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Forensic Investigation of Electrical Conduct Copper Bead Microstructure as an Effort to Identify Causes of Fire

Sulistiana Agung Riyanto[1], Deni Ferdian[2]
[1,2)]Department of Metallurgy and Material Engineering, Faculty of Engineering, Universitas Indonesia
Depok 16424, Indonesia
Email : sulistiana.agung@ui.ac.id

Abstract

The purpose of this study was to evaluate the characteristics of the bead formed due to short circuit, overload and direct flame treatment on NYM 3x1.5 copper power cable. Handling of short circuit and overload is carried out at a current load of 800% of the current carrying capacity (144 Amperes) and direct flame treatment is carried out at a temperature of 960 degrees Celsius. The bead specimens formed from each treatment were examined and tested in the laboratory: chemical composition examination, visual inspection, macro and micro structural examination, hardness testing, and SEM-EDS examination. The difference in the characteristics of the arc bead that is formed under short circuit conditions and overload is that in short circuit conditions the damage point is localized at a certain point, namely at the short circuit contact point, while under overload conditions the point damage is localized at one or several specific locations along the wire. The macro characteristic of arc beads formed under short-circuit and overload conditions is that they contain many cavities and a clear transition boundary between the melted/re-solidified material and the non-melted material. While the characteristics of the granules in the form of globular formed in the direct flame treatment, do not show sharp transitions between melting/re-solidified materials. The micro structure of NYM 3x1.5 beads of electrically conducting copper wire material under the treatment conditions: short circuit, overload and direct ignition, is an alpha (α) phase dendritic structure.

Keywords: Short circuit; Overload; Direct flame; NYM 3x1.5; Bead

1. INTRODUCTION

Electrical factors as factors that cause fires can be preceded by various kinds of electrical events such as short circuits, overloads and other errors both in the selection/use of materials, as well as in the installation and causes of defects in electrical equipment [1]. In the event of an electrical fire, phenomena will be found in the electrical conductor in the form of deformation, for some incidents even the deformation that occurs is in the form of melting of the conductor which can cause the conductor to break. At the ends of the broken conductors, beads are often formed which in foreign terms are called bead [2]. Bead specimens resulting from short circuit, overload and direct flame treatments were characterized through chemical composition examination, visual inspection, macro and micro structural examination, hardness testing and SEM-EDS examination.

The purpose of this study was to determine the micro structural characteristics of the phenomenon of the NYM 3x1.5 copper electrical conductor bead which was

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deformed due to short circuit, overload and due to receiving heat from the environment (direct flame) during a fire.

2. METHOD

2.1 Material and Treatment

In this study the test sample used was one type of cable from the conducting cable which is commonly used by the general public found in material and electrical equipment stores. The size of the cable diameter is 1.38 mm with a Current Conducting Capability (KHA) of 4.0 kVA or 18 Ampere [3].

The treatment applied to the NYM 3x1.5 power cable is short circuit and overload at each load current of 800% KHA (144 Amperes) and direct flame treatment at 960 degrees Celsius [4, 5, 6], each specimen is coded as shown in the Table. 1.

Table 1. Identification for sample.

No	No Sample	Identification
1	Cu0	Initial state of electrical conductor
2	SCN800	Electrical conductive wire with short circuit treatment conditions at 800% KHA
3	OLN800	Electrically conductive wire under overload treatment conditions at 800% KHA
4	DFN960	Electrical conducting wire with direct flame treatment conditions at a temperature of 960 degrees Celsius

The first sample was prepared as an original electrical conductor wire of copper from NYM 3x1.5 electrical cable.

2.2 Empirical calculations

ICEA (Insulated Cable Engineers Association) of the United States department of mining states that the relationship between current strength and temperature of copper conductors in a short circuit situation [7] is as follows:

$$\left(\frac{I}{A}\right)^2 tF_{ac} = 0.0297 log_{10}\left(\frac{T_f+234}{T_i+234}\right) \quad (1)$$

Where:

I = short circuit current (A)

A = surface of conductor, circular mil (c mils = 1/6400 full turn)

t = short circuit grace period (seconds)

Fac = surface effect or AC/DC ratio.

