

# Influence of Overcurrent Value on Thermal Degradation Process of Flame-Retardant XLPE Copper Wire

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**Abstract:** Flame-retardant cross-linked polyethylene (XLPE) insulated copper wires are widely used in hazardous environments, yet systematic studies on their pyrolysis behavior under slight overcurrent conditions remain scarce. This study investigates the thermal degradation characteristics of flame-retardant XLPE copper wires subjected to slight overcurrent values (70-100 A) using thermogravimetric analysis at heating rates of 10-40 °C/min. Results indicate that the pyrolysis process comprises three stages with two distinct mass loss peaks. The total mass loss stabilizes at 58±2% (90% occurring at 200-520 °C), with residual mass of 42%. Characteristic temperatures shift to lower values as overcurrent increases, with 100 A samples showing a 10 °C forward shift in the third stage. The 20 °C/min heating rate approaches maximum pyrolytic state. At 100 A, outer insulation exhibits significant degradation with reduced mass loss (43±2%), suggesting this as the critical threshold for kinetic parameter variation. These findings provide theoretical support for identifying slight overcurrent faults in fire investigations.

**Keywords:** Flame-Retardant XLPE Copper Wire; Slight Overcurrent; Pyrolysis Characteristics; Thermogravimetric Analysis; Fire Investigation

## 1. Introduction

The identification and exclusion of fires caused by electrical faults constitute a paramount aspect of fire incident investigation. Overcurrent represents one of the most common electrical faults leading to fires, defined as the phenomenon of conductor heating resulting from current exceeding the rated capacity[1,2]. When excessive electrical appliances are connected or overvoltage faults occur, the current through the conductor increases, causing temperature rise and subsequent thermal decomposition and

aging of the cable insulation. Overcurrent faults pose significant fire hazards and may readily initiate fires; therefore, accurate determination of overcurrent fault values is crucial for fire investigators to establish the cause of ignition[3]. Investigations have revealed that in numerous actual fire scenarios, electrical fires may not necessarily result from external heating or short-duration high currents. As stated in the *SFPE Handbook of Fire Protection Engineering*[4], when the current through a conductor remains below four times the safety current for extended periods, structural and compositional changes in the insulation layer may occur, potentially leading to fire initiation. Literature review indicates that research on overcurrent faults exceeding four times the safety current is relatively mature; however, technical support for accurately identifying and characterizing slight overcurrent faults below this threshold in copper conductors remains inadequate[5].

When electrical protection devices in buildings malfunction or are improperly configured, overcurrent faults can readily lead to fires, which is inextricably linked to the flammability of cable insulation sheath materials. Currently, cross-linked polyethylene (XLPE) insulated cables, characterized by high thermal stability, are increasingly employed in various complex engineering applications[6,7]. Recently, flame-retardant XLPE insulated cables suitable for large entertainment venues and hazardous chemical facilities[8,9] have emerged in the market, substantially reducing the fire risk associated with XLPE insulated cables. However, due to the scarcity of systematic research on the influence of slight overcurrent values on the pyrolysis behavior of copper conductor insulation, particularly flame-retardant XLPE, fire investigators have failed to recognize the specific differences in pyrolysis characteristics between normal and slight overcurrent-affected flame-retardant XLPE copper wires, leading to misconceptions regarding actual slight

overcurrent conditions at fire scenes and difficulties in accurately reconstructing the fire initiation process and determining the true cause of electrical faults. When copper conductor insulation materials undergo thermal exposure or aging, their pyrolysis kinetic functions undergo corresponding changes[10,11]. Therefore, investigating the pyrolysis behavior of flame-retardant XLPE copper wires subjected to slight overcurrent faults can provide theoretical foundations and data support for fire investigators to accurately identify slight overcurrent fault values, while also offering reference and assistance for electrical fire prevention and routine maintenance operations.

## 2. Materials

### 2.1 Main Equipment and Instruments

Electrical fire fault simulation and trace preparation apparatus: Specifically designed for studying fires caused by electrical line and accessory faults, comprising a power cabinet, control cabinet, and combustion chamber. Current adjustment range: 30-300 A; voltage adjustment range: 0-660 V (AC 50 Hz). Designed independently by China People's Police University.

