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Copper Wire Characterisation for Fire Source Determination

Dissertation submitted in partial fulfillment for the Degree of
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(Forensic Science)

NORLYIANA BINTI MESRUN

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

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ABSTRACT

Electrical fire is a fire started by electrical means. During investigation, fire investigators need to prove the cause of these fires if the cases involve electrical failures or malfunctions. 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 study, two different manufactured electrical wires, which were yellow and red insulated copper wire samples, were subjected to external flame and electrical overcurrent conditions. Different intensities of simulated fire conditions, namely instant, slightly and severely heated were introduced to the samples. Through microscopic examination, the cross sectional morphological features between insulated copper wire burnt by external flame and electrical overcurrent condition were distinct. However, this method was not reliable enough to be applied in real burnt cases where most electrical wiring were completely burnt, making the cross sectional features hard to be examined. The application of Fourier Transform Infra-red technique on the polymeric insulator of the wire samples showed slightly varying spectra through visual observation on the basis of simulated fire conditions. Principal Component Analysis of the burnt insulators provided an objective characterisation where the source of fire, either external flame or electrical means could be distinguished. The results have signaled the high potential of the technique as a tool for fire source determination. In conclusion, the study could help differentiate and characterise burnt wires based on their fire source. The findings provided information for forensic analyses and also aided the fire investigation, especially on electrical fire cases.

ABSTRAK

Kebakaran elektrik merupakan sesuatu kebakaran yang berpunca daripada sumber elektrik. Ketika siasatan dijalankan, penyiasat kebakaran perlu membuktikan punca kebakaran sama ada kebakaran tersebut melibatkan kegagalan atau kerosakan elektrik. Oleh itu, kajian ini berfokus kepada pengelasan wayar tembaga untuk mengenal pasti punca kebakaran, melihat dari sudut pandangan baru dari segi ciri-ciri kerosakan antara wayar tembaga yang terbakar disebabkan api luaran dengan wayar tembaga yang terbakar disebabkan arus elektrik. Dalam kajian ini, dua jenis sampel wayar tembaga berpenebat telah dibakar dengan api luaran dan keadaan arus elektrik secara berlebihan. Sampel berkenaan telah dibakar dengan tiga tahap kebakaran berbeza iaitu pembakaran serta-merta, ringan dan teruk. Melalui pemeriksaan mikroskopik, ciri morfologi keratan rentas wayar tembaga berpenebat yang dibakar dengan api luaran dan keadaan arus elektrik berlebihan adalah berbeza. Tetapi, teknik ini tidak begitu praktikal untuk diaplikasikan dalam kes kebakaran sebenar kerana kebanyakan wayar elektrik akan terbakar sepenuhnya, menjadikan ciri-ciri keratan rentas wayar tersebut sukar untuk diperiksa. Teknik Transformasi Fourier Infra Merah yang diaplikasikan terhadap penebat polimer sampel wayar menunjukkan spektra penebat terbakar yang berbeza sedikit melalui pemerhatian visual berdasarkan keadaan yang menyerupai kebakaran sebenar. Analisis Komponen Utama terhadap penebat yang dibakar memberi pengelasan objektif dan punca kebakaran sebagai akibat oleh api luaran atau arus elektrik yang berlebihan dapat dibezakan. Hasil analisis tersebut menunjukkan potensi yang tinggi dalam penentuan punca kebakaran. Secara kesimpulannya, kajian ini dapat membantu dalam membezakan dan menklasifikasikan wayar terbakar berdasarkan punca kebakaran. Hasil kajian ini dapat memberi maklumat dalam penganalisaan forensik dan membantu dalam penyiasatan kebakaran, terutamanya dalam kes-kes yang melibatkan elektrik sebagai punca kebakaran.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Generally, the cause of fire can be divided into two types, namely incendiary fire and accidental fire. When a fire investigator identified a fire as incendiary fire, its means that the fire is caused by a person who intentionally ignited the fire under circumstances in which the person knows that the fire should not be ignited (NFPA 921, 2004). In contrast, accidental fire is an occurence of fire where the cause of the fire does not involve intentional human act to ignite or spread the fire into an area where the fire should not be (NFPA 921, 2004). Therefore, it is important for a fire investigator to be able to determine the cause of fire whether it is incendiary or accidentally conclusively. Thus, the outcome of this study could contribute as the evidence of association between a fire incident and the cause of that fire.

1.2 Introduction

1.2.1 Fire

Fire is a chemical reaction involving rapid oxidation process. A fire evolves light and heat at different intensities (NFPA 921, 2004). For a fire to occur, four elements must be present simultaneously and they can be represented by a fire tetrahedron as illustrated in Figure 1.1. A fire tetrahedron consists of four components, namely fuel, heat, oxidising agent and unlimited chemical chain reaction. Control or removal of one or more of the components can inhibit fire (NFPA 921, 2004).

