Forensic Analysis of Copper Wire for Fire Source Determination

Norlyiana Mesrun, Mohd Saharul Nizam Abdul Rahim,
Nik Fakhuruddin Nik Hassan, Kah Haw Chang*

Forensic Science programme, School of Health Sciences, Health Campus, Universiti Sains Malaysia, 16150 Kubang Kerian, Kelantan

ABSTRACT: Electrical fire involves either electrical failure or deliberate act as the source of fire must be proven during the fire investigation. Copper wires are widely used in structure wiring and electrical appliances and they are frequently associated with fire. Therefore, this study focused on the characterisation of copper wire for fire source determination to provide an insight on the feature damage patterns between external flame burnt wires and electrically burnt wires. In this work, electrical wires from two different manufacturers were tested on different simulated fire conditions, *i.e.* those burned by external flame and electrical overcurrrent condition respectively. Through microscopic examination, the cross sectional morphological features between the two copper wires by different conditions were distinct. The application of Fourier Transform Infra-red spectroscopy technique on the polymeric insulator of the wire samples showed slightly varying spectra for wires following different simulated fire conditions. Further principal component analysis on the FTIR spectra provided a more objective characterisation for samples subjected to external flame and overcurrent conditions. The results signaled the potential of the technique as a tool for fire source determination. In conclusion, the study could differentiate and characterise burnt wires based on their fire sources, aiding the fire investigation, especially in electrical fire cases.

Keywords: forensic analysis, fire, electrical fire, copper wire, overcurrent

Introduction

Electrical fire is described as structure fire that involved some kind of electrical failure or malfunction to ignite a fire that can only be assumed after all possible accidental causes of fire are eliminated by the fire investigator [1]. Copper wires that are widely used in structure wiring and electrical appliances are frequently associated with fire. Electrical overcurrent is a condition where the current flows exceed the acceptable safety standards of that particular conductor, depending on the duration and magnitude of the overcurrent [2]. When overcurrent occurs, the entire circuit is heated through which the current flows which could then affect the thermoplastic insulator of the conductor and prolong heating of the conductor could lead to fire ignition [3]. During fire investigation, the excessive current through a wiring that cause the internal electrical damages must be able to differentiate with external flame damages.

Delplace and Vos (1983) characterised the internal electrical damages with the presence of beads on the copper conductor, abrupt changes in cross sectional appearance of the wires, and also damage on adjacent conductors or metal cable shielding [4]. In contrast, external flame damage were characterised with the presence of dripping or flow of copper, local and gradual thinning or thickening of wires, irregular shapes as well as the absence of drawing die marks [4]. Apart from that, the PVC insulators tend to be softened and sagged away due to internal heating but tend to char and tightly attach to the conductor if exposed to external flame [3]. Liu *et. al* (2011) also added that the inner PVC insulator layer experienced a lot of damage in internal heating [5]. Examination of beads and globules frequently utilised for determination of electrical as the source of fire but many researchers, *i.e.* Levinson (1977) [6], Babrauskas (2003) [7] and Wright *et al.* (2014) [8] agreed that the examination solely based on the external appearance of beads and globules was not a reliable indicator on the cause of their formation.

In every fire cases, a fire investigator is required to determine the cause of fires [9]. Therefore, it is important for a forensic investigator to have an in-depth investigation on the copper wires as to conclude whether or not a fire could have due to faulty electrical appliances or by the exertion of flame due to other consequences. This work was conducted to study the morphological features of the cross section of copper wire due to external flame and eletrical means. Moreover, the burned insulators were also analysed using Fourier Transform Infra-red spectroscopy technique (FTIR) to examine their profile changes, and further characterise by principal component analysis (PCA).

Materials and Methods

In this work, two types of insulated electrical wires (labeled as R and Y) were used. Each samples were cut into 15 cm in length and labeled accordingly. All the prepared samples were subjected to respective simulated conditions as in Table 1.