Drying oven: DHG-9140C, Hangzhou Lantian Laboratory Instrument Factory.

Simultaneous thermal analyzer: STA 449 F5, NETZSCH Scientific Instruments Trading (Germany) Co., Ltd.

### 2.2 Sample Preparation Process

This study primarily investigates the evolution of pyrolysis characteristics of flame-retardant XLPE insulation under slight overcurrent faults as the overcurrent value increases, providing theoretical reference and data support for accurately identifying slight overcurrent faults and determining fault values. Accordingly, 40 cm segments of 2.5 mm<sup>2</sup> flame-retardant XLPE copper wire were connected to the electrical fire fault simulation and trace preparation apparatus, with current values set at 70 A, 80 A, 90 A, and 100 A, respectively. The wires were energized continuously for 1 hour to ensure thermal equilibrium between heating and heat dissipation, maintaining stable temperature conditions for an extended period. The entire sample preparation process was recorded using a conventional video camera. Flame-retardant XLPE copper wire samples under different slight overcurrent fault

conditions were obtained and sealed in polyethylene bags to maintain a clean and dry environment in Figure 1.

To achieve precise and uniform grinding of copper conductor insulation materials into powder form, the prepared samples with different slight overcurrent values were first stripped of insulation using wire cutters, ensuring complete separation between the insulation layer and internal conductor core. The outermost insulation layer was subjected to preliminary grinding, followed by precision grinding using an electric file to ensure uniform thickness of the ground outer insulation layer, with sample diameter controlled not to exceed 0.2 mm. For grinding the inner insulation layer, scissors were used to cut along the copper conductor insulation, which was then flattened and pressed using a tablet press, maintaining consistent pressure for each pressing operation and uniform flattened insulation thickness. The same grinding procedure was subsequently applied to the flattened insulation surface. Finally, after grinding both the inner and outer layers of the copper conductor insulation, the insulation powder was placed in a clean, dry petri dish and dried in a 90 °C oven for 12 hours to thoroughly remove moisture.



**Figure 1. Copper Wire Samples under Different Slight Overcurrent Conditions**

### 2.3 Thermal Analysis Experimental Method

Following the grinding preparation of copper conductor insulation materials, thermal analysis experiments were conducted. Sample mass for each experiment was controlled at 4±0.3 mg, with gas flow rate of 80 ml/min. Heating rates of 10, 20, 30, and 40 °C/min were selected, with a temperature range of 35-1000 °C. The FTIR pipeline cavity temperature was set at 220 °C to prevent condensation of pyrolysis gases. To more accurately analyze the influence of slight overcurrent on the pyrolysis process of flame-retardant XLPE in copper conductors, thermal analysis experiments were conducted under nitrogen atmosphere. To determine the specific reactions occurring during the pyrolysis process of flame-retardant XLPE copper conductor

insulation materials, four slow heating rates (10, 20, 30, and 40 °C/min) were selected to ensure experimental reliability. Based on preliminary experimental data analysis, the exothermic reaction was not completely terminated at a

pyrolysis temperature of 650 °C; therefore, the pyrolysis temperature range for this experiment was selected as 35-1000 °C to ensure complete pyrolysis reactions. The experimental scheme is presented in Table 1.

**Table 1. Thermal Analysis Experimental Scheme**

Test Sample	Atmosphere	Temperature Range (°C)	Heating Rate (°C/min)
Flame-retardant PE (0 A)	Nitrogen	35- 1000	10,20,30,40
Flame-retardant PE (70 A)	Nitrogen	35- 1000	10,20,30,40
Flame-retardant PE (80 A)	Nitrogen	35- 1000	10,20,30,40
Flame-retardant PE (90 A)	Nitrogen	35- 1000	10,20,30,40
Flame-retardant PE (100 A)	Nitrogen	35- 1000	10,20,30,40

