surface color before and after the aging experiment, to obtain the effects of light on the aging characteristics of the color-changing coating.

Wet Aging Test

The wet aging test was mainly performed to study the influence of humidity parameters on the performance of the reversible color-changing coating. The experimental steps were as follows: the color-changing coating samples were placed in the test chamber; the temperature was maintained at 25 °C, and a humidifier was used to adjust the relative humidity of the test chamber to study the effect of humidity on the aging characteristics of the color-changing coating. In addition, the color-changing coating was completely immersed in deionized water for an immersion aging test, and the surface condition of the coating before and after aging was photographed with a camera to obtain the changes in the characteristics of the color-changing coating when it was completely immersed in water.

2.5.2. Natural Aging Test

The natural aging test was mainly performed to study the changes in the performance of the reversible color-changing coating after being affected by natural environmental factors (light, temperature, humidity, wind speed, dirt, etc.). The experimental steps were as follows: the reversible color-changing coating samples were divided into 2 groups; one group was placed in an indoor constant temperature (25 °C) environment as the control group, and the other group was placed in outdoor conditions to simulate natural aging. Every 16 h, the temperature of the coating at 5 different positions were recorded. The average temperature was recorded as the test site temperature, as shown in Figure 4. A Nikon D750 camera was used to capture the surface condition of the coating during the aging process to obtain the natural aging characteristics of the color-changing coating.

2.5.3. Testing Method for Color-Changing Performance of Reversible Color-Changing Coating

The aging of the color-changing coating was characterized by the change (lightening) in color, reduction in color area, and deterioration of color change reversibility after the aging of the color-changing coating. In view of this, the percentage of color area of the color-changing coating, saturation (S), and color change reversibility were used as the characteristics to quantitatively characterize the aging performance of the color-changing coating.

The percentage of color area (p) is the ratio of the colored area in the coating to the total area of the coating:
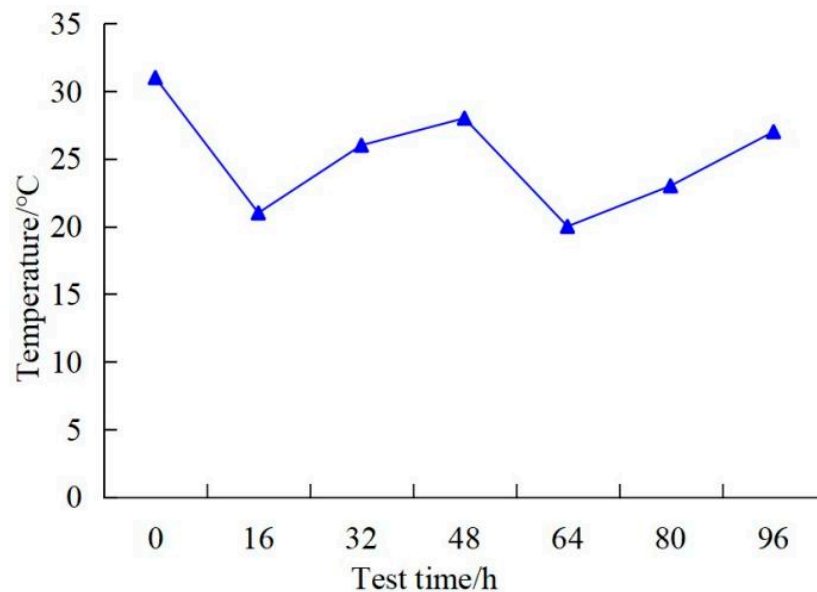
$$p = \frac{\iint f(x,y)dxdy}{S} \times 100\% \tag{1}$$

where p is the percentage of the area of the color-changing region, $f(x,y)$ is the boundary function of the color-changing region in the coating, and S is the total area of the coating.

In this paper, a camera was used to photograph the surface condition of the color-changing coating before and after aging, and MATLAB R2018a software was used to

identify the discolored area and calculate the area of the picture, so as to obtain the area percentage of the discolored area of the coating before and after aging.

Figure 4. Temperature variations at the experimental site.

Saturation (S) is the ratio of colored components in the color phase, which can intuitively reflect the color change ability of the color-changing coating. The more serious the deterioration of the coating, the lighter the surface color is and the smaller the S value will be. MATLAB software was used to write code to quantify the saturation of the reversible color-changing coating to characterize the coating's aging characteristics.

Color change reversibility ($|\Delta S|$) reflects the coating's color change reversibility performance. A larger $|\Delta S|$ value indicates that the coating's color change is more obvious as it ages, i.e., its color change reversibility is better.