Table 1: The simulated fire conditions on wire samples

Simulated fire condition	Description
Control (C)	Unburnt insulated copper wire.
Instant external flame (IF)	Insulated copper wire was burnt by flame exerted from an acetylene torch (Map Pro™, Boulder City, NV) for a very short period of time (about three seconds), producing an instant external burn.
Slightly external flame (SF)	Insulated copper wire was burnt by flame exerted from an acetylene torch for about ten seconds, producing a slightly external burn.
Severely external flame (VF)	Insulated copper wire was burnt by flame exerted from an acetylene torch for more than 10 seconds producing a severely external burn.
Slightly electrical fault (SE)	Insulated copper wire was connected to a complete circuit, consisting of a switch and a transformer at two different ends. The electrical current supply was stopped before the wire was burnt to produce a silghtly overcurrent condition.
Severely electrical fault (VE)	Insulated copper wire was connected to a complete circuit, consisting of a switch and a transformer at two different ends. The electrical current supply was stopped once the wire was burnt entirely to produce a severely overcurrent condition.

The diameter of all the wire samples was measured using Vernier calipers. Three measurements of each sample were taken followed by the determination of the mean and standard deviation. Leica MZ16 stereomicroscope (Leica Microsystem, Heerbrugs, Switzerland) equipped with Leica MC170 HD digital microscope camera (Leica Microsystem, Heerbrugs, Switzerland) was utilised to examine the cross section of the wire samples. Each samples were captured at magnification power ranging from 20× and 32×, and the characteristics on cross sectional features were observed.

The organic profiles of the insulated layer of copper wires, both unburned and burned samples, were studied using FTIR Tensor 27 (Bruker Corporation, Billerica, MA), utilising FTIR-Attenuated Total Reflectance (FTIR-ATR) technique. OPUS 7.0.122 software (Bruker Corporation, Billerica, MA) was used in spectra analysis. In FTIR analyses, absorbance versus wavelength spectrum of the insulated layer was obtained through 16 scans with scan ranges between 500 to 4000 wavenumber (cm^{-1}). Note that all the analyses were performed on both the outer layer and inner layer of the insulators. The spectrum of each sample, taken in triplicates, were compared and evaluated. The data from FTIR analyses was further analysed using Minitab 16 software (Minitab Inc.) for characterisation of the copper wire based on PCA.

Results and Discussion

Diameter measurement of the insulated copper wires subjected to different simulated fire conditions

Table 2 illustrates the diameter measurement of insulated copper wires, both control and those subjected to different simulated fire conditions.

Table 2: Diameter of insulated copper wires in different simulated fire conditions

Simulated fire conditions	Diameter (mean ± SD mm)	
	Red (R)	Yellow (Y)
C	3.10 ± 0.0100	3.25 ± 0.0200
IF	3.10 ± 0.0265	3.30 ± 0.0306
SF	3.03 ± 0.0351	3.37 ± 0.0231
VF	3.25 ± 0.191	4.51 ± 1.23
SE	3.15 ± 0.0289	3.27 ± 0.0231
VE	3.69 ± 0.191	3.62 ± 0.217

Copper wire appears as a single cylindrical strand, covering the copper conductor with the insulator. In our work, the diameter of control Y was slightly greater than the diameter of control R with diameter of 3.25 ± 0.0200 mm and 3.10 ± 0.0100 mm, respectively. This suggested that different manufacturers could produce insulated copper wires of slightly varying diameter, and these variations could be due to the thickness of the insulator that covered the copper conductor. Note that the minimum cross scetional areas of the conductors were strictly controlled by Energy Commission (EC) and 1.5 mm^2 type wires were used in this work [10]. These copper wires are These electrical wires are the evidence that commonly encountered at fire scenes, experienced by one of the author and they are recommended to be used in lighting and fan circuits[10]. All the diameters measurement of control samples showed very minor variations. The observation showed that the manufacturing processes of these electrical wires were carried out with a stringent quality control to ensure the materials used were of the desired quality and the final products were of uniform physical appearance, meeting the requirement and standards.