**3. Results and Discussion**

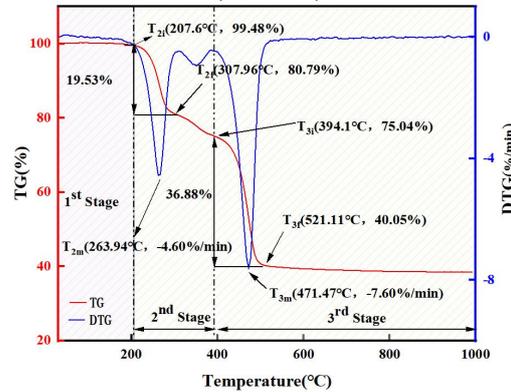
**3.1 Characteristic Temperatures of Pyrolysis for Flame-Retardant XLPE Wire Insulation Materials**

At a heating rate of 10 °C/min, the influence of temperature gradient and mass gradient on the sample during pyrolysis is minimal; therefore, a heating rate of 10 °C/min was selected for TG curves of copper conductor insulation materials under different slight overcurrent fault values to further investigate the variation of insulation material mass loss with increasing temperature. By differentiating the TG curves, DTG curves representing the mass loss rate of flame-retardant XLPE under different slight overcurrent fault values were obtained. Through TG-DTG curve analysis, the thermal weight loss stages and characteristic changes of flame-retardant XLPE copper conductor insulation were determined, including initial temperature, peak temperature, and final temperature of various characteristic changes, as well as mass loss conditions at each weight loss stage. Comparative analysis of thermal weight loss characteristics of flame-retardant XLPE insulation materials under different slight overcurrent values provides theoretical support for determining the variation patterns of thermal weight loss characteristics of insulation materials under different slight overcurrent values.

**3.1.1 Characteristic pyrolysis temperatures of unused wire insulation materials**

Figure 2 presents the TG-DTG curves of unused wire insulation material at a heating rate of 10 °C/min. Based on the curve characteristics, three distinct stages were identified, which can be classified according to characteristic temperatures as: initial mass loss temperature

(Ti), where the TG curve begins to decline (DTG=0); maximum mass loss temperature (Tm), where the TG curve reaches maximum slope (DTG at maximum value); and final mass loss temperature (Tf), where the TG curve becomes horizontal (DTG=0).