The reversible color-changing coating to be tested was placed on a constant-temperature heating table at 75 °C until it was completely discolored, and then removed and cooled to room temperature for 10 min to allow it to completely reverse the color change. This was then repeated 20 times, and the absolute value of the change in saturation before and after the 20th discoloration of the coating $|\Delta S|$ was extracted. In view of the requirements of the temperature testing of power equipment, this study proposed that $|\Delta S| > 60\%$ color change reversibility is excellent, $|\Delta S|$ between 40% and 60% color change reversibility is good, and $|\Delta S| < 40\%$ color change reversibility is poor.
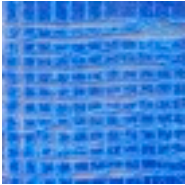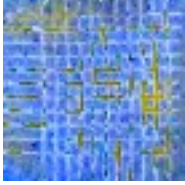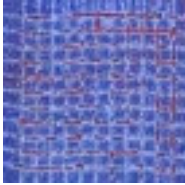
3. Test Results and Analysis

3.1. Reversible Color-Changing Coating Adhesion Properties

3.1.1. The Influence of Substrate on Coating Adhesion Properties

Copper sheets, aluminum sheets, epoxy glass sheets, and silicone rubber were used as representatives of common substrates for power equipment, and the adhesion of the color-changing coating to these substrates is shown in Table 2.

From Table 2, it can be seen that the adhesion level of the color-changing coating on the copper and aluminum sheets was given a grade of 2, while the adhesion level of the color-changing coating on the epoxy resin glass panels and silicone rubber sheets was given a grade of 1. This indicates that the substrate material affects the adhesion performance of the reversible color-changing coating, and that the adhesion of the color-changing coating on the surfaces of the epoxy resin glass panels and the silicone rubber surfaces was better than on the surfaces of the metals.

Table 2. Adhesion of color-changing coating to different substrate surfaces.

Substrates	Copper Sheet	Aluminum Sheet	Epoxy Resin Glass Plate	Silicone Rubber Sheet
Adhesion effect				
Adhesion grade	2	2	1	1

The main reasons for these findings are as follows:

(1) The adhesion performance of the color-changing coating is related to the combination of the paint film and the substrate, and the adhesion force is closely related to the surface condition of the substrate. The surfaces of silicone rubber sheets and epoxy resin glass plates are rough, allowing the color-changing coating and substrate to bond between the concave and convex areas. When subjected to external forces, this area of the coating will transfer the force to the substrate, produce a strong reaction force, and inhibit the sliding and deformation of the color-changing coating, so that the paint film and the substrate maintain contact. Therefore, the adhesion of the color-changing coating to the surface of the silicone rubber and epoxy resin glass plates was relatively superior.
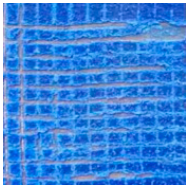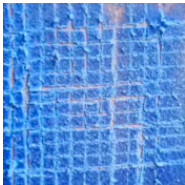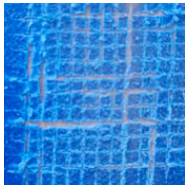
(2) The surface of copper and aluminum has high smoothness, and the bonding force between the color-changing coating and the surface of the metal substrate is relatively small. When the color-changing coating is subjected to external forces, the inhibitory effect of the metal substrate on the sliding of the coating is relatively small, resulting in slightly poorer adhesion of the color-changing coating on the surface of copper and aluminum compared to the surface of the silicone rubber and epoxy resin glass panels.

In summary, increasing the surface roughness of the substrate can improve the adhesion of the color-changing coating, but the adhesion level of the reversible color-changing coating on different substrates only differs by two grades. According to the DB42/T 1851-2022 [20], it can be seen that the adhesion performance of the reversible color-changing coating meet the requirements for the field application of the coating for the self-testing of temperature by the power equipment.

3.1.2. The Influence of Roughness on Coating Adhesion Properties

On the basis of the above research, the characterization of the effect of roughness on the adhesion performance of the coating was carried out, and the adhesion effect of the color-changing coating to surfaces with different degrees of roughness is shown in Table 3.

Table 3. Adhesion performance of color-changing coating on surfaces with different degrees of roughness.