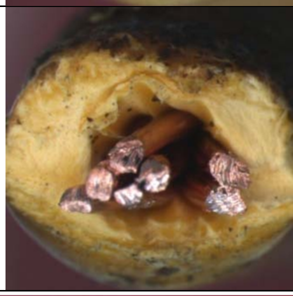
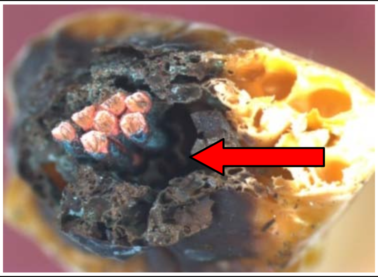
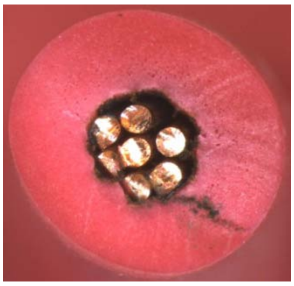
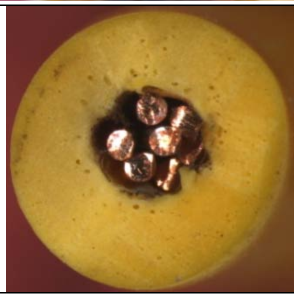
The diameter of the wires, both R and Y samples, showed variations when subjected to burning. In simulated external flame burning, the diameter of instant and slightly burnt of Y samples were slightly increased by respective 0.05 mm and 0.12 mm compared to control. However, the diameter of R samples subjected to instant external flame burnt did not change much compared to control. With slightly external flame, the diameter of the sample was found to be smaller than the control. This observation could be due to the softening and deformation of the insulation materials. Upon heating, a phenomenon known as sleeving which is the softening and sagging of thermoplastic insulation occurred [3], in which the insulation material melted and the original cylindrical structure changed [6]. However, severe burnt wires recorded an averaged-diameter of 3.25 ± 0.191 mm and 4.51 ± 1.23 mm for R and Y, respectively, indicating a significant increase in diameter as compared to control samples. Similar observation was also noticed with samples subjected to both slightly and severely overcurrent.

Most solid materials expand upon heating, including plastic materials that make up the insulation of electrical wires [11]. Note that the composition of wire samples was not examined in this study. Generally, the heating of flame and externally and electrical overcurrent internally caused the increase in the diameter of the wires, resulted from the expansion of insulation materials. These materials melt and cause swelling and sagging away from the copper conductor [3]. Severely burnt recorded a high increase in diameter with relatively greater standard deviation as shown in our experiment and this is probably due to the deformation of the insulation layer that occurred only at the point with prolonged heating. In other words, the change of insulator diameter differed at different points along the wire is affected by the duration of heating and also the flame temperature at the point of heating. From our observation, the degree of heat applied to an electrical wire could hardly be differentiated, especially for those exerted with instant and slightly flame or overcurrent. However, extended period of heating on an electrical wire, both by external flame and electrical overcurrent, greatly affected the physical appearance of the insulating materials, particularly the diameter.

Microscopic examination of the cross section of insulated copper wires subjected to different fire conditions

Microscopic examination of the cross sectional features of copper wires examined under microscope with magnification of 20 × showed the original bronze colour of the copper conductor and smooth surface of the outer insulation layer of the fresh wire. Their outer insulation layers lost their original surface integrity with deposition of charred insulating materials present as black carbonecous materials surrounding the outer insulation layer upon instant and slightly external burning (Table 3). However, the copper conductors were generally not affected by the short period of heatingas they were protected by the insulation. The inner insulation layer was being protected from the flame, showing no charred product although some swelling and melting can be observed on the surface. In contrast, severely external flame burnt produced significant features where prolonged heating caused disfiguration of the entire insulation layer. In some instances, the copper conductors were affected depending on the duration and magnitude of heating. Also, there was blue colouration on the surface of the conductor as shown by the arrow in Table 3, and this phenomenon was probably due to the oxidation of the copper conductor by the acid produced [2].

Table 3: Cross-sectional images of copper wires upon heating

Simulated fire conditions	**Cross-sectional images**	
	R	**Y**
C		
IF		
SF		
VF		
SE		
VE		

Our observation showes that slightly burnt due to electrical overcurrent condition did not affect much on the wire overall appearance compared to control. Deposition of charred products was found on the inner insulation layer of the conductor, while the outer insulation remained intact. Upon severe overcurrent, the inner layer of insulation was greatly affected with the presence of charred products attached to the copper conductors. Blue colouration of the copper conductor was also observed in most of the samples, indicating oxidative reaction. The outer part of the insulation material could also affected by the heat and flame arisen over the duration of heating.

Our experimental results clearly showed that the burning due to electrical overcurrent condition arisen from the copper conductor affected the inner insulation layer first as opposed by external burning by fire. The copper conductor gets hotter with continual supplying of current, and reach to ignition with enough duration and magnitude of current cupply [5]. The burning process cause the insulating materials to be charred off as black carbonecous materials.