Tf = final temperature after change in current (C)

Ti = initial temperature before change in current (C)

The temperature of the copper conductor that occurs at the overload current according to the standards from the IEEE (Institute of Electrical and Electronic Engineers) follows the following equation [7]:

$$\frac{I_0}{I_n} = \sqrt{\frac{\frac{T-T_a}{T_n-T_a}-\left(\frac{I_i}{I_n}\right)^2 e^{-t/K}}{1-e^{-t/K}}\left(\frac{230+T_n}{230+T}\right)} \quad (2)$$

Where:

I0 = over current (A)

In = normal current (A)

T = conductor temperature (C)

Tn = normal temperature of the conductor (C)

Ta = ambient temperature (C)

Ii = current before overload (A)

t = grace period for overload (seconds)

K = constant that depends on the size of the conductor.

3. RESULT AND DISCUSSION

The experiment of making ‘bead’ samples from each NYM 3x1.5 copper electrical conductor sample with three different treatment groups namely short circuit and overload treatment with current: 800% of ability to conduct current (144 Ampere) and direct flame heating with a heating temperature between 900-1000^{o}C (960^{o}C). The results obtained from these experiments as shown in Figure 3.1.

Figure 3.1 Short Circuit, Overload and Direct Flame treatment experiments.

3.1 Chemical Composition

The results of examining the chemical composition of the NYM 3x1.5 copper wire are shown in Table. 2 below:

Table. 2 Data on the results of the examination of the chemical composition of the material for electrically conductive copper wire.

Unsur	Result of Chemical Composition Test (%-wt)	Chemical Composition Standard: C12200 - *(phosphorus deoxidized copper, high residual phosphorus)* [8]. (%-wt)
Pb	0,0553	-
P	0,0108	0,0200
Mn	0,0136	-
Fe	0,0762	-
Ni	0,1120	-
Cu	**99,500**	**99,900**

The results of the chemical composition examination showed that the NYM 3x1.5 copper electrical conductor wire material as a whole complies with or belongs to the type C12200 - copper (phosphorus deoxidized copper, high residual phosphorus) with a purity level of 99.90%, but the chemical composition of the copper wire material used as NYM 3x1.5 electrical conductor has a purity level of 99.50% meaning that in the manufacturing process there are still impurities as other unwanted elements with a total content of 0.4%. The presence of these impurities will reduce the electrical conductivity of the electrically conducting wire material, besides that it will also affect the increase in the strength of the material.

3.2 Visual Inspection

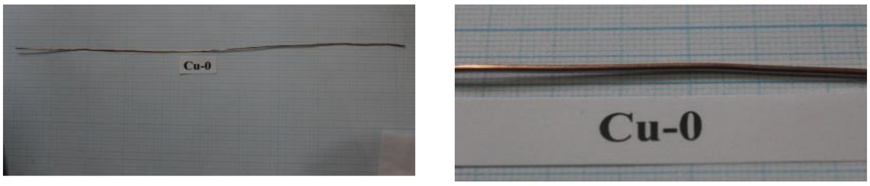

Figure 3.2 Visual inspection of the initial condition of the copper wire.

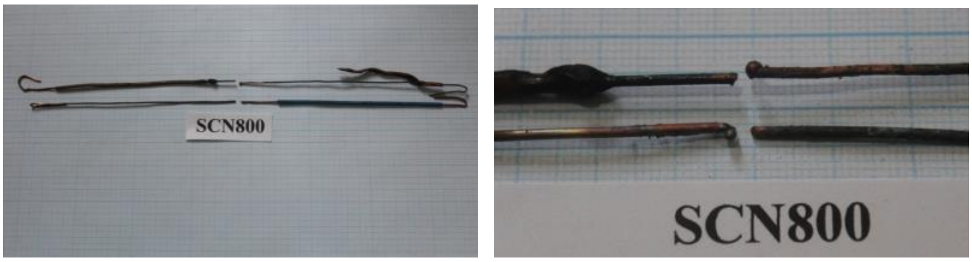

Figure 3.3 Visual inspection of copper wire of short circuit condition, current 800% ACC (144 Amperes).

