Science and Technology Indonesia
e-ISSN:2580-4391 *p*-ISSN:2580-4405
Vol. 9, No. 3, July 2024

Research Paper

Electromigration Effects in Overcurrent PVC-Insulated Copper Wire: Failure and Deformation Impacts

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Abstract

Electromigration is a critical issue in materials science and electrical engineering, significantly impacting the reliability and efficiency of electrical systems. This study investigates the electromigration behavior of PVC-insulated copper wires under various overcurrent conditions, focusing on material degradation and electrical performance. Copper cables, identified as 046620.3 Eterna CU/PVC 1.5 mm^2, were subjected to currents ranging from 0 to 110 A. The mean time to failure (MTTF) was calculated using Black's equation, revealing a sharp decline in MTTF with increasing current density. Surface morphology analysis using SEM showed the formation of voids and hillocks at higher currents, indicating severe electromigration damage. XRF analysis demonstrated significant changes in the elemental composition, particularly a reduction in copper content and an increase in chlorine and other elements, suggesting degradation of the PVC insulation. FTIR spectroscopy revealed substantial chemical changes in the PVC material, especially under extreme overcurrent conditions, highlighting dehydrochlorination and carbonyl group formation. There is a clear relationship between overcurrent conditions and electromigration phenomena, as evidenced by the observed damage to surface morphology, changes in elemental composition, and alterations in the chemical structure of PVC. The mechanisms and causes of electromigration are explained comprehensively in this work, illustrating how increased overcurrent accelerates the electromigration process, leading to the formation of voids and hillocks in the copper conductor. This damage is accompanied by a significant reduction in copper content and an increase in chlorine levels, indicating the degradation of PVC insulation. FTIR spectra further confirmed these findings by showing chemical changes such as dehydrochlorination and carbonyl group formation under high current stress. The MTTF values reflect the severity of these impacts, with samples exposed to higher currents showing drastically reduced lifespans. For instance, samples subjected to 100 A and 110 A currents exhibited MTTF values of 0.2 minutes and 0.004 minutes, respectively.

Keywords
Electromigration, Overcurrent, Copper Wires, PVC Insulation, Electrical Reliability

Received: 22 March 2024, Accepted: 5 June 2024
https://doi.org/10.26554/sti.2024.9.3.735-744

1. INTRODUCTION

Electromigration is a significant phenomenon in materials science and electrical engineering, where the momentum transfers from conducting electrons to metal atoms causes gradual displacement of the metal (Ho et al., 2022). This process typically occurs in metal conductors, such as copper wires, when they are subjected to high-density electric currents (Zahedmaesh et al., 2021). The relentless movement of electrons can dislodge metal atoms from their lattice sites, leading to the formation of voids and hillocks within the conductor (Huang et al., 2024). Over time, these structural anomalies can accumulate, resulting in increased electrical resistance, localized heating, and ultimately, failure of the conductor. In practical applications, such as in microelectronic devices and power distribution systems, electromigration-induced degradation can compromise the reliability and efficiency of the entire system. For instance, in integrated circuits, the formation of voids can interrupt electrical pathways, causing open circuits, while hillocks can create short circuits by bridging adjacent conductors (Kurukuru and Khan, 2022). In power cables, these effects can lead to catastrophic failures, especially under conditions of overcurrent, where the current exceeds the designed capacity of the wire, exacerbating the electromigration effects. The severity of electromigration is influenced by several factors, including the temperature, current density, and the materials used in the conductor and its insulation (Andritsos et al., 2020; Hasan et al., 2021). Higher temperatures and current densities accelerate the diffusion of metal atoms, while the choice of insulating material can impact the thermal and electrical stress experienced by the conductor (Humaidi et al., 2023).

For example, PVC insulation is widely used due to its good electrical insulating properties and cost-effectiveness. However, under overcurrent conditions, PVC can degrade, leading to increased thermal stress and further accelerating electromigration in the underlying copper wire (Nassiet et al., 2021). The degradation of PVC typically begins with the softening of the material, followed by thermal decomposition, which releases hydrochloric acid and other byproducts (Zheng et al., 2023). These byproducts can chemically interact with the copper wire, exacerbating corrosion and creating additional pathways for electron movement, thereby intensifying the electromigration process (Patil et al., 2021). Additionally, the thermal expansion mismatch between the PVC insulation and the copper wire can induce mechanical stresses, promoting the formation of cracks and voids in the insulation (Deng et al., 2023; Mokryak et al., 2022). These defects can expose the copper wire to the environment, increasing the risk of oxidation and further deterioration.