In contrast, external heating causing insulating materials to start burning from the outer layer. With excessive burning, the insulating materials could melted while still tightly held to the copper conductor [3]. During observation, we found that the Y samples experienced greater damage in both simulated fire conditions as compared to R samples. As such, the composition of these two wire samples could be different, leading to relatively higher resistence towards fire in R samples. In general, internal heating showed damages on the inner insulation without affecting the outer insulation layer unless it was severely heated and vice versa when exerted by external flame. Therefore, the careful observation of electrical wire encountered in a fire scene is crucial for the identification of fire cause, if there is any leftover evidence.

Comparison of FTIR spectra between electrical wires subjected to different fire conditions

The inner and outer layers of the insulators were examined using FTIR spectroscopy technique to determine any change in their profiles upon different fire conditions. Generally, the organic profiles of both inner and outer insulation layer could be changed on the basis of the type of burning. Heat and flame arisen from the fire external caused damage to the outer insulation layer, and in most instances did not affect the inner insulation layer especially those with slightly fire introduction. In contrast, an electrical wire subjected to overcurrent condition could introduce more effect to the inner insulation layer. However, with extended duration and greater magnitude of fire, neither the inner or the outer insulation layer could be secured, leading to slightly different FTIR spectra on analysis. FTIR spectra of the insulating materials for both sample R and Y were obtained and compared as in Fig. 1.

The data obtained from FTIR analyses were further analysed by PCA for more reliable differentiation between the samples burnt by external fire and electrical means. The peaks between 1000 and 1750 cm^{-1} were chosen to compare the FTIR profiles of burned insulators, as this region was found to give distinct grouping of both inner and outer insulation profiles, for both R and Y samples. Fig. 2 and Fig. 3 illustrate the score plots of respective R and Y samples with different simulated fire conditions. Note that the “I” and “O” in the score plots indicate the inner and outer insulation layers, respectively. The “a” and “b” show the duplicate samples for each conditions.