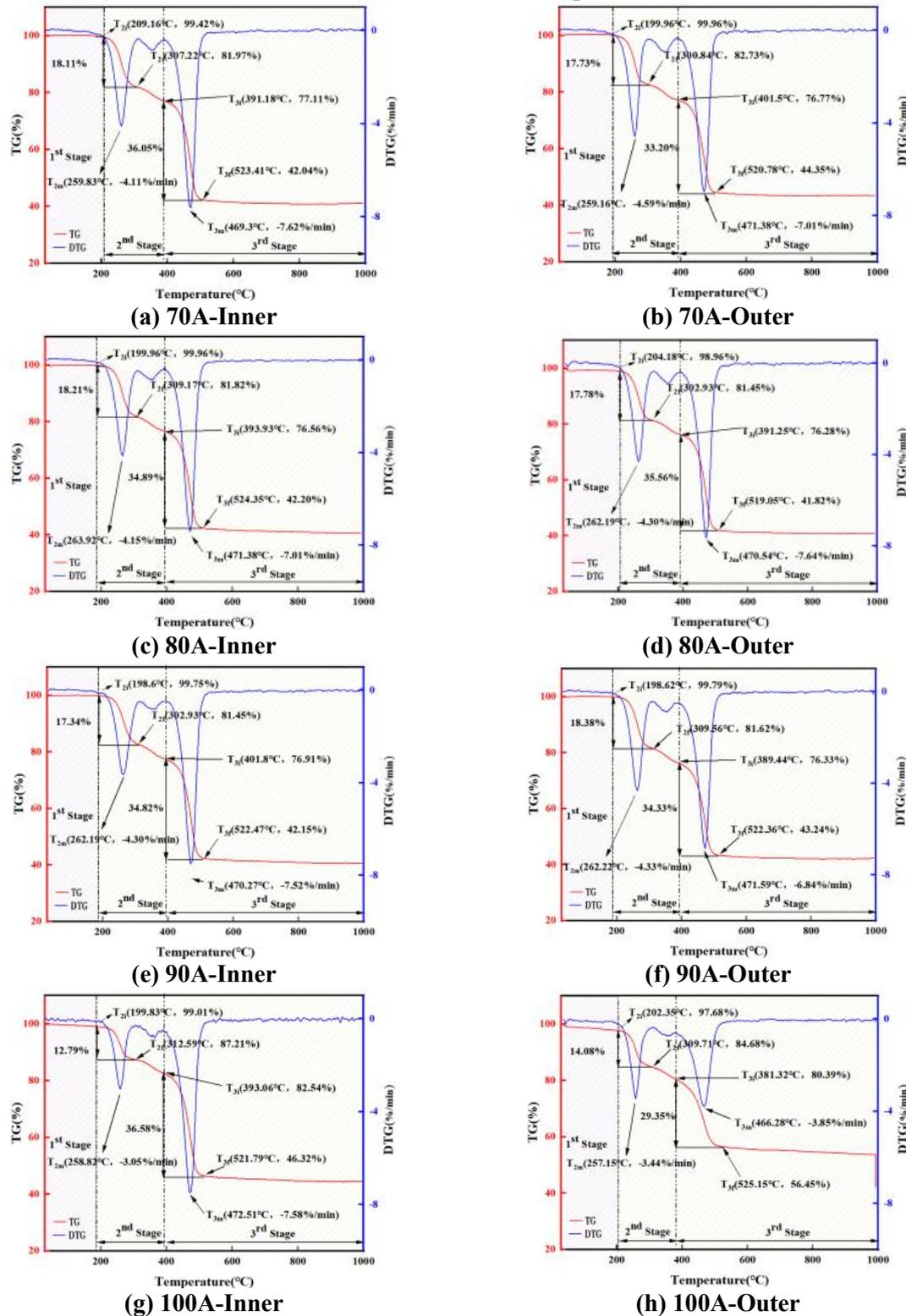


**Figure 2. TG-DTG Curves of Flame-Retardant Cross-Linked Polyethylene for Unused Copper Wire (10°C/min)**

Analysis of the TG-DTG curves in Figure 2 reveals that the thermal degradation process of unused flame-retardant XLPE copper conductor can be divided into three stages, with the main thermal degradation processes occurring in the second and third stages. In the first stage, at approximately 200 °C, the TG curve begins to decline, initiating the thermal degradation process with mass loss of approximately 0.5%, primarily due to evaporation of moisture and light volatiles. In the second stage, a distinct mass loss of 19.53% was observed, with the maximum mass loss temperature reaching 263.94 °C and corresponding DTG of -4.6 °C/min. In the third stage, the flame-retardant material exhibited a mass loss rate of 36.88%, significantly higher than that of the second stage, indicating that a more intense pyrolysis process occurred in unused flame-retardant XLPE copper conductor after 394.1 °C.

flame-retardant XLPE wire insulation materials

under slight overcurrent



**Figure 3. TG-DTG Curves of Flame-Retardant Cross-Linked Polyethylene for Copper Wire Subjected to Slight Overcurrent (10 °C/min)**

Analysis of the curves in Figure 3 indicates that the thermal degradation process of flame-retardant XLPE subjected to four slight overcurrent values (70 A, 80 A, 90 A, and 100 A) can be divided into three stages, with the main

thermal degradation processes also occurring in the second and third stages. In the first stage, accompanied by the release of moisture and light volatiles, the mass loss rate of the insulation layer was approximately 5%, with temperatures