Several methods have been proposed and investigated to address the effects of electromigration in electrical wiring. Initial studies primarily focused on the metallurgical aspects, analyzing the microstructural changes in copper due to electromigration (Huang et al., 2024). Researchers observed that electromigration causes voids and hillocks in the metal lattice, leading to increased electrical resistance and potential failure. Advanced research expanded to explore various insulation materials, with PVC being a common choice due to its cost-effectiveness and decent insulating properties (Grosu, 2022). These studies aimed to find insulation materials that could withstand higher temperatures and reduce the thermal stress on copper wires. Recent advancements have incorporated real-time monitoring and predictive modeling techniques, enabling the anticipation and prevention of electromigration-induced failures before they become critical (Li et al., 2024a; Wang et al., 2023; Zhang et al., 2021).

Among the existing solutions, the incorporation of alloying elements in copper wires has shown promise in mitigating electromigration effects. Studies have demonstrated that adding small amounts of elements like silver or magnesium can significantly enhance the resistance to electromigration (Almaghamsi, 2024). These alloying elements help to stabilize the copper matrix, reduce atomic diffusion rates, and improve the overall durability of the wires under high current densities. Additionally, researchers have explored the use of more robust insulation materials, such as cross-linked polyethylene (XLPE), which offers superior thermal and electrical endurance compared to PVC (Li et al., 2024b). XLPE insulation can withstand higher temperatures and provides better protection against thermal degradation, thus reducing the rate of electromigration in the underlying copper wire. However, these methods often introduce complexities in manufacturing and cost, limiting their widespread adoption. The addition of alloying elements requires precise control over the composition and processing of the copper wires, which can increase production costs. Similarly, while XLPE offers enhanced performance, it is more expensive and challenging to process than PVC, making it less attractive for cost-sensitive applications. As a result, there is a need for a balanced approach that combines effective electromigration mitigation with practical considerations of manufacturing feasibility and cost.

Despite these advancements, previous research has limitations. Many studies focus on either the material properties or the electrical performance, rarely integrating both aspects comprehensively. Moreover, most research has been conducted under ideal laboratory conditions, which do not fully represent real-world operating environments where variables such as fluctuating temperatures and mechanical stresses come into play. A few researchers have focused on the real-time degradation patterns in PVC-insulated wires, yet there is a lack of studies addressing the combined impact of overcurrent and electromigration in these systems. Therefore, this research intends to fill this gap by investigating the electromigration behavior of PVC-insulated copper wires under overcurrent conditions, emphasizing both material degradation and electrical performance in realistic operating scenarios. The objectives of this research are to elucidate the mechanisms of failure and deformation due to electromigration, propose improved wire compositions and insulation strategies, and develop predictive models to enhance the reliability of electrical systems. This study aims to provide a comprehensive understanding the detrimental effects of electromigration in everyday electrical applications.

2. EXPERIMENTAL SECTION

2.1 Materials

The samples used in this study are copper (Cu) cables insulated with Polyvinyl Chloride (PVC), measuring 1×1.5 mm (NYA). These cables are specifically identified as brand 046620.3 Eterna CU/PVC 1.5 mm^2 450/7500 NYA and Current injector TnR PCU 2 MKS CT Ratio 500/5A. These cables are commonly used for electrical installations in homes or medium-sized buildings.

2.2 Methods

In this research, six different treatments were applied to the samples, with each sample coded as CPC-x, where "x" denotes the current strength applied: 0, 21, 50, 70, 100, and 110 A, respectively. The current received by each sample was adjusted using a series of resistors. For currents above 24 A, the electrical circuit was equipped with a current injector to achieve and maintain the desired current value. The electrocution scheme is illustrated in Figure 1. To ensure that the test duration for each sample is 5 minutes, a stopwatch is used during the testing process.

The electromigration was analyzed by calculating the mean time to failure (MTTF) in hours using Equation (1) (Black's equation), where C is a proportional constant (value set to 1),

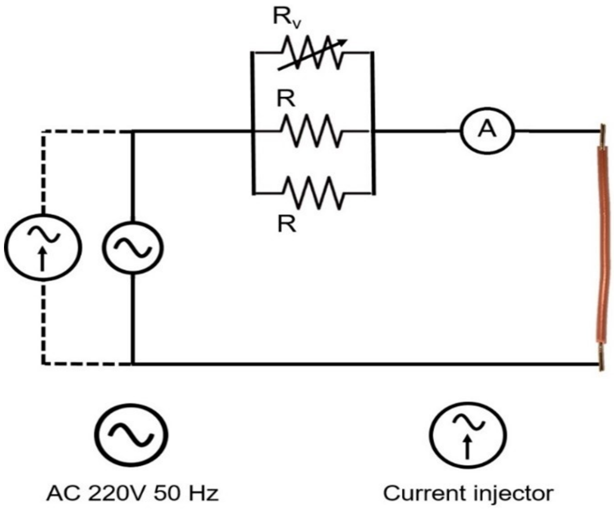

Figure 1. Electrical Circuit Schematic for Electrocuting PVC-Insulated Copper Wires

Ea is the activation energy (1.84250355×10^{-19} J), n is the diffusion constant (value of 2, according to Tu and Gusak (2020)), K is the Boltzmann constant (1.38×10^{-23} J/K), T is the sample temperature in Kelvin, and J is the current density. The current density J (A/m^2) is calculated using Equation (2), where I and A are the electric current (A) and the cross-sectional area of the sample (m^2), respectively.