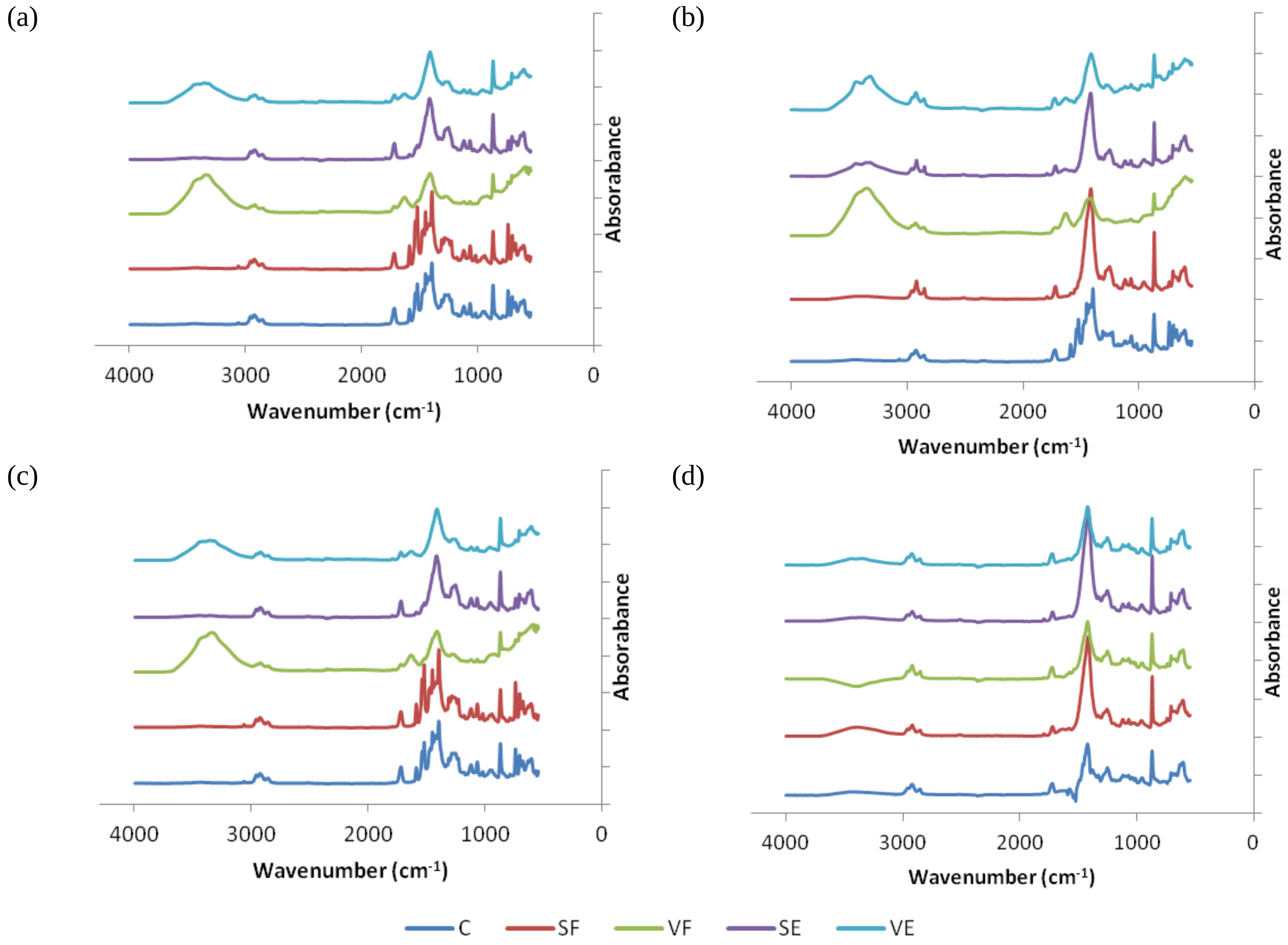


Fig. 1: Comparison of FTIR spectra between electrical wires subjected to different fire conditions; (a) inner layer of insulated R, (b) outer layer of insulated R, (c) inner layer of insulated Y, and (d) outer layer of insulated Y.

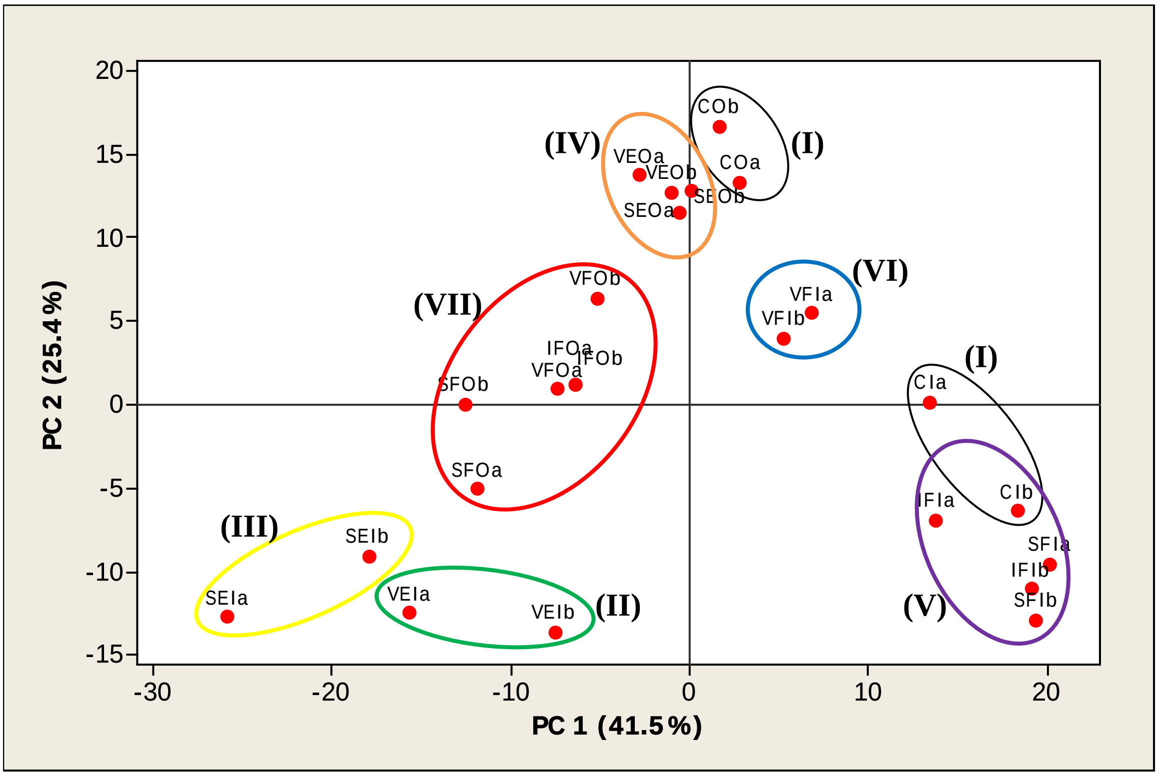


Fig. 2: Score plot of R samples subjected to different fire conditions with data points range between 1000 - 1750 cm^{-1}