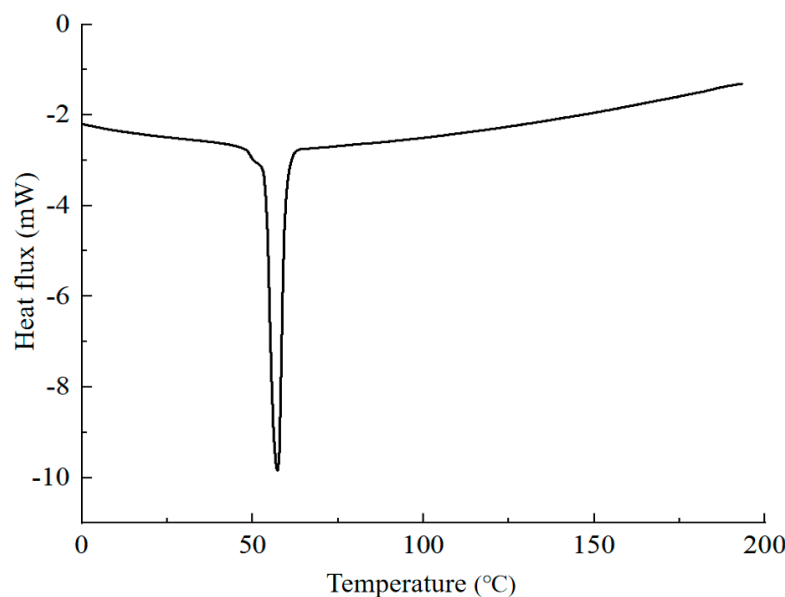| Roughness/μm	0.15	1.39	2.71
Adhesion effect			
Adhesion grade	2	1	1

According to Table 3, it can be seen that increasing the surface roughness of the metal substrate improved the adhesion performance of the color-changing coating. When the

surface roughness of the substrate was increased from 0.15 μm to 2.71 μm, the adhesion level increased from grade 2 to grade 1. The main reason is that by increasing the surface roughness of the substrate, the contact area between the coating and the substrate surface increases, i.e., the bonding degree between the coating and the substrate increases, which enhances the inhibition effect of the substrate on the sliding of the coating, and thus improves the adhesion performance of the color-changing coating.

3.2. Thermal Analysis of Reversible Color-Changing Coating

The differential scanning calorimetry analysis (DSC) chart is shown in Figure 5.

Figure 5. Differential scanning calorimetric analysis of color-changing coating.

As can be seen in Figure 5, a sharp peak appeared on the DSC curve in the range of 49–59 °C, with a peak temperature of 57 °C. In the temperature range of 0–200 °C, there was only one peak. The main reason for this is that the melting point of the solvent octadecanol in the color-changing material is 56 °C, which is close to the peak temperature, indicating that at this temperature, the solvent octadecanol in the microcapsules of the color-changing coating is undergoing a phase change. In this temperature range, the coating exhibited a fading phenomenon, and the color-changing temperature range was basically consistent with the sharp peak range seen in the DSC results. In addition, the DSC curve only had one peak and no other impurity peaks appeared. With the increase in temperature, no other substances underwent a phase transition, indicating that the thermal performance of the reversible color-changing coatings was stable.

3.3. Laboratory Accelerated Aging Characteristics of Reversible Color-Changing Coating

3.3.1. Characteristics of Reversible Color-Changing Coating after Thermal Aging

The temperature of the aging test chamber was set to 40 °C, 60 °C and 80 °C, and the changes in the properties of the reversible color-changing coating after 48 h of aging are shown in Table 4.
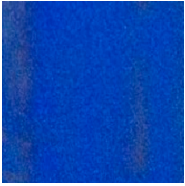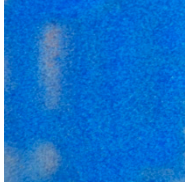
From Table 4, the following observations can be made:

(1) Thermal aging at 40–60 °C for 48 h did not cause obvious changes in saturation (96.4% to 79.5–87.6%, a reduction of only 8.8–16.9%), that is, the coating's surface color was only slightly lighter, and it still maintained a good color-changing performance.

(2) After thermal aging at 80 °C for 48 h, the percentage of the area of the color-changing area of the coating decreased from 99.6% to 88.9%, a decrease of 10.7%, and the saturation degree decreased to 71.6%, a decrease of 24.8%, i.e., the discoloration of the

color-changing coating surface underwent a more obvious fading phenomenon, and the coating deterioration was relatively large.

(3) Temperature significantly affects the degree of deterioration of the reversible color-changing coating, and the higher the thermal aging temperature, the faster the aging rate. The reason for this is that if the coating is at a high temperature for a long period of time, its molecular structure will be changed, and then decomposition, coking and other chemical changes occur. In addition, the base coat RTV-II and the other material components will be dehydrogenated at high temperatures, resulting in irreversible coking and carbonization of the solvent in the color-changing material components, causing the destruction of the conjugate color structure.

Table 4. Effects of thermal aging on color-changing coating.