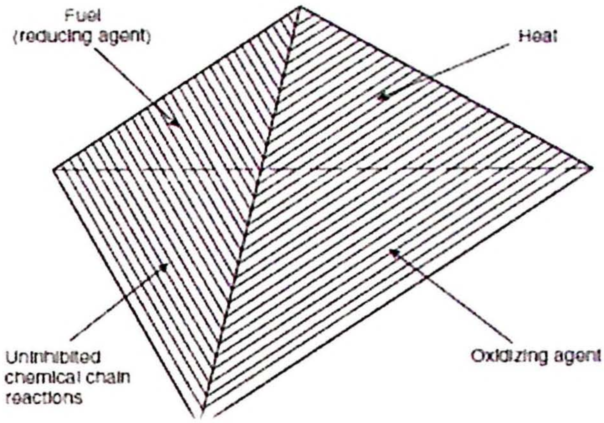

Figure 1.1: Fire tetrahedron (Source: NFPA 921, 2004)

1.2.2 Statistics of fire occucrrence in Malaysia

Table 1.1 shows the statistics on fire breakouts from 2007 to 2013 reported by Fire and Rescue Department of Malaysia (FRDM) along with the reported number of deaths, injuries and estimated loss due to fire breakouts.

Table 1.1: Statistics on fire breakouts, Malaysia, 2007-2013

Item	Year						
	2007	2008	2009	2010	2011	2012	2013
Number of fire breakouts	20,225	21,524	29,417	29,052	28,741	29,848	33,640
Number of deaths [a]	80	88	76	89	80	98	72
Number of injuries	67	79	71	82	81	152	165
Estimated loss (RM million)	865.29	1,048.57	1,057.04	756.70	927.49	1,116.15	1,990.46

[a] Refers to instant death at the place of occurence

(Source : Fire and Rescue Department of Malaysia, 2015)

The statisctics showed an increasing trend on the total number of fire breakouts from 2007 to 2013 (FRDM, 2015). In 2013, the statistics revealed the highest occurence of fire breakouts compared to the previous years with total a of 33,640 cases. It also noted the highest number of injuries due to fire occurence with total of 165 injury cases in that particular year. In spite of the highest fire breakouts and injury cases, the number of deaths was the lowest compared to the previous years which declared only 72 deaths, decreased by 26 from 98 deaths reported in 2012. Note that the deaths figures referred to instant death at the place of fire occurence.

Besides deaths and injuries, fire can cause structural damage, property destruction and paralysing economical activities, leading to huge loss of money to the fire victims. FRDM proclaimed the highest estimated loss due to fire breakouts was in year 2013 with approximately RM1,990.46 million compared to previous years. It was a sharp increment by RM874.31 million from RM1,116.15 million in 2012. Table 1.2 tabulates the number of fire breakouts in Malaysia by sources reported by FRDM from 2007 to 2013 (FRDM, 2015).

Table 1.2: Number of fire breakouts by source, Malaysia, 2007-2013

Source of fire breakouts	2007	2008	2009	2010	2011	2012	2013
Electricity	4,021	4,401	5,410	5,878	6,431	5,382	3,802
Cigarette butts	1,558	1,609	1,981	1,808	1,433	892	777
Sparks of fire	667	777	731	812	683	523	390
Fire crackers/fireworks	69	72	70	115	81	68	56
Mosquito coil/candle/joss-stick	400	345	317	302	351	211	182
Gas stove/kerosene	1,138	1,286	1,466	1,481	1,605	1,410	1,064
Spontaneous reaction	385	429	419	575	531	493	281
Arson	4,994	5,841	7,933	8,172	6,681	6,663	5,482
Incendiary arson	1,157	1,216	2,041	1,929	1,711	1,658	1,156
Chemical reaction	37	28	28	66	62	31	18
Children playing with matches/fire	253	233	206	215	178	134	136
Others	2,372	2,938	4,879	3,875	4,676	7,357	17,130
Unknown source	3,174	2,349	3,936	3,826	4,318	2,026	3,166
Total	20,225	21,524	29,417	29,052	28,741	26,848	33,640

(Source : FRDM, 2015)

The sources of fire were determined by the FRDM based on the investigation (FRDM, 2015). For unidentified sources, they were groups into the unknown source category. Based on the statistics, the primary cause of fire breakouts in Malaysia from 2007 to 2012 was mainly contributed by arson. Meanwhile, 2013 recorded "other sources" as the major cause of fire breakouts in that year. In 2013 alone, arson and electricity also served as the main factor contributing to the causes of fire breakouts.