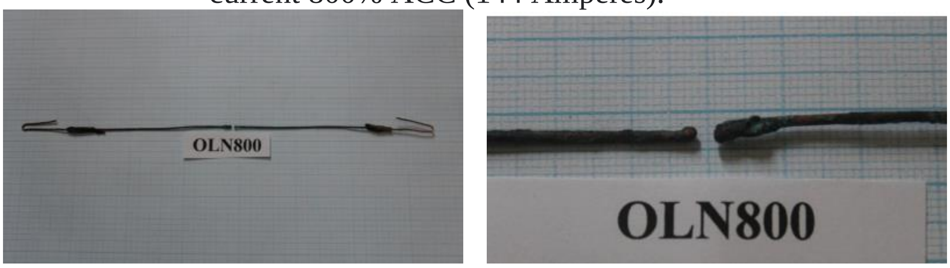

Figure 3.4 Visual inspection of copper wire of overload condition, current 800% ACC (144 Amperes).

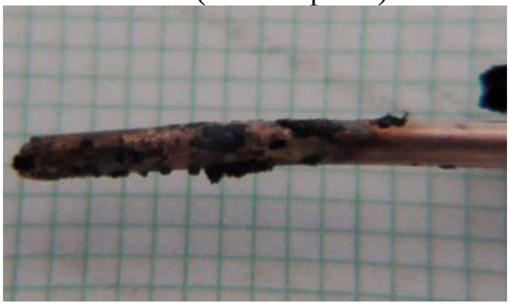

Figure 3.5 Visual inspection of copper wire of direct flame treatment, temperature 960^{o}C.

Figure 3.1 shows a visual inspection of the NYM 3x1.5 electrically conducting copper wire in the initial conditions. In particular the characteristics of the beads formed in the short circuit treatment Figure. 3.3. The surface shape of the bead tip is round and smooth, the damage point is localized at a certain point, namely at the short circuit contact point. Damage areas can be identified which are interconnected from the cable conductors and the loss of material in the form of a localized basin. Also, several small bead and scratch-shaped holes scattered over a large area narrow [9].

Whereas specifically the characteristics of the beads formed during the overload treatment Figure. 3.4. The surface shape of the bead tip is round and smooth, the crash point is localized to one or more specific locations, and the damaged areas can be identified along the conducting wires.

As well as the characteristics of the beads in the form of lumps formed in the heating Treatment with direct flame Figure. 3.5. Melt wire is round in shape (different from beads), and visually, flame-melted wire does not show sharp transitions between molten/re-solidified material [10].

3.3 Macro and Micro Structural Examination

Based on the examination of the macro and micro structures it can also be stated that the beads as shown in Figure 3.6– Figure 3.9, usually show three zones/ regions [11]: 1. The surface layer, which contains many cavities. 2. An intermediate layer that does not melt, but re-crystallizes, and 3. The inner layer, where the material does not melt and does not crystallize again.

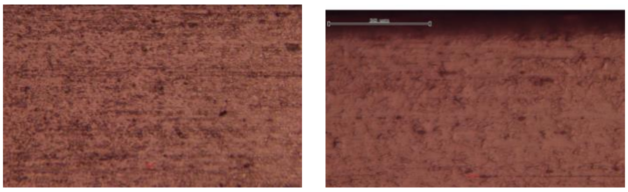

Figure 3.6 Results of examining the macro and micro structures of copper wire in the initial conditions.

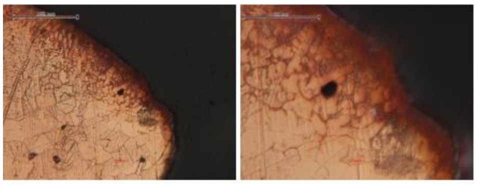

Figure 3.7 Results of inspection of the macro and micro structures of copper wire experimental results of short circuit treatment at 800% ACC (144 Ampere).

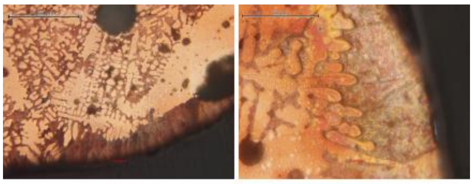

Figure 3.8 Results of examining the macro and micro structures of copper wire from the overload treatment experiment, current 800% ACC (144 Ampere).

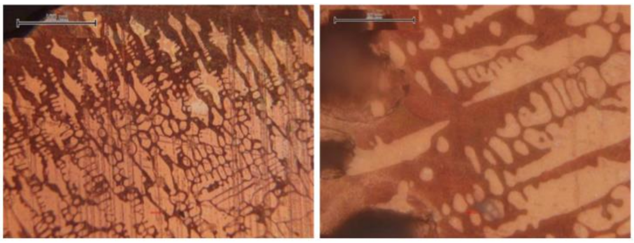

Figure 3.9 The results of examining the macro and micro structures of copper wire as a result of direct flame heating experiments at a temperature of around 960 degrees Celsius.