This analysis helps in understanding the electromigration behavior and predicting the mean time to failure of the samples. Next, the surface morphology of the samples is examined using a scanning electron microscope (SEM) Zeiss EVO MA10, 200 V to 30 kV. This analysis focuses on identifying morphological changes such as the formation of hillocks and voids, which are typical indicators of electromigration-induced damage. Following the SEM analysis, changes in the elemental composition of the samples are investigated using X-ray fluorescence (XRF) Torontech Scopex ROHS Analyzer, Up to 50 kV, 100 W. This technique provides insights into the diffusion of metal atoms and any compositional alterations resulting from electromigration. Lastly, alterations in the chemical structure of PVC insulation are examined using Fourier Transform Infrared (FTIR) Spectroscopy The Agilent Cary 670, 9000-375 cm^{-1}. This analysis detects any chemical changes in the PVC material due to the thermal and electrical stresses induced by electromigration.

$$\text{MTTF} = \frac{C}{J^n}.e^{\frac{E_a}{kT}} \tag{1}$$

$$J = \frac{I}{A} \tag{2}$$

3. RESULTS AND DISCUSSION

3.1 Electromigration Phenomenon of Overcurrent PVC-Insulated Copper Wires

Electromigration is a critical phenomenon that occurs in metal conductors under high-density electric currents. It involves the gradual displacement of metal atoms due to the momentum transfer from conducting electrons. This displacement leads to the formation of voids and hillocks, which increase electrical resistance and can ultimately cause the failure of the conductor. Electromigration is particularly problematic in applications where reliability and longevity of electrical components are paramount, such as in microelectronic devices and power distribution systems.

The cross-sectional area of a cable is a crucial parameter in analyzing its electrical properties, such as current density. For a cable with a diameter of 1.5 mm, the cross-sectional area can be calculated using Equation (3) as the formula for the area of a circle, where r is the radius of the cable. Given that the diameter is 1.5 mm, the radius r is half of the diameter, which is 0.75 mm. Substituting this value into the formula, the cross-sectional area A is:

$$\begin{aligned} A &= \pi.r^2 \\ A &= 3.14159 \times (0.75 \text{ mm}) \\ A &= 1.76715 \text{ mm}^2 \end{aligned} \tag{3}$$

Therefore, the cross-sectional area of the cable is approximately 1.76715 mm^2. This precise calculation is essential for determining the current density in the cable, which is a key factor in the study of electromigration effects. The mean time to failure (MTTF) data for PVC-insulated copper wires under different electrical currents are presented in Table 1. With no applied current, the MTTF of CPC-0 is infinite, indicating that without electrical stress, the wires can theoretically last indefinitely. This serves as a baseline for comparing the effects of various current levels on the electromigration process.

As the current increases, the MTTF decreases significantly, illustrating the direct impact of current density on the lifespan of the wires. For instance, CPC-21, which is subjected to a current of 21 A, has a current density of 11,883,541.3 A/m^2 and an MTTF of approximately 3,173 hours (or about 1,142,276,446 seconds). This considerable lifespan under a relatively low current density is consistent with previous studies, such as those by Zitao et al. (2021), who reported similar lifespans for copper interconnects under moderate current densities.

The sample CPC-50, with a current of 50 A and a current density of 28,294,145.94 A/m^2, shows a drastic reduction in MTTF to approximately 1.2 hours (or about 4,325.55 seconds). This sharp decline is indicative of the increased stress and accelerated electromigration at higher current densities. Prasad et al. (2023) similarly observed that higher current densities lead to rapid degradation and failure of metal conductors, reinforcing the critical influence of current density on

Table 1. Mean Time to Failure of Overcurrent PVC-Insulated Copper Wires

Samples	Electrical Currents (A)	Current Densities (A/m^2)	MTTF (Hours)	MTTF (Seconds)
CPC-0	0	0	∞ (infinity)	∞ (infinity)
CPC-21	21	11883541.3	3172.990128	11422764.46
CPC-50	50	28294145.94	1.201540439	4325.545579
CPC-70	70	39611804.32	6.73072×10^{-5}	0.242305974
CPC-100	100	56588291.88	7.91641×10^{-11}	2.84991×10^{-7}
CPC-110	110	62247121.07	4.60088×10^{-12}	1.65632×10^{-8}

electromigration rates. Further increasing the current to 70 A (CPC-70) results in a current density of 39,611,804.32 A/m^2 and an MTTF of just 67.3 microseconds (0.242 seconds). The near-instantaneous failure under these conditions highlights the severe impact of high current densities on the structural integrity of the copper wires. This phenomenon is supported by Tu and Gusak (2020) findings, which demonstrate that extreme current densities can cause immediate and catastrophic electromigration effects.