As mentioned, fire caused by "other sources" served as the major contributor to the total number of fire breakouts with 17,130 cases (50.92%), a sharp increment by 9,773 cases from 2012. "Other sources" included lightning, vegetation fire and open burning as the sources of fire breakouts in Malaysia. Fire has been used for forest clearance to make way for agriculture and settlement which often lead to uncontrolled fire and cause fire breakout on adjacent forest (Page *et. al*, 2013). Climate change over the Southeast Asia especially El-Nino phenomenon as well as agricultural expansion served as some of the major contributing sources of fire breakouts (Page *et. al*, 2013). El-Nino phenomenon caused the Southeast Asia region to experience lower rainfall or in other words caused drought which increased the probability for spontaneous fire due to high temperature (Page *et. al*, 2013).

Arson cases served as the second major contributing source of fire breakouts in that year with 16.30% of the total cases were recorded. Between 2007 and 2012, arson contributed as the major source of fire but it showed fluctuated trend (FRDM, 2015). According to Kocsis (2002), arson mainly committed with six possible motives, including profit, animosity, vandalism, crime concealment, political objective and psychopathological factors. The desire to gain profit or benefit from setting a fire such as for insurances claims were frequently committed by arsonists due to the arsonist's poor financial condition. Other than that, an arsonist can be motivated to set a fire because of hatred, anger and revenge towards certain people surrounding the arsonist (Kocsis, 2002).

In addition, electricity served as the third contributor to fire breakouts on 2013 with total 3,802 cases (11.30%), decreased from 5,382 cases reported on 2012. The high number of fire breakouts caused by electricity were majorly due to overcurrent load that exceed the allowed maximum capacity of wiring system, especially in buildings (Sinar Harian, 2012). These were happened as a result of unawareness of the risk of overcurrent incidents that can lead to fire among Malaysian. Thus, FRDM has the responsibility to teach and demonstrate the fire safety management at home and also at work place to Malaysia citizen, with the aim to prevent the occurrence of fires and minimize the risks of such incidents.

Figure 1.2 illustrates the number of fire breakouts caused by electricity and "unknown source" in relation to the total number of fire breakouts from 2007 to 2013. The "unknown source" was an issue that needed to be investigated by the authorities. If the source of fire cannot be identified, the authorities could not accurately establish the proper intervention and prevention towards such cases.

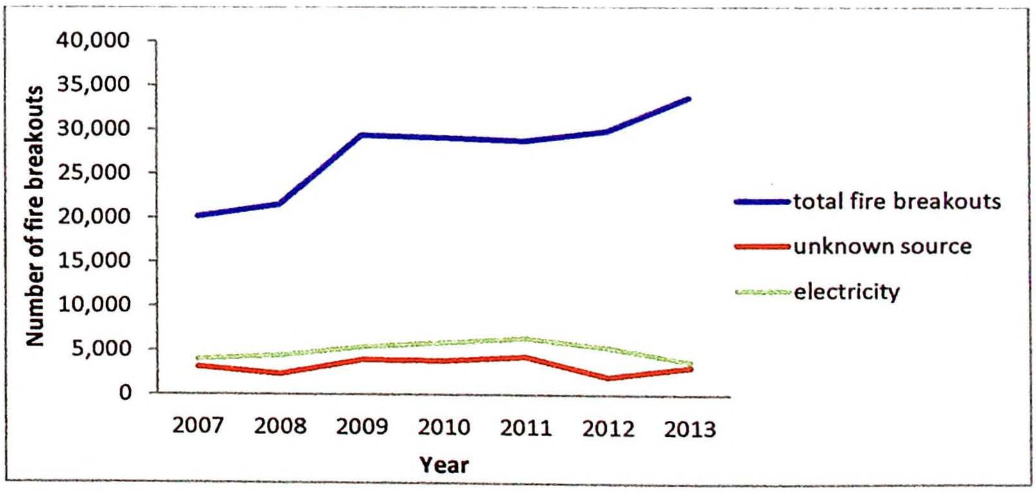

Figure 1.2: Number of fire breakout caused by electricity and unknown source in Malaysia, 2007-2013

The occurrence of fire due to electricity was increased steadily from 2007 to 2011, but continue to showed a decreasing trend since 2011 to 2013. Meanwhile, the number of unknown source that lead to fire occurence showed fluctuated trend within the seven years period. The high number of electrical fires as well as the concern of unknown sources were alarming FRDM to boost their fire investigators' expertise to unfold the source of fire breakouts. The department has the responsibility to figure out the cause that lead to such situations, in order to reduce the fire cases and also to plan the necessary step or interventions to overcome the problems.

1.2.3 Electrical fire

Electrical fire is categorised as an accidental fire as long as the fire investigator does not have the proof to pinpoint an individual with an intention to start the fire by electrical mean. It is described as structure fire that involved some kind of electrical failure or malfunction to ignite a fire (Hall, 2013). In general, it can only be assumed after all possible accidental causes of fire are eliminated by the fire investigator, which is a difficult and tough task. However, a fire investigator must concern that the presence of electrical wiring or equipment at or near the fire origin does not necessarily mean that the fire was caused by the electrical energy (NFPA 921, 2004).