Based on observations of the microstructure also shows the following characteristics [12, 13]:

1. The microstructure of copper electrical conducting wire is an alpha (α) phase with uniform and homogeneous fine grains.
2. Microstructure of copper electrical conductor wire with short circuit treatment, changes in micro structure only on the bead.

3. Microstructure of copper electrical conductor wire with overload treatment, there is a change in the micro structure along the conductor wire.
4. Microstructure of copper electrical conductor wire with direct flame treatment, micro structural changes occur at the tip and neck of the bead.

Arc beads due to overload treatment, the heat generated occurs and is almost the same along the conductor, so it can also cause a lot of conductor disconnection or the beads formed, compared to the beads formed due to short circuit or direct fire. Arc beads due to the short circuit treatment, the time and mechanism are very different from other treatments, in this short circuit treatment the time is relatively very short and accompanied by throwing of melted material (spatter), so that the damage appears significant in the form of holes (pitting) due to the during re-crystallization many air voids were formed, and damage in the form of holes was also seen on the bead. As a result of the direct flame treatment of the arc bead, metal oxides, especially copper oxide, can be formed, and the melting and re-crystallization processes can occur slowly, which can also cause defects due to trapped air [12].

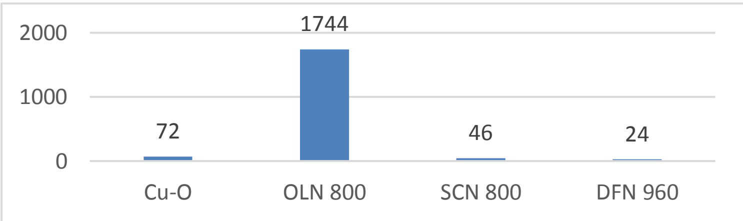

Figure. 3.10 Grain size (micron) comparison graph of various conditions of electrically conducting copper wire

In the beads due to the overload treatment (OLN 800), the heat generated occurs and is almost the same along the conductor, so that it can also cause many pieces of the conductor to occur or the beads to be formed, compared to the beads formed due to a short circuit or with a direct flame. This is what causes the grain size in the micro structure to be relatively larger compared to other treatments.

3.4 Hardness Testing

The hardness test was carried out microscopically on electrically treated copper wires (short circuit and overload) and direct flame treatment. Data on hardness test results are shown in Figure 3.11.

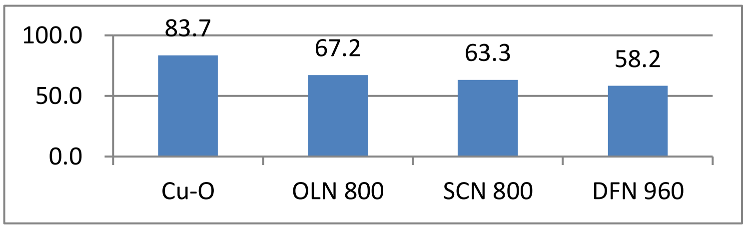

Figure. 3.11 Hardness comparison graph (HV) of various conditions of electrically conducting copper wire.

In each condition of short circuit, overload, and direct flame treatment it can be stated that the amount of current and temperature received by the electrically conducting copper wire will cause a decrease in the hardness of the copper wire.

3.5 SEM-EDS Examination

The results of SEM-EDS examination of copper wire and beads formed from the results of short circuit and overload treatment experiments as well as the results of direct flame heating experiments are shown in Figure 3.12 to 3.15.

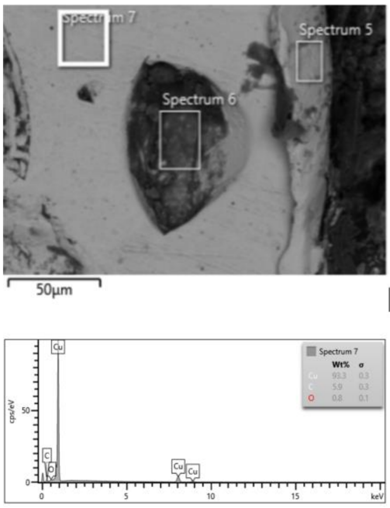

Figure 3.12 Results of SEM-EDS inspection of copper wire at initial conditions.