At even higher currents, such as 100 A (CPC-100) and 110 A (CPC-110), the current densities reach 56,588,291.88 A/m^2 and 62,247,121.07 A/m^2, respectively. The MTTF for these samples plummets to nanosecond and picosecond ranges, illustrating the unsustainable conditions these wires face under such electrical loads. The data for CPC-100 shows an MTTF of approximately 7.9×10^{-11} hours (or 2.85×10^{-7} seconds), while CPC-110 has an MTTF of about 4.6×10^{-12} hours (or 1.66×10^{-8} seconds). These findings align with the theoretical predictions and empirical data from other high-stress electromigration studies, underscoring the critical thresholds beyond which copper wires cannot maintain their integrity (Zhang et al., 2021).

The correlation between current density and MTTF observed in this study is consistent with the results of prior research. One such study is by Zhao et al. (2024), Their research delves into the reliability of electronic packaging under harsh conditions, specifically the exposure to fire smoke. The study's findings highlight how environmental factors and material interactions critically influence the failure mechanisms of electronic components, reinforcing the importance of studying electromigration under various conditions to understand and mitigate its effects. Relating these findings to the current research on PVC-insulated copper wires, several parallels can be drawn. Zhao et al. (2024) work on the failure mechanisms of BGA packages under fire smoke atmospheres demonstrates the significant impact of environmental factors and material interactions on electronic component failure. Similarly, our study emphasizes the detrimental effects of overcurrent conditions on PVC-insulated copper wires, where the degradation of PVC insulation exacerbates electromigration, leading to accelerated failure.

Another relevant study by Ceric et al. (2023), they employed physics-based modeling and simulation to analyze the statistical properties of electromigration failure and the influence of varying temperature and geometric properties. Their comprehensive analysis revealed that temperature and current density significantly impact the mean failure time and the associated standard deviation, aligning with experimental observations. Ceric et al. (2023) statistical analysis of electromigration in gold interconnects further supports the notion that material properties and current density are pivotal in determining the MTTF. Just as gold interconnects show varied failure times based on temperature and current density, this study results indicate that higher current densities drastically reduce the MTTF of copper wires. This is evident in the steep decline in MTTF from 3,173 hours at a current density of approximately 11.9×10^6 A/m^2 (CPC-21) to mere fractions of a second at current densities above 28.3×10^6 A/m^2 (CPC-50 and higher). The exponential decrease in MTTF with increasing current density corroborates the predictions made by Black's equation and is well-documented in the literature (Waliullah et al., 2024). For example, Black's equation, as used in this study, accurately predicts the catastrophic failure times observed at higher currents, reflecting the significant impact of current density and temperature on the electromigration process.

3.2 Surface Morphology

The surface morphology of PVC-insulated copper wires under various overcurrent conditions was examined using scanning electron microscopy (SEM). Figure 2 presents SEM images for each sample, providing detailed insights into the changes in surface structure due to electromigration and thermal stress. The SEM image of CPC-0 reveals a pristine surface morphology with no observable defects. The surface remains smooth, indicating that in the absence of electrical current, the copper wire maintains its structural integrity. This serves as a control reference, showing that without the influence of current-induced electromigration or thermal stress, the wire remains undamaged.

For CPC-21, the SEM image shows a surface that does not experience significant defects. There are only minor spots that do not indicate substantial damage. The temperature of the cable when the current is applied reaches 55°C, which is relatively low and does not induce notable structural changes.