Regarding to the issue, a fire investigator must then have a decent knowledge and understanding about electricity and electrical system in order to determine if the fire is caused by electricity failure and also to distinguish the internal electrical damages and external flame damages. Internal electrical damage is the fire that started within the system due to electrical failure or malfunction, whereas the external damage by flame is the damage due to a fire from the outside of electrical system (Redsicker & O'Conner, 1997).

Generally, in order for a fire to be ignited from an electrical source, there are two factors that be must be presented simultaneously (NFPA 921, 2004). Firstly, the electrical wiring, equipment, or component must have been energised from a building's wiring, an emergency system, a battery, or some other source (NFPA 921, 2004). In other words, it must be proven that electricity had been flown inside the wiring to ensure the electrical system as the source of fire. Secondly, there must be sufficient heat and temperature to ignite a close combustible material produced by electrical energy at the point of origin by the electrical source (NFPA 921, 2004). Sufficient heat and temperature can be generated by various means, such as short-circuit and ground-fault parting arcs, excessive current through wiring or equipment, resistance heating, or by ordinary sources like lightbulbs, heaters, and cooking equipment (NFPA 921, 2004).

Ignition can only occur when the temperature of electrical source is maintained long enough to bring the adjacent fuel up to its ignition temperature with the presence of appropriate mixture of air to allow a combustion to be ignited (NFPA 921, 2004). Therefore, a fire investigator must firstly identify the source of electrical heat before the determination of electrical fire. Besides, a fire investigator also must identify the path or method of heat transfer between the heat source and the first ignited fuel or combustible materials (NFPA 921, 2004).

Overcurrent is a condition in which the current flows in a conductor exceed the acceptable safety standards of that particular conductor (NFPA 921, 2004). The duration and magnitude of the overcurrent are the factors that determine if an ignition is possible to occur (NFPA 921, 2004). When there is an overcurrent condition, it heats the entire circuit through which the current flows. With increasing current magnitude or longer persistant of time, the heat could affect the thermoplastic materials that insulated the conductors in a circuit. As the conductor becomes hotter and reaches its melting temperature, blisters are formed alongside the conductor's surfaces, leading to an ignition of fire (Ettling, 1978). Therefore, overcurrent or excessive current through a wiring can cause the internal electrical damages.

On the other hands, fires from external source generally could also cause a succession of changes on the copper wires. When the copper wires are exposed to external flame, oxidation and discolouration could be occurred. After a period of time, there will be evolution of gases from the copper as the metal reaches its melting point that causes internal cavities and small blisters on the surface of the copper (Ettling, 1978). Also, the surface of the copper distorted where the striation created on the surface of the conductor during the manufacturing process becomes obliterated (NFPA 921, 2004).

1.2.4 Electrical wiring system

According to the National Electrical Code (2008), all conductors must be insulated in exemption where covered or bare conductors are specifically permitted elsewhere in the code (NFPA 70, 2008). In Malaysia, the use of insulated copper conductor is mandatory, especially in the installation or extension of wiring system according to Energy Commission (EC, 2008). Insulation prevents current from taking the unwanted paths and also protects against dangerous voltages in places that would be hazardous to people (NFPA 921, 2004). Insulating materials are made of any material that can be applied readily to conductors, does not conduct electricity, and retains its properties for a long period of time even at elevated temperatures (NFPA 921, 2004). There are many types of insulation applied to conductors such as polyvinyl chloride or PVC, rubber, polyethylene, and other polyolefins (NFPA 921, 2004).

Almost all electrical wiring composed of relatively high purity copper due to its high thermal and electrical conductivies. It is an excellent conductor due to the relatively little resistance to movement of conduction electrons under an electric field. Additionally, the outermost electrons of these conductors have a large mean free path, which requires only small cross section of copper to carry a high current (Pops, 1997). Commonly, aluminium wire does not survive in a fire as its melting temperature is very low (660 °C or 1219°F) resulting in the lost of arc damage evidence (Delplace & Vos, 1983). In Malaysia, the use of aluminium conductor is prohibited in building wiring system (EC, 2008).

1.3 Problem statement

Most electrical wiring in buildings and appliances utilised copper as conductor. In many instances, certain degree of damage can be found on that wire after a fire. The damages include the melting of copper conductors, formation of globules and beads as well as the thinning of the copper conductors. During investigation of fire cases, it is important for a fire investigator to determine the cause of the damages, either by heat of flame (external fire) or by the overcurrent fault in the wiring system. This study focused on the microscopic examination of the cross sectional features of externally and electrically burnt copper wire, the Fourier Transform Infra-red (FTIR) analyses as well as Principal Compent Analysis (PCA) of the burnt insulator of the electrical wires. The outcome of this study could serve as an evidence to distinguish between external flame and electrical fault damages on the burnt copper wire.