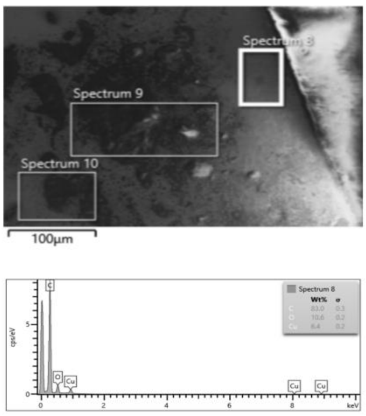

Figure 3.13 The results of SEM-EDS examination of copper wire beads as a result of the 800% KHA (144 Amperes), short circuit treatment.

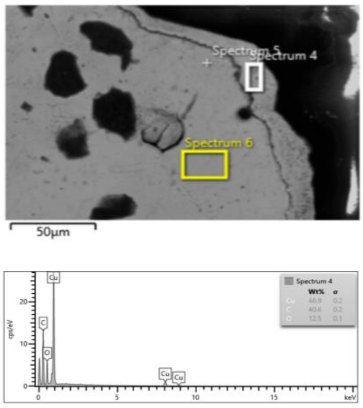

Figure 3.14 The results of SEM-EDS examination of copper wire beads as a result of the 800% KHA (144 Amperes), overload treatment.

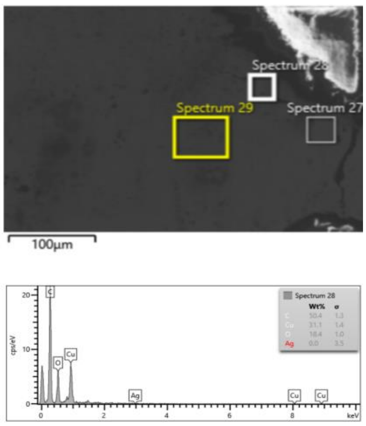

Figure 3.15 The results of SEM-EDS examination of copper wire beads as a result of the direct flame treatment at 960 degree Celsius.

Furthermore, based on the SEM-EDS examination, several things can be identified that are in accordance with the results of the macro and micro structure examination, namely as follows: Bow beads contain many voids. Top/surface layer, middle layer and inner layer are clearly visible, and the presence of elemental oxygen was detected.

3.5 Result of Empirical calculations

The relationship between the electric current passing through the electric wire conductor is presented in equations 1 and 2, so that this relationship can be described graphically as shown in Figures 3.16 and 3.17.

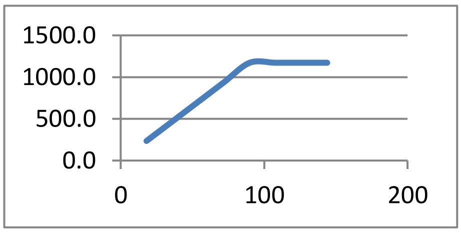

Figure 3.16 The relationship between the load electric current and the temperature (^{o} C) that occurs in the NYM 3x1.5 copper conductor in a short circuit condition.

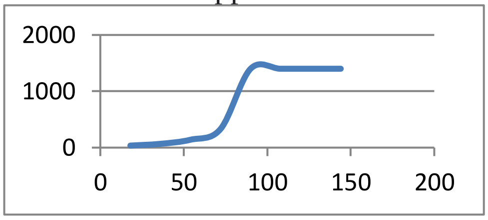

Figure 3.17 The relationship between the load electric current and the temperature (^{o} C) that occurs in the NYM 3x1.5 copper conductor in a overload condition.

Based on the results of the empirical calculations above which are calculated based on the time of electric current of 60 seconds, electrical disturbances in the form of short circuits or overloads indicate that for the NYM 3x1.5 type of electrical cable, the temperature will increase until it reaches the melting point of copper wire (1083^{o}C) when energized electric current 800% ACC of 144 Amperes. Based on the graph calculation of the relationship between current (amperes) and temperature (^{o} C) shown in Fig. 3.16 and 3.17 above, it can be seen that the amount of electric current (Amperes) that can cause a temperature rise to reach the melting point of the copper conducting wire material (1083^{o}C) in a shot circuit fault is 83.2 Amperes, while in an overload fault it is 84.7 Amperes.