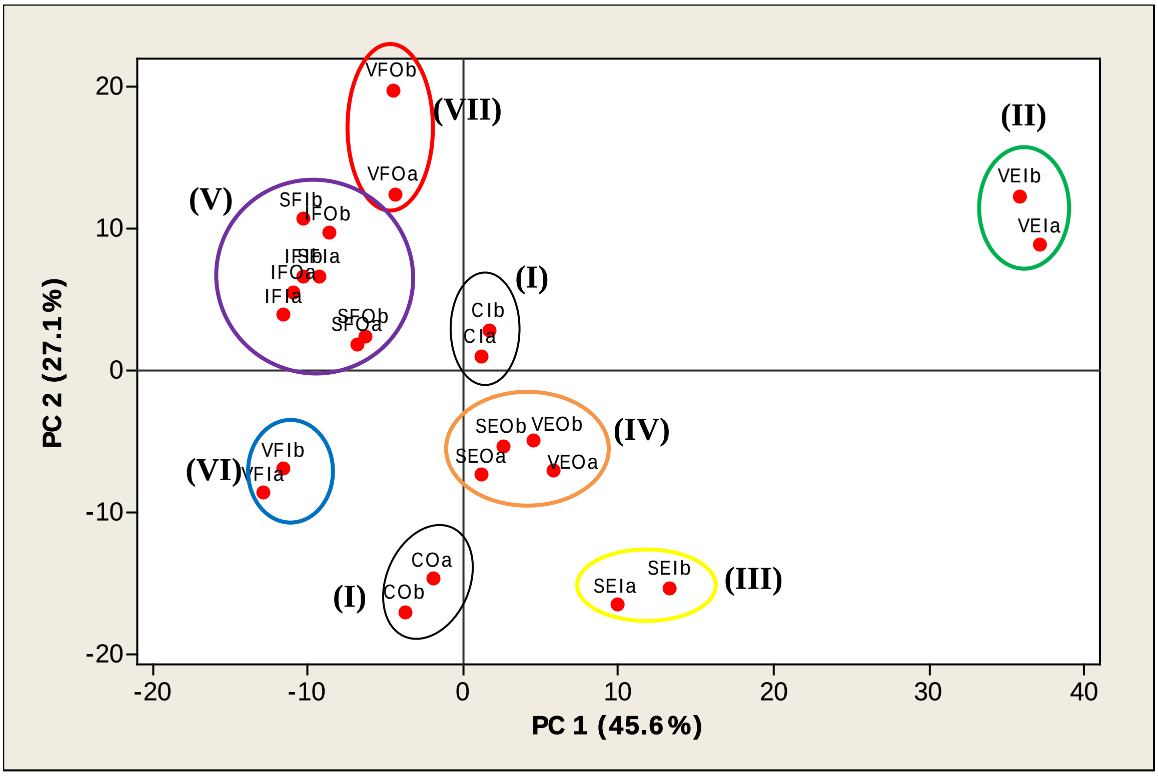


Fig. 3: Score plot of Y samples subjected to different fire conditions with data points range between 1000 - 1750 cm^{-1}

From the score plot in Figure 3, the data points indicated insulators burnt by external flame and electrical overcurrent condition were also separated from the rest. The data points representing the electrically burnt samples were separated far away from the control cluster (black circle- I). Points showing the inner layer of samples subjected to slightly and severely electrical burnt of inner insulator were clustered and formed their own group at the upper right corner (green circle- II) and at the lower center of the score plot (yellow circle- III), respectively. Severely electrical burnt of the inner layer of Y samples were very distinct as they were located very far from other groups. Meanwhile, the group with the inner layer insulator of slightly electrical burnt was located not very far with cluster of outer layer of slightly and severely electrical burnt samples (orange circle- IV). On the other hand, the data points indicating the instant and slightly burnt of the inner and outer insulation layers by external flame were grouped together (purple circle- V) while the those subjected to severely burnt formed their own groups. The cluster of inner insualtion layer was marked VI whereas the cluster of outer insulation layer was marked VII. Note that the cluster that marked VII was still closely located with the cluster that marked V. Generally, the samples were grouped independently on the basis of their fire causes. The data points representing external flame burnt of insulators were grouped on the left side of the score plot whereas those points indicating electrical means were grouped on the right side of the plot. Additionally, the electrical burnt samples could be further distinguished, especially the inner layer samples which formed two distinct groups from the outer layer samples. The samples subjected to external flame could be hardly differentiated as they were closely located in the score plot except those with severely burning.