1.4 Aim and objectives

The aim of this research is to characterise the copper wire for fire source determination. In order to achieve the aim, the objectives of this study are as follow :

1. To investigate the difference in the diameter of unburn and burnt copper wire.
2. To examine the cross section of damaged copper wire caused by external and internal fire.
3. To analyse the organic profiles of insulator in copper wires subjected to external flame and electrical overcurrent scenarios using FTIR technique and to characterise the burnt insulators using PCA.

1.5 General approach

The general approach of the study is shown as in Figure 1.3. There were four phases involved in the study to achieve the aim and objectives of this study, namely the preparation of samples, measurement of the samples, microscopic examination of the cross section of the samples, as well as FTIR and PCA analysis of the insulation layer of the samples.

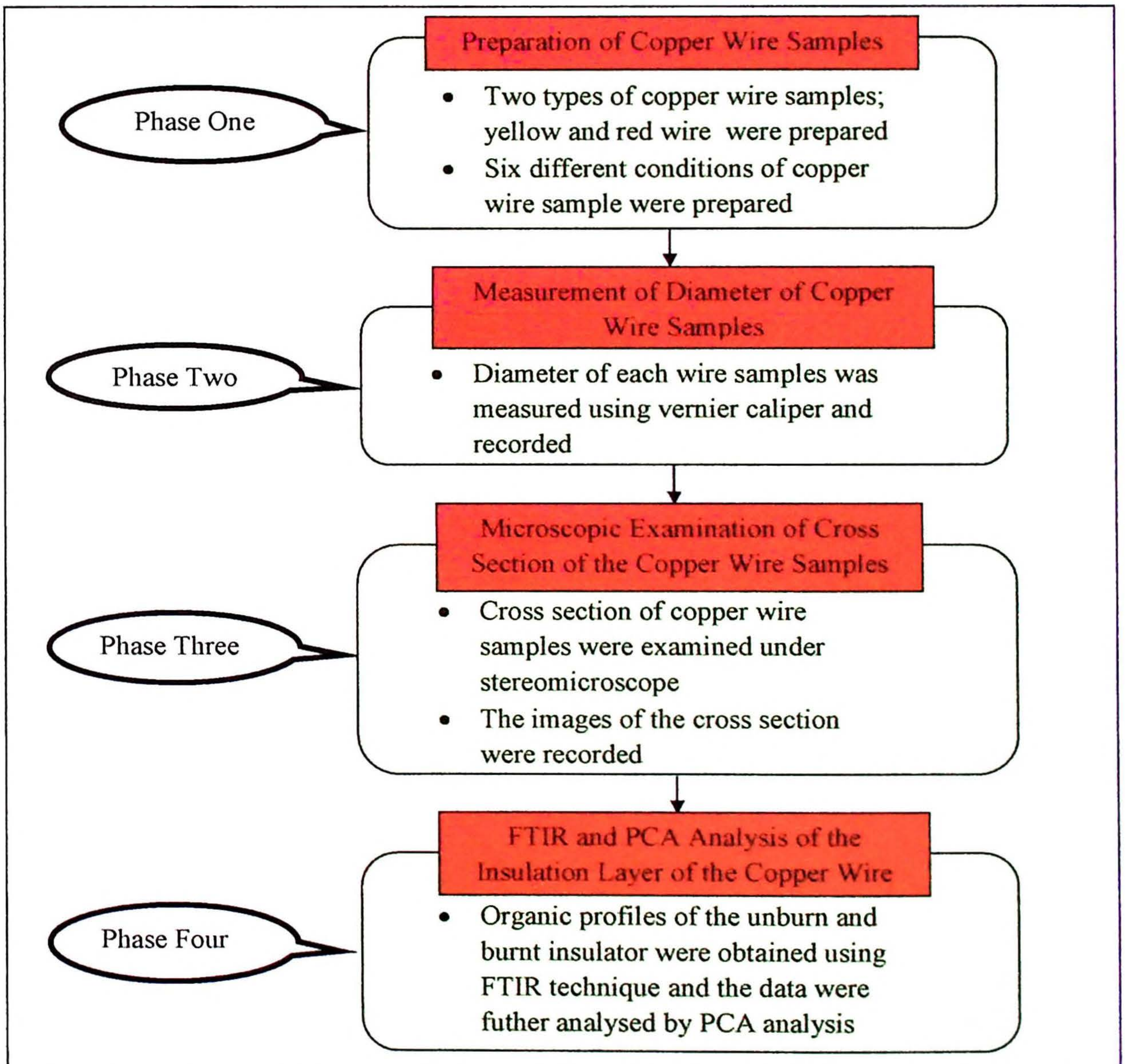

Figure 1.3: Flow chart showing of the general approach of the study

1.6 Significance of the study

Although beads and globules being the main signature for electrical originating fire investigation, this research attempted to focus on the characteristics of the cross section of the copper wires subjected to external flame and electrical fire burns. This research interest was on what happen within the copper wire due to external and electrical heating through the cross sectional microscopic examination of the insulated copper wire. Beside that, FTIR analysis of the burnt insulators showing different organic profiles due to different degree and source of burning could assist in electrical fire investigation. Further PCA analysis helps in characterisation of these burnt insulators on the basis of their causes of burning.

CHAPTER TWO

LITERATURE REVIEW

2.1 Microscopic examination of fire-damaged copper wire

Electrical faults in wiring systems produce certain characteristic damages that could be recognised after a fire. These characteristics frequently found on the conductors as well as on the insulation of these conductors which could be examined microscopically. The copper's cherry discolouration, the changes in cross section appearance, the sagging of insulation as well as the presence of sharp line demarcation could be the certain characteristic damages that can be examined microscopically.

2.1.1 Cherry discolouration of copper conductor

According to Redsicker and O'Conner (1997), heat applied to a copper conductor discoloured it to a cherry-red hue. In other words, it underwent cherry discolouration. The depth of the discolouration can help fire investigator to identify the sources of the heat by scrapping the surface of the conductor and examining the colour. If the original colour of the conductor was visible, the source of the heat was most likely from external source as the discolouration occurred only on the surface of that particular wire (Redsicker & O'Conner, 1997). If the cherry discolouration ran throughout the diameter of the conductor, the source of the damage was most likely from internal source either due to an electrical short, arcing, or other internal electrical problem (Redsicker & O'Conner, 1997).

2.1.2 Changes in cross section of copper wire