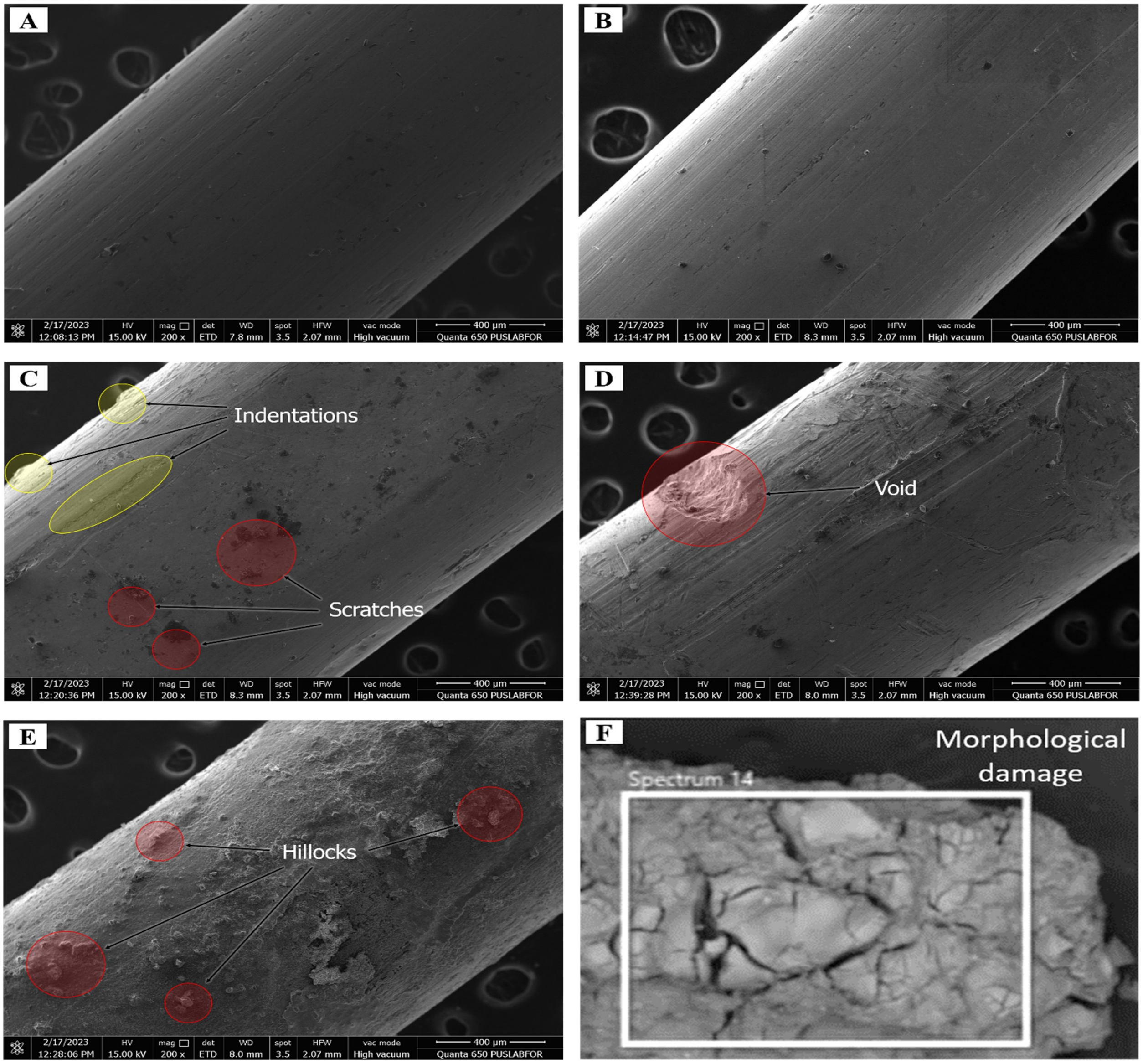

Figure 2. SEM Images of Overcurrent PVC-Insulated Copper Wires with Electrical Currents: 0 A (A), 21 A (B), 50 A (C), 70 A (D), 100 A (E), and 110 A (F)

This aligns with the MTTF data, which shows a relatively long lifespan under moderate current density, indicating that the wire can withstand such conditions without severe morphological alterations. The surface morphology of CPC-50 starts to show more prominent changes. The SEM image reveals a few spots on the surface. When the current is applied, this cable emits thin smoke, and the temperature reaches 114°C. This higher temperature begins to cause minor thermal degradation of the PVC insulation and slight surface irregularities in the copper wire (Bonardo et al., 2023; Li et al., 2024b). The emission of smoke suggests that the PVC insulation is starting to decompose, releasing byproducts that can exacerbate electromigration stage by introducing contaminants and additional stresses on the copper wire (Kotsovinos et al., 2020).

At a current of 70 A, the SEM image for CPC-70 shows a significantly rougher surface with several scratches and indentations. The presence of voids is also identified, indicating damage that creates holes in the copper wire. These voids are a direct consequence of electromigration, where the momentum transfer from conducting electrons displaces metal atoms, leading to the formation of voids. The temperature of the cable reaches a level where substantial thermal stress contributes to these morphological changes (Deng et al., 2023). This roughened surface and the formation of voids correlate with the sharply reduced MTTF, highlighting the severe impact of higher current densities. The SEM image of CPC-100 shows an even rougher surface morphology with several hillocks identified. These hillocks are formations caused by the accumulation of displaced metal atoms, which is a typical characteristic of electromigration. The temperature reaches an extreme of 800°C, causing the PVC insulation to degrade significantly and leading to intense thermal stress on the copper wire. The presence of numerous voids, although smaller and more evenly distributed, indicates continuous and accelerated electromigration (Prasad et al., 2023). These observations are consistent with the near-instantaneous MTTF recorded, reflecting the unsustainable conditions at such high current densities.