primarily concentrated below 200 °C. In the second stage, the inner layer of flame-retardant XLPE insulation material under the four slight overcurrent values underwent pyrolysis at approximately 200 °C, with mass loss rates of 18.11%, 18.21%, 17.34%, and 12.79%, respectively. It can be observed that when the slight overcurrent values ranged from 70-90 A, the mass loss rate of the insulation material stabilized at approximately 18%, whereas at 100 A, the mass loss rate showed significant reduction. In the third stage, pyrolysis of flame-retardant XLPE insulation material primarily occurred at 390-400 °C, with mass loss rates of 36.05%, 34.89%, 34.82%, and 36.58%, respectively, indicating relatively stable mass loss rates under these four slight overcurrent values. Comparative analysis further reveals that the mass loss rate in the third stage was significantly higher than that in the second stage. Table 2 and Table 3 list the characteristic temperatures and corresponding times for the second and third pyrolysis stages of 0 A, 70 A, 80 A, 90 A, and 100 A samples at a heating rate of 10 °C/min. The second stage temperature

range is primarily 200-310 °C, while the third stage temperature range is mainly 320-530 °C, with the intermediate region considered as the transition zone between the second and third stages. For the 100 A sample, the characteristic temperature points shifted forward, particularly in the third stage, advancing by nearly 10 °C compared to other slight overcurrent values. The primary reason for this phenomenon is the preheating effect of slight overcurrent on the insulation material; as the slight overcurrent increases, more Joule heat is generated, further elevating the temperature and causing more pronounced damage to the insulation material. At a heating rate of 10 °C/min, the pyrolysis process of both inner and outer surface layers of the insulation material can be divided into two stages. The initial and final characteristic temperature points of the second and third stages and the characteristic temperature points at maximum mass loss are essentially consistent, and as the slight overcurrent value increases, the characteristic temperature points of pyrolysis on the same side surface all shift forward.

**Table 2. Characteristic Temperature Points of Copper Conductor Samples under Different Slight Overcurrent Values at 10 °C/min Heating Rate for Pyrolysis Stage 2**

$\beta = 10$ (°C min <sup>-1</sup> )	Tinitial (°C)	Tmax (°C)	Tfinal (°C)	DTGmax (% min <sup>-1</sup> )	Timeinitial (min)	Timemax (min)	Timefinal (min)	$\Delta m$ (%)
0 A	207.6	263.94	307.96	-4.60	18.20	23.45	27.69	19.53
70A-Inner	209.16	259.83	307.22	-4.11	18.34	23.05	27.62	18.11
70A-Outer	199.96	259.16	300.84	-4.59	17.51	22.98	26.99	17.73
80A-Inner	200.39	263.92	309.17	-4.15	17.59	23.47	27.83	18.21
80A-Outer	204.18	262.19	302.93	-4.30	17.94	23.30	27.21	17.78
90A-Inner	198.6	261.39	309.63	-3.71	17.44	23.25	27.9	17.34
90A-Outer	198.62	262.22	309.56	-4.33	17.44	23.33	27.9	18.38
100A-Inner	199.83	258.82	312.59	-3.05	17.51	22.98	28.18	12.79
100A-Outer	202.35	257.15	309.71	-3.44	17.79	22.84	27.9	14.08

**Table 3. Characteristic Temperature Points of Copper Conductor Samples under Different Slight Overcurrent Values at 10 °C/min Heating Rate for Pyrolysis Stage 3**

$\beta = 10$ (°C min <sup>-1</sup> )	Tinitial (°C)	Tmax (°C)	Tfinal (°C)	DTGmax (% min <sup>-1</sup> )	Timeinitial (min)	Timemax (min)	Timefinal (min)	$\Delta m$ (%)
0 A	394.10	471.47	521.11	-7.60	36.28	44.1	49.11	36.88
70A-Inner	391.18	469.3	523.41	-7.62	35.99	43.89	49.35	36.05
70A-Outer	401.5	471.38	520.78	-7.01	37.03	44.1	49.08	33.20
80A-Inner	393.93	471.43	524.35	-7.42	36.27	44.1	49.43	34.89
80A-Outer	391.25	470.54	519.05	-7.64	36.00	44.02	48.91	35.56
90A-Inner	401.8	470.27	522.47	-7.52	37.1	44.02	49.28	34.82
90A-Outer	389.44	471.59	522.36	-6.84	35.38	44.16	49.28	34.33
100A-Inner	393.06	472.51	521.79	-7.58	36.21	44.23	49.21	36.58
100A-Outer	381.32	466.28	525.15	-3.85	35.03	43.61	49.56	29.35