In 1983, Delplace and Vos established a close parallel between the pattern left after a combustion and the location of short circuits. Damages by electrical overcurrent (internal fire) were characterised by the presence of abrupt changes in cross sectional appearance, beads of copper, projection of copper and damage on adjacent conductors or metal cable shielding. In contrast, characteristics of damages from external flame were the presence of dripping or flow of copper which influenced by gravity, local and gradual thinning or thickening of wires, irregular shapes as well as the absence of drawing die marks (Delplace & Vos, 1983). Drawing die marks or the striations created on the conductor surface during manufacture was obliterated when copper conductors exposed to fire (NFPA 921, 2004).

2.1.3 Softening and sagging of insulations

According to Ettling (1978), insulating materials underwent a phenomenon called sleeving which was the softening and sagging of thermoplastic insulation of an electrical wire. In an overcurrent phenomenon with sufficient heat and time, insulation could be pyrolysed due to the thermal conductivity of the conductor (Beland, 1984). The plasticised PVC insulator was softened and sagged away from the conductor as it is heated from inside. In contrast, insulation that exposed to external flame tends to melt and burn while tightly hold to the conductor (Ettling, 1978). Levinson (1977) also suggested that melted, burned or missing insulation was the evidence that the wire was heated electrically, or internally (Levinson, 1977).

2.1.4 The presence of sharp line of demarcation

The presence of sharp line of demarcation between the melted and unmelted conductor surfaces was an indicator to identify beads and also to distinguish it from globules (Wright *et. al*, 2014). Ettling (1978) proposed that a rounded point could be formed on the end of copper conductors when they were heated beyond their melting point (Ettling, 1978). Moreover, a pronounced bead could be formed at the end of the broken copper conductors resulted from small arc due to overcurrent (Ettling, 1978). This characterristic was also found on copper conductors that experienced a short circuit or ground fault (Ettling, 1978). NFPA (2014) suggested the necessity of magnification and minor cleaning of arc beads to detect the demarcation line between melted and unmelted regions on a conductor in which the polished cross sections of arc beads could indicate high internal porosities (NFPA, 2014 cited by Wright *et. al*, 2014).

However, Babrauskas (2003) claimed that beads and globules could not be differentiated based on their external shape, surface smoothness, surface roughness, or size based on his review of various techniques that had been proposed for determining bead or globule that caused by fire or caused a fire (Babrauskas, 2003). Wright *et. al* (2014) agreed and stated that examination solely based on external appearances of beads and globules was not the reliable indicator on the cause of their formation (Wright *et. al*, 2014). In addition, Levinson (1977) also stated that the presence of beaded wire ends itself was not an evidence of electrical arcing even electrical arcs were expected to produce beads. The production of such droplets could also be produced when a wire was heated by external fire. In other hands, the absence of droplets was not a proof that the wire was not energised (Levinson, 1977).