For CPC-110, the SEM image depicts a destroyed surface morphology with no recognizable normal structure. The surface is highly irregular with hillocks scattered throughout. The temperature under this condition reaches an alarming 1091°C, leading to the burning of the sample. This extreme thermal environment causes the PVC insulation to completely fail and exacerbates the formation of voids and hillocks. The severe morphological damage observed confirms the catastrophic impact of extreme overcurrent conditions, which align with the minimal MTTF values, essentially rendering the wire nonfunctional almost instantaneously (Ho et al., 2022; Zahedmaesh et al., 2021).

The observed changes in surface morphology across the different samples illustrate the progressive impact of increasing current densities and temperatures on PVC-insulated copper wires. The formation of voids and hillocks, as seen in the SEM images, are hallmark indicators of electromigration. The voids are caused by the migration of copper atoms from high-current-density regions, leading to gaps that weaken the wire. Concurrently, hillocks form where displaced atoms accumulate, creating protrusions that can disrupt the integrity of the conductor.

The environmental and material factors critically influence failure mechanisms. In our study, the degradation of PVC insulation under high temperatures exacerbates electromigration, similar to how smoke particles affected the BGA packages (Zhao et al., 2024). The thermal decomposition of PVC at high currents releases byproducts that further stress the copper wire, akin to the corrosion products observed by Zhao et al. (2024). in fire smoke atmospheres. The higher current densities and temperatures drastically reduce the MTTF in metallic interconnects due to accelerated electromigration.

3.3 Changes in The Elemental Composition

The elemental composition of PVC-insulated copper wires was analyzed using X-ray fluorescence (XRF) to understand the impact of electromigration under various overcurrent conditions. Table 2 presents the concentration of various elements in parts per million (PPM) for each sample. In the CPC-0 sample, copper concentration is high (98969 PPM), which is expected in an unaltered copper wire. However, in CPC-50, the copper content drops significantly to 59926 PPM, indicating severe copper loss due to electromigration. This loss is exacerbated at higher temperatures and currents, with CPC-100 showing a reduction to 73075 PPM. Surprisingly, CPC-110 shows a dramatic increase to 881278 PPM, which suggests possible contamination or measurement anomalies due to extreme conditions altering the sample matrix.

The chlorine content rises notably in CPC-21 (4819 PPM) and CPC-110 (7256 PPM). This is indicative of the degradation of PVC insulation, as chlorine is a primary component of PVC. As the temperature increases, PVC decomposes, releasing chlorine which then interacts with the copper wire, potentially forming corrosive compounds that exacerbate electromigration and material degradation. Calcium content increases with higher currents and temperatures, peaking in CPC-110 (4397 PPM). This increase is likely due to the degradation of filler materials within the PVC or external contamination from the environment during the high-temperature experiments (Kurukuru and Khan, 2022). Lead shows a significant decrease in concentration with increasing temperature and current, dropping to almost negligible levels in CPC-50 (0.7 PPM) but rising sharply in CPC-110 (274 PPM). The initial decrease could be due to lead melting or evaporating at high temperatures, while the later increase suggests re-deposition or contamination during extreme conditions (Ceric et al., 2023). The concentrations of barium and antimony fluctuate across the samples but generally increase at higher temperatures and currents. This suggests that these elements, possibly from additives in the PVC or contaminants, are more stable or become more detectable under higher thermal stress.

Silver and tin, which may be present as trace alloying elements in the copper wire, show increases in their concentrations, particularly under extreme conditions (CPC-110). This could be due to the migration and accumulation of these elements in certain regions of the wire. Arsenic, on the other hand, increases significantly in CPC-21 and CPC-110, indicating possible contamination or interaction with the environment during the experiments. Manganese shows a peak in concentration in CPC-21 (40.9 PPM) and CPC-110 (41.9 PPM), suggesting it may be involved in the degradation processes or may come from environmental contamination.

Electromigration induces significant changes in the elemental composition of the copper wires, especially at higher current densities and temperatures. The observed reduction in copper content and the increase in elements like chlorine, lead, and calcium suggest that the PVC insulation is degrading and interacting with the copper wire, leading to corrosion and material loss (Zhao et al., 2024). The fluctuations in the concentrations of other elements like silver, tin, and manganese indicate complex interactions between the wire and its environment under stress. These changes underscore the multifaceted nature of electromigration, which involves not just the physical displacement of atoms but also chemical interactions that further degrade the material.