It can be stated that according to the PUIL 2000 and SPLN 42-2:1992 standards, NYM 3x1.5 copper electrical conductor has the following meaning: N (standard copper conductor cable), Y (PVC inner insulating sheath), M (PVC outer insulating sheath), this type of cable is a type (multi-core) with 3 cores or 3 cores and a cross-sectional area of 1.5 mm2 and a rated voltage, re (round wire cross-section) of 300/500 Volts and has a ACC (Ability to Conduct Current), which is the maximum current that can flow continuously by the conductor under certain conditions without causing a temperature increase that exceeds a certain value, namely 18 Ampere. Meanwhile, copper wire as a conductor of electricity has high electrical conductivity, namely 57 $\Omega\, mm^2/m$ at 20° C and a temperature coefficient (α) of copper 0.004 /° C.

Also can be stated that characteristics of the beads: 1. The beads due to the short circuit treatment, the timing and mechanism are very different from other treatments, in the short circuit treatment the time is relatively very short and is accompanied by throwing of melted material (spatter), so that the damage appears significant in the form of holes (pitting) because at the time of re-crystallization many air cavities were formed, and damage in the form of holes was also visible on the bead. 2. The beads due to overload treatment, the heat generated occurs and is almost the same along the conductor, so that it can also cause many pieces of the conductor to occur or the beads formed, compared to the beads formed due to short circuits or direct flames. 3. The beads due to direct flame treatment for ±5 minutes, metal oxides, especially copper oxide, can be formed and this is also the case with the melting and re-crystallization processes, which can occur slowly so that they can also cause defects due to trapped air.

Overall in all treatment conditions: short circuit, overload current with an electric current load below 800% ACC (144 A) there is a relative difference in grain size which is still relevant compared to the grain size of the microstructure the starting material of the electrically conducting copper wire, except for the treatment which causes the melting and freezing process to occur when the melting temperature is reached so that a dendritic phase is formed which is relatively hard and brittle. Changes in the microstructure cause changes in the mechanical properties of the material, and the microstructure is greatly influenced by the treatment received by the material. Overall, in all treatment conditions: short circuit, overload and direct flame, relatively caused a decrease in hardness compared to the initial hardness of electrically conducting copper wire. This is due to changes in the microstructure associated with the grains, namely re-crystallization and grain growth and even the melting and freezing processes when the melting temperature is reached. The presence of oxygen elements in the beads indicates the formation of copper oxide.

The amount of current (Amperes) that can cause the temperature of the NYM 3x1.5 copper conductor wire to rise to its melting point (1083° C) in short circuit and overload electrical disturbances is relatively the same, namely between 83-85 Amperes, this also evidenced by the formation of beads. Based on the comparison between the 2 graphs above, it can also be stated that the temperature increase in electrically conducting copper wire in the short circuit treatment is relatively higher than the overload treatment. Certain contacts while in overload conditions, the current that causes heat to occur along the copper conductor wire.

4. CONCLUSION

Based on the results of research on the characterization of bead due to the effect of short circuit, overload and direct flame treatment, conclusions can be drawn including:

1) The damage point short circuit conditions is localized at a certain point, while under overload conditions the point damage is localized at one or several specific locations along the wire.
2) The macro characteristic of arc beads formed under short circuit and overload conditions is that they contain many cavities and a clear transition boundary between the melted/re-solidified material and the non-melted material. While the characteristics of the granules in the form of globular formed in the direct flame treatment, do not show sharp transitions between melting/re-solidified materials.
3) The micro structure of NYM 3x1.5 beads under short circuit, overload and direct ignition conditions is an alpha (α) phase dendritic structure. Overall in short circuit, overload conditions, the current with an electric current load below 800% ACC (144 A) there is a relative difference in grain size which is still relevant compared to the grain size of the micro structure of raw material, except for the treatment which causes the melting and freezing process to occur when the melting temperature is reached so that a dendritic phase is formed which is relatively hard and brittle.
4) The overall hardness (HV) of short circuit, overload and direct flame conditions is relatively causing a decrease in hardness compared to the initial hardness of the raw material (85.6 HV).

5) Based on the SEM-EDS examination, several things can be identified that are in accordance with the results of the macro and micro structure examination, the presence of elemental of oxygen element.
6) The amount of current (Amperes) that can cause an increase in the temperature of the NYM 3x1.5 copper conductor wire until it reaches its melting point (1083^{o} C) during short circuit and overload electrical faults is relatively the same, namely between 83-85 Amperes.

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