2.2 Changes of insulation layer involved in fire

Liu *et. al* (2011) found that the first mass change and endothermal peak onset temperature for overcurrent and fire insulation layer to be different in which the cause of the fire can be probed using differential scanning calorimetry (DSC) analysis. The onset temperature of inner insulation layer is higher than that of outer insulation layer. In an overload condition (five times or more current flow), the inner and outer layer of the conductor live in different temperature. The inner PVC insulator layer damaged a lot at higher temperature and released a large amount of hydrochloric acid and volatile matter (Liu *et. al*, 2011).

Great damage can be observed on the inner and outer layer of insulator providing a longer period of overcurrent condition. Under this condition, the inner and outer layer of insulation layer were burnt severely which turned most of the insulation layer into carbide (Liu *et. al*, 2011). In contrast, the DSC analysis of insulation layer that was burnt externally showed that the onset temperature of outer insulation layer was higher than that of inner insulation layer. Observation was contrasted to the insulator burnt by overcurrent. Thus, Liu *et. al* (2011) suggested the possibility to distinguish PVC insulation residues between overcurrent and fire condition (Liu *et. al*, 2011). With such changes, spectra of electrical and external fire heating of insulators from FTIR analysis were expected to show differences between the varied conditions.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Materials

Materials utilised in this study were listed as follows:

i) Yellow insulated copper wire consists of stranded copper conductor

ii) Red insulated copper wire consists of stranded copper conductor

iii) Cutting pliers

iv) Scissors

v) Vernier calipers

3.2 Equipments

Equipments used in this study were as follows:

i) Transformer

ii) Acetylene torch (Map Pro™, Boulder City, NV)

iii) LEICA MZ16 Stereomicroscope (Leica Microsystem, Heerbrugs, Switzerland)

iv) LEICA TL RC1 Transmitted Light Base Rotterman Contrast Technique (Leica Microsystem, Heerbrugs, Switzerland)

v) LEICA MC 170 HD Digital Microscope Camera (Leica Microsystem, Heerbrugs, Switzerland)

vi) Dell 24" LCD HD TV Model S2440L (Dell, Round Rock, TX)

vii) Bruker FTIR Tensor 27 (Bruker Corporation, Billerica, MA)

3.3 Preparation of copper wire samples

For the purpose of visual examination, two electrical wire samples were studied. Each wire samples were cut to 15 cm using wire cutter and labeled accordingly. All the prepared wire samples were subjected to respective simulated scenarios as in Table 3.1 followed by the visual and microscopic examination.

Table 3.1: Different fire conditions subjected to wire samples

Burning condition	Descriptions
Control	An unburnt yellow insulated copper wire and an unburnt red insulated copper wire.
Instant external flame	A yellow and red insulated copper wire was burnt by flame from an acetylene torch for a very short period of time (about five seconds) producing an instant external burn to the copper wire sample.
Slightly external flame	A yellow and red insulated copper wire was burnt by flame from an acetylene torch for about 10 seconds producing a slight external burn to the copper wire sample.
Severely external flame	A yellow and red insulated copper wire were burnt by flame from an acetylene torch for more than 10 seconds producing a severe external burn to the copper wire sample.
Slightly electrical fault	A yellow and red insulated copper wire were connected to a complete circuit which consisted of a switch and a transformer, respectively. A slight overcurrent fault was introduced to the copper wire samples. The supply of electrical current was stopped before the wire was burnt entirely.
Severely electrical fault	A yellow and red insulated copper wire were connected to a complete circuit which consisted of a switch and a transformer, respectively. A severe overcurrent fault was introduced to the copper wire sample. The supply of electrical current was stopped once the electrical wire was burnt.

3.3.1 Introduction of external burnt of copper wire samples

The copper wire was clamped on two pieces of thin woods and paper clips were utilised on these two thin woods, holding the wire properly. Paper clips were utilised to fix the copper wire. The samples were then burnt by flame from acetylene torch producing instant, slightly and severely external burns to the wire samples, respectively. After that, the copper wire samples were packed separately according to the simulated conditions to prevent the mixing of samples. The samples were utilised for diameter measurement, followed by microscopic examination of cross section of these wire samples.

3.3.2 Introduction of overcurrent fault to the wire samples (internal burn)

The insulations of the wire samples were removed one centimeter from each end, respectively. After preparing the samples, one end of the copper wire was connected with the clamp connecting to the positive pole (+) of the transformer and another end was connected to the negative pole (-). Then, overcurrent condition was introduced by turning on the switch, and the current allowed to flow through the electrical wire. Supply of electrical current was stopped before burning to produce slightly burnt samples whereas the supply of electrical current was stopped immediately once the wire burning started to produce severely burnt samples. All the samples were clearly labeled and examined under microscope.