Temperature	Surface Effect	p (%)	S (%)	|ΔS|
Unheated		99.6	96.4	Excellent
40 °C		99.3	87.6	Excellent
60 °C		99.3	79.5	Excellent
80 °C		88.9	71.6	Good

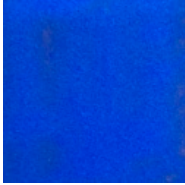3.3.2. Characteristics of Reversible Color-Changing Coating after Light-Induced Aging

The changes in the properties of the coating after 48 h of irradiation using incandescent light (400~760 nm) and UV light (10~400 nm) are shown in Table 5.

From Table 5, the following observations can be made:

(1) The percentage of the colored area of the coating remained unchanged after 48 h of white light irradiation. However, the saturation degree decreased slightly from 96.4% to 86.4%, i.e., the white light made the surface color of the coating slightly lighter, which increased the deterioration rate of the coating to a certain extent.

(2) After 48 h of UV irradiation, the area of the colored area of the coating decreased slightly from 99.2% to 97.6%. The saturation degree decreased significantly from 96.4% to 72.3%, i.e., there was a more obvious fading phenomenon of the coating after UV aging.

(3) Compared with white light, the accelerating effect of UV light on coating deterioration was more obvious. The reason for this is that light has a decomposition effect on

the components of reversible color-changing coatings. The decomposition product is mainly soluble in water or other solvents, resulting in discoloration, changes in chemical properties and so on. In addition, UV light has shorter wavelengths and greater energy, which has a stronger decomposition effect on reversible color-changing coatings, thus accelerating the deterioration process.

Table 5. Characteristics of the effect of light-induced aging on color-changing coating.

Light Condition	Surface Effect	p (%)	S (%)	|ΔS|
Darkness		99.2	96.4	Excellent
White light irradiation		99.2	86.4	Excellent
Ultraviolet light irradiation		97.6	72.3	Good

3.3.3. Characteristics of Reversible Color-Changing Coating after Wet Aging

The southern region of China often experiences high temperatures, high humidity and other harsh environments in the summer; during the summer season, the power load increase is more obvious, and a reversible color-changing coating that can maintain good performance in high humidity environments is important for maintaining its function. We conducted experimental research under different relative humidity and complete immersion conditions. The performance of the coatings after 48 h of wet aging is shown in Table 6.
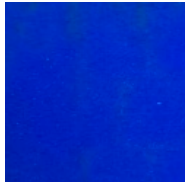
From Table 6, the following observations can be made:

(1) The percentage of the color area did not significantly change after aging for 48 h at a relative humidity of 50%~90%. The color-changing reversibility was maintained at a good level. With the increase in the relative humidity, the saturation degree was reduced from 96.4% to 86.3%, which means that the degradation degree of the coating was very small at a relative humidity of 50~90%.

(2) After being completely immersed in water for 48 h, the percentage of the color area decreased from 99.2% to 5.0%, and the saturation degree decreased from 96.4% to 15.7%. This indicates that the coating color faded and lost its reversibility after 48 h of water immersion.

The reason for these findings is that exposure to water leads to the loss of color-changing coating components to a certain extent. The rate of loss of color-changing components is significantly accelerated when color-changing coating is completely immersed in water. This prompts the decomposition of the color-changing materials' conjugate coloring structure gradually, so that the coating color fades away. However, from a practical application point of view, the possibility of the coating being completely immersed in water is
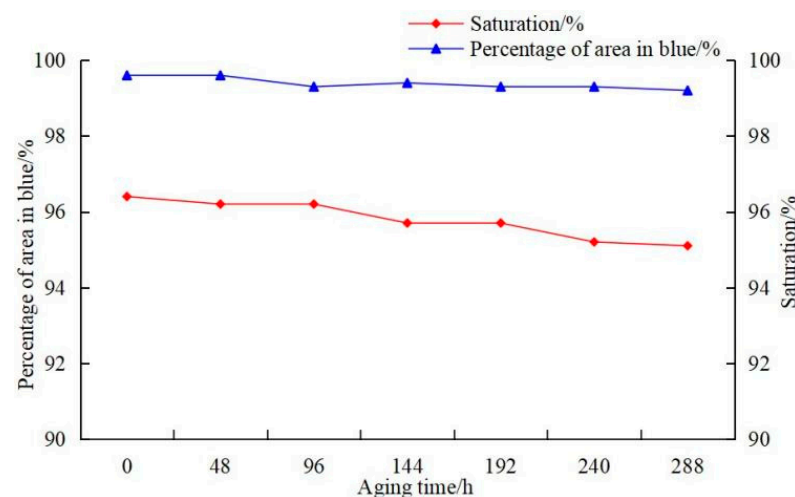
very small. Thus, the effect of humidity on the deterioration of reversible color-changing coatings is relatively small.