Figure 3 illustrates the XRF spectrum graph of overcurrent

Table 2. Elemental Composition of PVC-Insulated Copper Wires

Elements (ppm)	Samples					
	CPC-0	CPC-21	CPC-50	CPC-70	CPC-100	CPC-110
Cu	98969	99253	59926	123639	73075	881278
Cl	1088	4819	454	1575	3032	7256
Ca	207	1257	222	350	1016	4397
Pb	55.2	13.5	0.7	11.8	16.8	274
Ba	17.4	49.3	28.9	35.3	17.4	299
Sb	97	34.4	133	27.6	159	105
Ag	37.2	44.8	63.2	49.9	23.0	98
As	1.9	19.1	1.2	0.3	6.4	25.2
Sn	51.2	57.8	73.1	42.7	67.0	76.5
Mn	6.7	40.9	3.1	8.8	6	41.9

PVC-insulated copper wires, presenting a visual representation of the data in Table 2. The spectrum provides insights into the elemental composition changes under different current conditions. Notably, two peaks are observed in the Rayleigh and Compton scatter zones between energy levels of 16-18 keV for each sample. However, the intensity of these peaks decreases with increasing electric current. In the CPC-110 sample, both peaks disappear entirely. This reduction in peak intensity correlates with the degradation of the PVC insulation and the subsequent impact on the copper wire. As the current increases, the PVC decomposes more rapidly, releasing chlorine and other byproducts that interact with the copper wire. This interaction likely alters the elemental composition and the structure of the wire surface, diminishing the scattering effects observed in the XRF spectrum. This reduction in peaks in the CPC-110 sample indicates severe degradation, where the structural integrity of the wire is compromised to the point that it no longer exhibits the same scattering properties. This observation is consistent with the extreme temperature (1091°C) and current conditions that cause significant physical and chemical transformations in the wire, leading to the loss of distinctive scattering features in the XRF spectrum (Andritsos et al., 2020).

3.4 Chemical Structure of PVC Insulator

Figure 4 displays the FTIR spectra of PVC insulators from copper cables subjected to various overcurrent conditions, highlighting significant changes in the material's chemical structure. The CPC-0 sample shows distinct peaks at specific wavenumbers corresponding to characteristic vibrational group frequencies: C−Cl stretching at 711.601 cm^{-1}, 742.456 cm^{-1}, and 873.591 cm^{-1}; CO stretching at 1722.11 cm^{-1}; and C−H stretching at 2919.68 cm^{-1}. As the current increases from 21 A to 70 A, the FTIR patterns retain the same peak positions but exhibit a notable decrease in transmittance intensity, indicating reduced signal strength and suggesting gradual degradation of the PVC material.

For samples CPC-100 and CPC-110, two broad peaks emerge at energy values of 330.45 KeV and 1419.34 KeV, corresponding to the presence of hydrated water and CH2 deformation, respectively. This significant change in the FTIR pattern suggests substantial structural alterations in the PVC due to severe overcurrent conditions. The degradation mechanism of PVC under overcurrent stress can be explained by the dehydrochlorination process (Cruz et al., 2021), which forms long conjugated double bonds or polyene sequences, leading to color changes and material weakening. This process accelerates in the presence of oxygen, resulting in carbonyl group formation, consistent with the observed FTIR peaks. The CPC-50 sample exhibits a FTIR pattern similar to CPC-0, implying no significant structural changes within the short exposure time of 5 minutes, despite an MTTF of around 72 minutes. Conversely, the CPC-70 sample, with an MTTF of 0.004 minutes, shows an FTIR pattern still relatively identical to CPC-50. This indicates that copper wire failure has not yet propagated