3.4 Diameter measurement of copper wire samples

The measurement was performed using vernier calipers (Figure 3.1). The diameter was measured at three different regions along the copper wire samples, represented by point A, B and C respectively, as illustrated in Figure 3.2. In every sample, three measurement at each region were taken to avoid gross error. Mean and standard deviation (SD) of diameter of each sample was calculated.

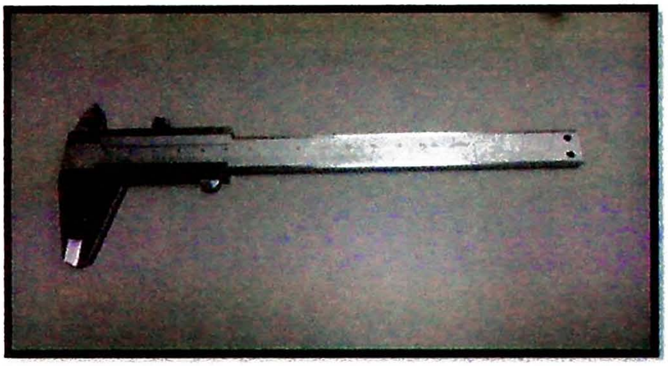

Figure 3.1: Vernier caliper

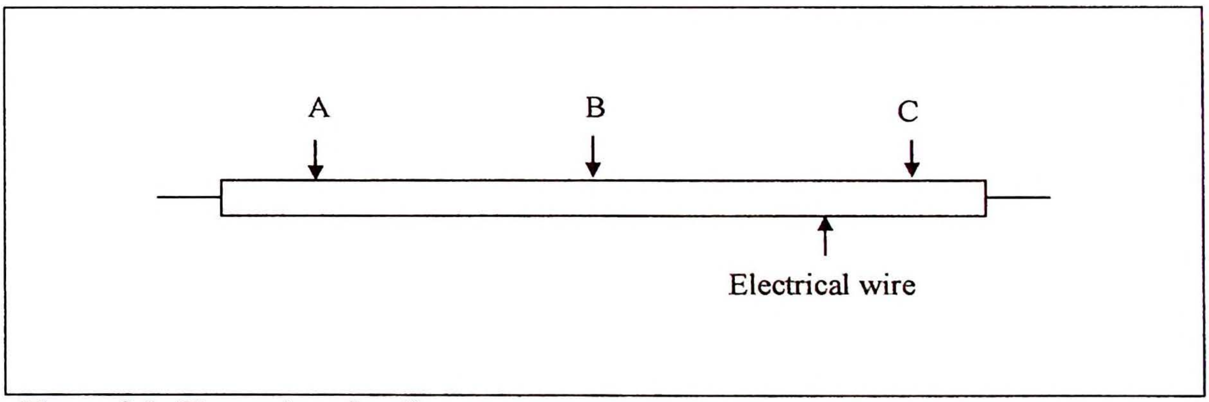

Figure 3.2: The regions for diameter measurement

3.5 Microscopic examination of the cross sectional features of the copper wire samples

In this study, LEICA MZ16 stereomicroscope was utilised. Digital images of the cross sectional features of wire samples were captured using LEICA MC170 HD digital microscope camera. The images were enhanced with the aid of LEICA TL RC1 Transmitted Light Base Rotterman contrast technique and they were visualised on Dell 24'' LCD HD screen TV model S2440L. Each sample was captured at magnification power ranging between 20X and 32X. The characteristics on cross sectional features for each sample were examined. Figure 3.3 illustrates the transmitted lightt base and stereomicroscope utilised in this study.

(a) (b)

Figure 3.3: (a) LEICA TL RC1 Transmitted Light Base, (b) LEICA MZ16 stereomicroscope

3.6 Fourier Transform Infra-red analysis of insulation layer

Organic profiles of insulator layer of copper wire was analysed using Fourier Transform Infra-red (FTIR) Tensor 27, a model from Bruker. FTIR–Attenuated Total Reflectance (FTIR-ATR) technique was utilised in this study. Before analysis, the insulation layer was separated from the copper conductor that initially covered by the insulator. A small portion of the insulator was cut and dissected. OPUS 7.0.122 software (Bruker Corporation, MA) was utilised for the spectra analysis In the analysis, absorbance versus wavelength spectrum of the insulation layer was obtained through 16 scans with scan ranges between 500 to 4000 wavenumber (cm^{-1}). All the samples analysed were stated in Table 3.1 (Section 3.3). Note that all the analyses were performed on both the outer layer and inner layer of the insulators.

The spectrum of each sample was taken in triplicate to ensure the repeatability. All spectra were compared and evaluated. The data from FTIR analyses was further analysed using Minitab 16 software (Minitab Inc.) for more specific and reliable characterisation of the copper wire based on PCA.

Figure 3.4: Bruker Tensor 27 FTIR