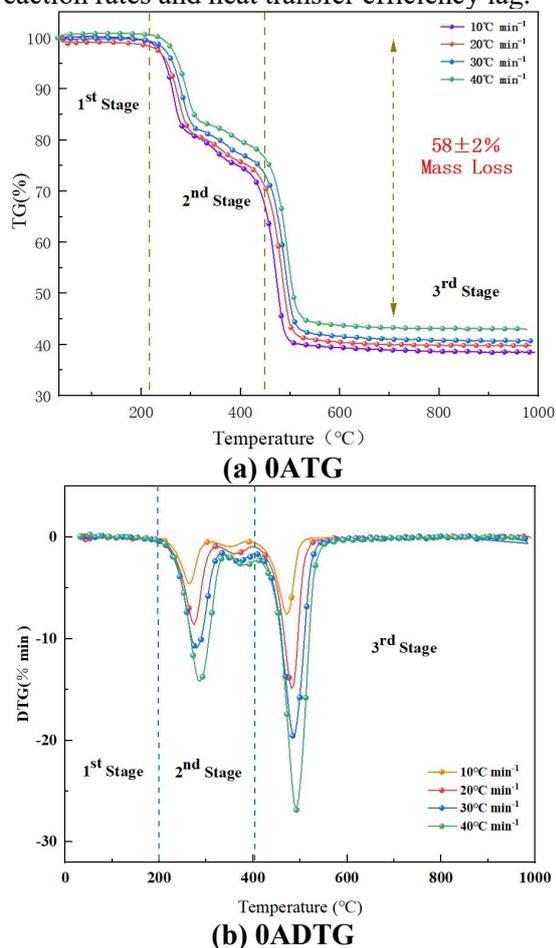
### 3.2 Influence of Heating Rate on Thermal Weight Loss Process of Insulation Materials

#### 3.2.1 Influence of heating rate on thermal weight loss of unused wire insulation materials

The mass loss and mass loss rate curves of unused copper conductor insulation materials at four different heating rates (10, 20, 30, and 40 °C/min) are shown in Figure 4. Analysis

reveals that the pyrolysis curves can be primarily divided into three stages with two thermal weight loss stages. Comparative horizontal analysis of TG and DTG curves of copper conductor insulation materials under different slight overcurrents shows that as the heating rate increases, the curves shift overall toward the high-temperature side, with the initial

temperature ( $T_i$ ), peak temperature ( $T_m$ ), final temperature ( $T_f$ ), and DTGm of each weight loss stage also increasing overall. Further analysis of the overall shift of thermogravimetric curves toward the high-temperature side suggests that this phenomenon may be caused by accelerated reaction rates and heat transfer efficiency lag.



**Figure 4. TG and DTG Curves of Unused Wire Insulation Material at Different Heating Rates**

### 3.2.2 Influence of heating rate on thermal weight loss process of flame-retardant XLPE wire insulation materials under slight overcurrent

The mass loss and mass loss rate curves of flame-retardant XLPE copper conductor insulation materials under different slight overcurrent values at four heating rates (10, 20, 30, and 40 °C/min) are shown in Figure 5. It can be observed that under different heating rates, the pyrolysis curves of insulation materials exhibit similar variation trends, primarily characterized by two thermal weight loss stages. Comparative analysis of TG and DTG curves of copper conductor insulation materials under different slight overcurrents reveals that as the heating rate increases, the thermogravimetric