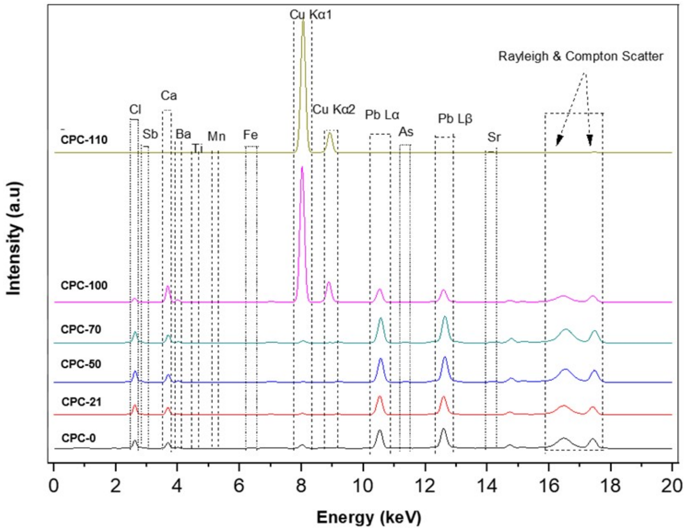

Figure 3. XRF Spectra of Overcurrent PVC-Insulated Copper Wires

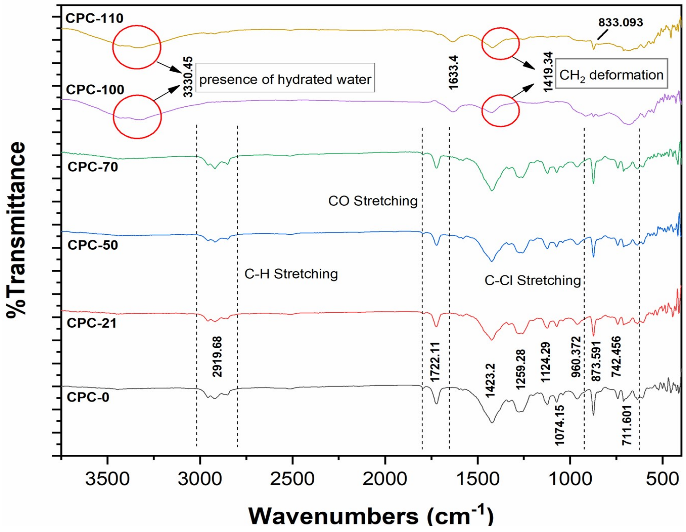

Figure 4. FTIR Spectra of PVC Insulator with Different Current Intensities

to substantial PVC deformation, as confirmed by SEM analysis, which reveals no significant morphological changes.

These findings align with recent research by Deng et al. (2023) on the thermo-oxidative decomposition behavior of PVC under overload conditions. Their study emphasized the increased fire hazard and lowered activation energies associated with higher overcurrent levels. Similarly, Hua et al. (2023) stated that the combined effects of thermal fields, leading to molecular structure destruction and insulation defects. This research reinforcing the understanding that overcurrent induces significant chemical changes in PVC insulators, necessitating improved materials and insulation strategies for enhanced durability and safety in electrical systems. The observed decrease in transmittance intensity and emergence of new peaks at higher current levels highlight the structural transformations induced by overcurrent stress.

The FTIR results, indicating chemical degradation, are corroborated by the SEM analysis of the PVC insulators subjected to various overcurrent conditions. For the CPC-0 sample, SEM images reveal a smooth, uniform surface, reflecting the material's pristine state with no apparent morphological defects. This visual confirmation of the chemical integrity aligns with the strong transmittance intensity observed in the FTIR spectra, showcasing the characteristic peaks of the PVC's molecular structure.

As the current increased to 21 A, SEM analysis of the corresponding samples showed initial signs of surface roughness and micro-cracking, although these changes were not extensively pronounced. This level of current induces minor physical alterations that correspond to the initial stages of the dehydrochlorination process, evidenced by the slight decrease in transmittance intensity in the FTIR spectra (Cruz et al., 2021). The material's surface begins to degrade subtly, indicating early degradation phases without substantial structural transformation.

In contrast, for the samples subjected to higher currents, specifically CPC-100 and CPC-110, SEM images depict significant morphological changes. These samples exhibit pronounced surface roughness, with deep cracks and pits forming across the PVC surface. Such severe physical deterioration is consistent with the substantial chemical structural alterations observed in the FTIR spectra, such as the emergence of broad peaks corresponding to hydrated water and CH_2 deformation. The extensive cracking and surface irregularities observed in SEM images are indicative of the advanced stages of dehydrochlorination and polyene formation, confirming the severe degradation mechanisms taking place under these overcurrent conditions (Estananto et al., 2023).

For the CPC-50 and CPC-70 samples, the SEM analysis provides further insights into the material's behavior under moderate overcurrent conditions. Despite an MTTF of 72 minutes for CPC-50, the SEM images reveal minimal surface deformation, which aligns with the FTIR pattern showing no significant structural changes. Similarly, the CPC-70 sample, with a drastically reduced MTTF of 0.004 minutes, exhibits no major surface morphological alterations in the SEM images. This lack of extensive deformation suggests that the failure mechanism in the copper wire has not significantly impacted the PVC insulator's surface structure within the short exposure time.

4. CONCLUSIONS

In conclusion, the increased current density significantly reduces the mean time to failure (MTTF), with the formation of voids and hillocks accelerating wire degradation. SEM analysis revealed progressive morphological damage, and XRF results indicated elemental changes, highlighting severe copper loss and PVC degradation. FTIR spectroscopy confirmed substantial chemical alterations in the PVC insulator, especially at higher currents, consistent with dehydrochlorination processes and structural breakdown. By integrating these observations, the study underscores the critical impact of overcurrent conditions on both the electrical and material properties of copper wires, emphasizing the need for improved wire compositions and insulation strategies. This research not only fills the gap in understanding real-time degradation patterns but also proposes predictive models to enhance the reliability and longevity of electrical systems in practical applications.

5. ACKNOWLEDGMENT

The author would like to express gratitude to the Bareskrim Polri Forensic Laboratory Center, Forensic Metallurgical Ballistics Subdivision Puslabfor Bareskrim Polri for funding this research. Special thanks are also extended to the research laboratories that provided invaluable support and resources: The Ballistics and Metallurgy Division at the Forensic Laboratory Center within the Criminal Investigation Agency of the Indonesian National Police, the Ballistics and Metallurgy Sub-sector at the North Sumatra Regional Police Forensic Laboratory Sector, and the Transmission and Distribution Laboratory at the Department of Electrical Engineering, Universitas Sumatera Utara.

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