Table 6. Performance of color-changing coating in different relative humidity conditions and submersion in water.

Relative Humidity	Surface Effect	p (%)	S (%)	|ΔS|
0		99.2	96.4	Excellent
50%~60%		99.2	92.4	Excellent
80%~90%		99.2	86.3	Excellent

3.4. Properties of Reversible Color-Changing Coating after Natural Aging

The characteristics of the reversible color-changing coatings after aging under indoor constant temperature (25 °C) and outdoor natural conditions are shown in Figure 6 and Table 7, respectively.
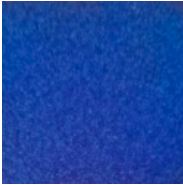

Figure 6. Characteristics of color-changing coating during aging under indoor conditions.

From Figure 6 and Table 7, the following observations can be made:

(1) The percentage of color area in the coating showed no significant change and remained at 99.3% after 288 h of indoor aging. The saturation was slightly reduced from 96.4% to 95.1%., i.e., after indoor aging for 288 h, the reversible color-changing coating's performance was maintain as good, and the degree of degradation was very small.

(2)   After 96 h of aging under outdoor natural conditions, there was no significant change in the percentage of color area of the coating, which decreased from 99.6% to 96.3%. However, the saturation decreased from 96.4% to 62.8%, i.e., the color of the coating became lighter and its color-changing reversibility decreased.

Table 7. Characteristics of color-changing coatings after aging under outdoor conditions.

Aging Time/h	Surface Effect	p (%)	S (%)	|ΔS|
0		99.6	96.4	Excellent
48		98.4	71.0	Excellent
96		96.3	62.8	Good

The reasons for this phenomenon are as follows:

(1)   There are unstable bonding structures in the molecular structure of color-changing materials, which are prone to fracturing under complex external environments such as sunlight exposure, leading to the deterioration and failure of reversible color-changing coatings.

(2)   The composition of the RTV-II base paint is relatively complex, containing many active chemical additives such as crosslinking agents, curing agents, accelerators, etc. It is easy to react with the functional groups of color-changing materials under heating and lighting conditions, inhibiting the formation of conjugated color structures and causing reversible color-changing coatings to fade. The coating is more suitable for coating on the surface of power equipment that is less affected by external environmental factors to achieve its temperature detection function.

4. Conclusions

The following conclusions were drawn:

(1)   Reversible color-changing materials for the self-detection of temperature by power equipment were prepared by a three-component method with a specific composition ratio (1:1:50 crystal violet lactone/bisphenol A/octadecanol). RTV-II was used as the base coat to prepare the reversible color-changing coating. The adhesion characteristics of the reversible color-changing coating varied slightly on different substrates. The adhesion of the color-changing coating to epoxy glass panels and silicone rubber surfaces was better than that on copper, aluminum and other metal surfaces. Increasing the surface roughness of the metal substrate improved the adhesion performance.

(2)   The reversible color-changing coating had stable thermal performance, and no substances underwent a phase transition with an increase in temperature. The accelerated aging test of the reversible color-changing coating was carried out in the laboratory, and the degradation degree of the coating was small after 48 h of thermal aging at

40~60 °C, while the degradation degree of the coating was relatively large at 80 °C. The degradation degree of the coating was positively correlated with the temperature. Light irradiation accelerated the aging rate of the coating. White light aging for 48 h slightly lightened the surface color of the coating. However, the coating degradation process was significantly accelerated under UV light irradiation conditions. The influence of humidity on the coating was not significant and the color-changing performance of the coating was maintained under the condition of 50%~90% relative humidity. However, the color of the coating faded after being completely immersed in water.

(3) After 288 h of aging under indoor conditions, the degradation of the coating was very small. The degradation rate was accelerated under outdoor natural conditions. After 96 h of aging, the coating's color became lighter and its performance decreased. The reversible color-changing coating is more suitable for applying to power equipment that is less affected by external environmental factors to realize its temperature detection function. These research results can provide a reference for the on-site application of reversible color-changing coatings for temperature detection of power equipment.

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Conflicts of Interest: Authors Guanke Liu, Wanwei Wang, Xiliang Dai, Rongfu Zhong, Haipeng Zhang were employed by the company Dongguan Power Supply Bureau of Guangdong Power Grid Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest. The authors declare that this study received funding from Science and Technology Project Funding of the China Southern Power Grid. The funder was involved in the study design, collection, analysis, interpretation of data, the writing of this article or the decision to submit it for publication.

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