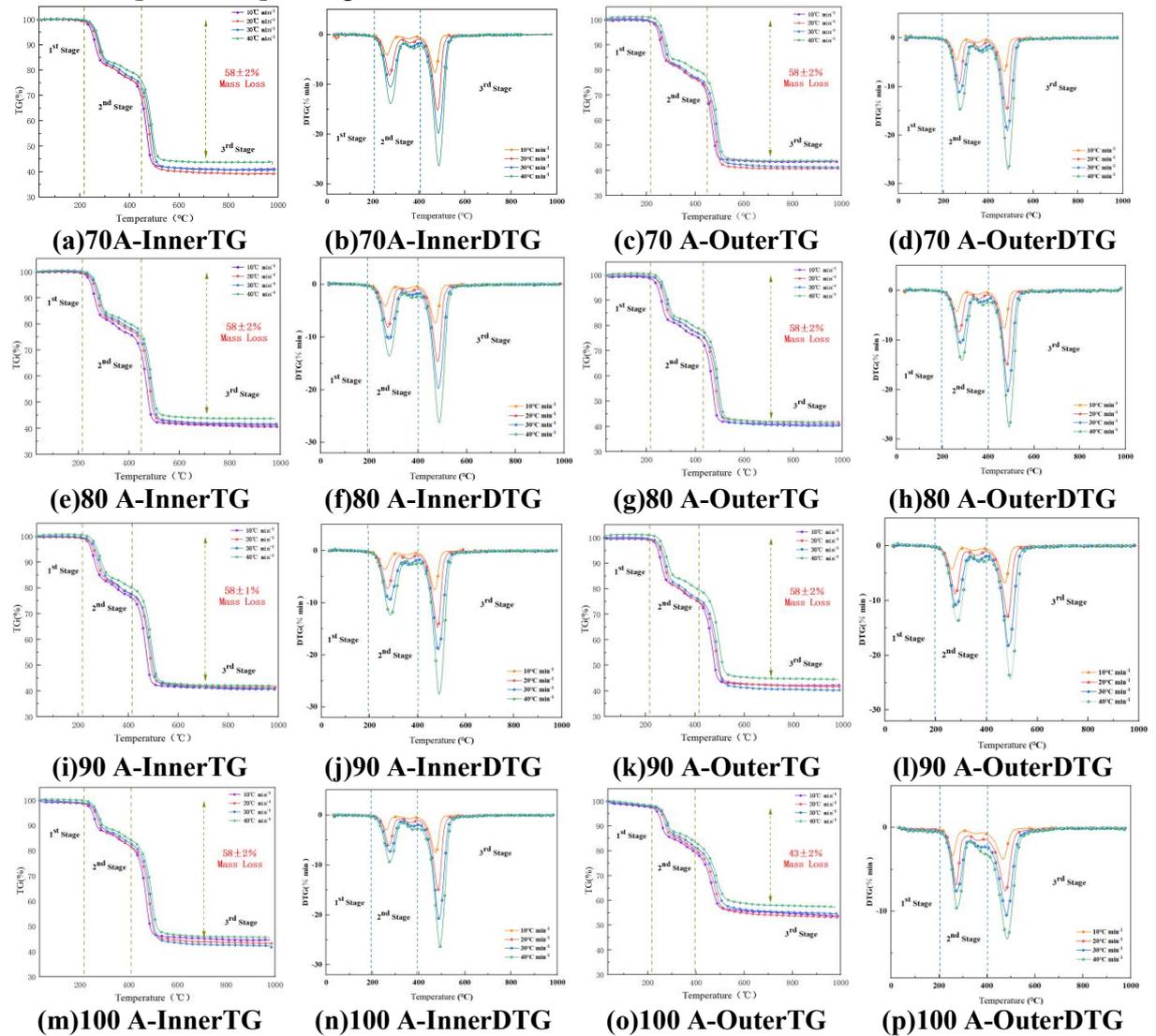
curves shift overall toward the high-temperature side. When the heating rate increased to 20 °C/min, the overall shift reached its maximum value; when further increased to 30 °C/min, the two TG curves nearly overlapped, showing differences only in the later stage of the second weight loss stage, indicating that the 20 °C/min heating rate may have approached the maximum pyrolysis state of flame-retardant XLPE insulation material. Comparative analysis shows that at a heating rate of 40 °C/min, the thermogravimetric curves shifted significantly toward the high-temperature side, possibly due to excessively rapid heating rates and heat transfer lag, while not excluding the possibility of baseline errors under the same heating rate in nitrogen atmosphere.