From Figure 2, the burned wires of R could be distinguished between those caused by external flame and electrical means. The inner insulation layer of sample R upon slightly (yellow circle- III) and severely electrical burnt (green circle- II) grouped themselves at the bottom left to the plot, although they were closely located between each other. On the other hand, the data points representing the outer insulation layer upon slightly and severely electrical burnt clustered together at the top of the plot (orange circle- IV) which located closely with the outer insulation layer of the control (black circle- I). For external flame condition, points representing the inner layer of wires which subjected to instant and slightly burnt were clustered together at the right bottom of the score plot (purple circle- V). Meanwhile, the severely burnt inner layer of R sample were grouped independently (blue circle- VI) while all the points indicating outer insulation layers with instant, slightly and severely burnt were clustered into one group at the left side of the plot (red circle- VII). Through PCA analysis, the electrical and external flame burnt of electrical wires R were distinguishable. The inner insulation layer due to electrical overcurrent condition formed their own clusters, away from the control. Meanwhile, the outer layer of electrical wires burnt by external flame also clustered into their own groups.

The insulators of electrical wires produce specific FTIR spectrum on the basis of functional group made up the organic compounds. In FTIR analysis, the spectra of the burnt insulator could hardly be differentiated based on type of simulated fire conditions through visual comparison. PCA helps reveal the minor differentiation between the spectra of different causes of fire.

Conclusion

We performed the physical examination and FTIR analyses performed on the electrical wires due to the thermal effect and also electrical means. The diameter of insulated copper wires subjected to different simulated fire conditions tends to increase, depending on the degree of the heat applied and also the period of heating. Microscopic examination of electrical wires upon external flame and electrical burnt showed distinct cross scetional appearances. However, the microscopic examination of the cross sectional features of completely burnt wire, especially in case of severe and prolonged heating could hardly determine their cause of fire, and their differentiation might only be possible with slightly burning conditions. Visual observation of FTIR spectra may be subjective or difficult to differentiate subtle dissimilarities between spectra of insulators upon different types of burning. The use of PCA showed that both the burnt insulators both by external flame and by electrical overcurrent conditions could be distinguished.

References

1. Hall Jr. JR. (2013) home electrical fires. Quincy: National Fire Protection Association.
2. NFPA. (2004). NFPA 921 guide for fire and explosion investigations. Quincy: National Fire Protection Association.
3. Ettling BV. (1978). Electrical wiring in building fires. Fire Technology 14(4): 317-325.
4. Delplace M., Vos E. (1983). Electric short circuits help the investigator determine where the fire started. Fire Technology 19(3): 185-191.
5. Liu S-J., Man D., Yu Li L., Zhao C-Z., Gao W., Liu X-L. (2011). Thermal analysis of pvc wire insulation residues in fire investigation. Procedia Engineering 11: 296-301.
6. Levinson DW. (1977). Copper metallurgy as a diagnostic tool for analysis of the origin of building fires. Fire Technology 13(3): 211-222.
7. Babrauskas V. (2003). Fires due to electric arcing: Can ‘cause’ beads be distinguished from ‘victim’ beads by physical or chemical testing? Fire and Materials 14: 189-201.
8. Wright SA., Loud JD., Blanchard RA. (2015). Globules and beads: what do they indicate about small-diameter copper conductors that have been through a fire? Fire Technology (2015), doi: 10.1007/s10694-014-0455-9.
9. Redsicker DR., O'Connor JJ. (1997). Practical fire and arson investigation 2nd ed. Baco Raton: CRC Press, Inc.
10. EC. (2008). Guidelines for electrical wiring in resident building. Malaysia: Energy Commission.
11. McKeen LW. (2007). The effect of temperature and other factors on plastics and elastomers 2nd ed. Oxford: Elsevier Inc.

Additional information and reprint request:
Chang Kah Haw
Email: changkh@usm.my
Forensic Science Programme
School of Health Sciences
Universiti Sains Malaysia
16150 Kubang Kerian
Kelantan, Malaysia
Tel: +609-7677624