Analysis of Figure 5 reveals that copper conductor insulation materials under different slight overcurrent values all underwent two thermal weight loss stages, with the total mass loss of both stages stabilizing at  $58\pm 2\%$  and the final residue averaging 42%. Furthermore, the residue amounts under different heating rates were nearly identical, indicating that heating rate has minimal effect on residue amount. Additionally, 90% of the total mass loss occurred within the temperature range of 200-520 °C, with minimal mass loss occurring before and after this range. Therefore, it can be inferred that the main pyrolysis reaction stage of copper conductor insulation materials under different slight overcurrent values occurs within the temperature range of 200-520 °C. Notably, although the outer layer of 100 A copper conductor insulation material also experienced two thermal weight loss stages, the total mass loss was  $43\pm 2\%$ , significantly lower than that of other types of conductor insulation materials, indicating higher final residue remaining than other conductor types, possibly due to excessively rapid heating rates or significant changes in the properties of the outer insulation material of copper conductor at 100 A.

Comparative analysis of DTG curves of copper conductor insulation materials under different slight overcurrents reveals that pyrolysis of copper conductor insulation materials under different slight overcurrent values primarily exhibits two peaks. At a heating rate of 10 °C/min, the mass loss peak value was minimal. However, as the heating rate continuously increased, the peak values also increased, showing a trend of shifting toward the

high-temperature side. Notably, comparative analysis indicates that the degree of peak shift in the first weight loss stage of DTG curves of copper conductor insulation materials under different slight overcurrents was greater than that in the second weight loss stage, but the peak values in the second weight loss stage were generally higher than those in the corresponding first stage, and the increase in peak values in the second weight loss stage was greater than that in

the first stage. Notably, for the DTG curve of the outer layer of 100 A copper conductor insulation material, although it also exhibited two peaks following the trend of shifting toward the high-temperature side, the peak values in both pyrolysis stages showed minimal variation, without the phenomenon of significant increase in the second pyrolysis stage compared to the first stage.



**Figure 5. TG and DTG Curves of Wire Insulation Material Subjected to Slight Overcurrent at Different Heating Rates**

**4. Conclusions**

This study investigated flame-retardant XLPE insulated cables subjected to different slight overcurrent fault treatments, primarily employing theoretical analysis methods to thoroughly examine the pyrolysis behavior of flame-retardant XLPE under different slight overcurrent faults, providing theoretical

reference and data support for identifying slight overcurrent faults in conductors and accurately determining slight overcurrent fault values. The main conclusions are as follows:

The pyrolysis process of flame-retardant XLPE wire insulation materials can be divided into three stages, with the total mass loss of the two thermal weight loss stages stabilizing at 58±2% and the final residue averaging 42%.

Approximately 90% of the total mass loss occurs within the temperature range of 200-520 °C. As slight overcurrent increases, the characteristic temperature points of pyrolysis on the same side surface of copper conductor insulation materials all shift forward, particularly for the 100 A sample in the third stage, where the characteristic temperature points advance by nearly 10 °C compared to other slight overcurrent values. Pyrolysis of copper conductor insulation materials under different slight overcurrent values primarily exhibits two peaks; as the heating rate continuously increases, the peak values also increase, showing a trend of shifting toward the high-temperature side. At a heating rate of 10 °C/min, the mass loss peak value is minimal, while the 20 °C/min heating rate essentially approaches the maximum pyrolysis state.

To further determine the critical slight overcurrent value for changes in pyrolysis kinetic parameters of flame-retardant XLPE, the differences in pyrolysis kinetic parameters between the inner and outer layers of conductor insulation were analyzed. This may be due to the increase in copper conductor temperature, causing the internal conductor core to enter the temperature rise process before the external insulation material, with temperature higher than that of the outer insulation layer. When the copper conductor insulation material was subjected to 100 A, obvious discoloration appeared on the exterior, and the insulation structure underwent relatively significant pyrolysis and damage. It is determined that the critical current value for changes in pyrolysis kinetic parameters of flame-retardant XLPE is near 100 A, but the accuracy of identifying flame-retardant XLPE in copper conductors subjected to slight overcurrent faults below 100 A is not high.

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