X-ray fluorescence spectrometry (XRFS) analysis of aluminum cable types commonly used in electric power distribution

B. J. Kwaha and O. M. Durodola
Department of Physics, University of Jos, Nigeria
kwahab68@yahoo.com

Abstract

A comparative analysis of 5 different aluminum cable types tagged J_1, J_2, J_3, J_4 and J_5 from 5 different cable manufacturing companies was carried out using 2 different test methods namely- x-ray fluorescence spectrometry (XRFS) and resistivity test with the main objective of ascertaining why some cables of the same gauge fail under the same load levels. Purity levels, resistivity and conductivity checks were performed. Equal dimensions of 5 cable brands were sampled and ground to fine powder. The percentage purity of each sample was determined through XRFS test. One set of similar samples was subjected to resistivity test. XRFS result shows that J_1 had purity of 99.30%, J_2, 99.10%, J_3, 98.50%, J_4, 99.20% and J_5, 98.80%. The cable types also had resistivity and conductivity values respectively as for J_1 [$2.324\times10^{-9}\ \Omega$ m & $430.29\times10^{6}\ (\Omega m)^{-1}$], J_2 [$3.921\times10^{-9}\ \Omega$ m & $255.04\times10^{6}\ (\Omega m)^{-1}$], J_3 [$2.689\times10^{-9}\ \Omega$ m & $371.89\times10^{6}\ (\Omega m)^{-1}$], J_4 [$2.614\times10^{-9}\ \Omega$ m & $382.56\times10^{6}\ (\Omega m)^{-1}$], and J_5 [$2.890\times10^{-9}\ \Omega$ m & $346.60\times10^{6}\ (\Omega m)^{-1}$]. Comparing these values to the standard resistivity value of pure aluminum [$2.82\times10^{-8}\ \Omega$ m] it would be seen that these results are in agreement with theoretically computed values. The XRFS test used in this research could be used to test the purity of aluminum before stretching into cables. It can also be used to determine the standard of aluminum products. The electrical resistivity test could be used to determine and set a standard resistivity and conductivity requirements to be met by different cable brands and types used in electric power distribution so as to curb the menace of cable failure and electric hazards.

Keywords: Qualitative analysis, aluminum, cable types.

Introduction

Aluminum is one of the most widely used metals for manufacturing different types of electrical cables. Its use as an option for electrical cables is on the increase. Although, reduced cost is the main incentive to the use of aluminum in cable making, other advantages are abound. Aluminum is one of the most economically viable metals and hence cables from it are cheaper than those of copper, their nearest competitor. Aluminum is the most abundant element on earth, after oxygen and silicon and makes up about 8% by weight of the earth's solid surface (Polmear, 1995). However, aluminum is too chemically reactive to occur in nature as a free metal, but mostly found in bauxite ore, Al_2O_3 combined in over 270 different minerals (Shakhashiri, 2007). Some desirable properties that make aluminum a suitable material for electrical cables and wires are its light weight, high electrical conductivity, high ductility, high strength, high resistance to corrosion and low cost. Aluminum is non-magnetic in nature (Elmsley, 2001; Tipler, 2004) and can be easily machined and recycled. Aluminum is an industrial metal produced commercially from bauxite by electrolysis with purity ranging from 99%-99.9% (Higgins, 1971). Pure aluminum metal is soft, but it is strengthened by alloying with copper, magnesium, silicon or manganese before it can be used (Higgins, 1971). When aluminum nears its melting point, it becomes "hot short" and crumbles easily.

This paper aims at comparing and assessing different brands of aluminum cables (wires) from various manufacturing companies to determine which are best for domestic electrification as chemical analysis and analyses of electrical properties will be carried out on each brand of cables (wires) to determine their constituent substances and impurity concentration cum electrical conductivity and resistivity.

Theoretical background

Chemical analysis: X-ray fluorescence spectrometry (XRFS)

XRFS is one of the most widely used methods for analytical techniques in industries today. The machine used consists of a high voltage source which powers the x-ray tube. The x-ray from the tube irradiates the milled sample generating secondary fluorescence which corresponds to the characteristic of each element in the sample. These characteristic x-rays are separated by spectrometer into individual wavelengths and energies and measured by a detector. The method is non-destructive and is used to identify and determine concentration of elements present in solids, liquids or powdered samples. XRFS can be applied over a wide range of concentration from 1 ppm to 100% (Larson, 2008). XRFS is also capable of measuring all elements from beryllium (Be) to uranium (U). XRFS can be applied in industries and research because of its ability to give accurate and reproducible analysis at very high speed. Samples for XRFS analysis should be presented to the spectrometer in a homogenous reproducible form. Metal samples must be milled or ground to give a flat surface. However, substances that undergo phase transitions may not be analyzed on this machine.

Determination of electrical properties

Electrical properties of cables (resistance & resistivity) are determined using the meter bridge set up shown in Fig.1. The unknown resistance R_1, of the length of wire AB is given by equation (1).

$$\frac{R_1}{R_2} = \frac{L}{100 - L} \qquad (1)$$

$$R_1 = \frac{LR_2}{100 - L}$$

The slope of a graph of R against L is used to determine the resistivity of the samples with equation (2), where d is the measured diameter of cable wire
$\rho = п(d/2)^2$x slope (2)

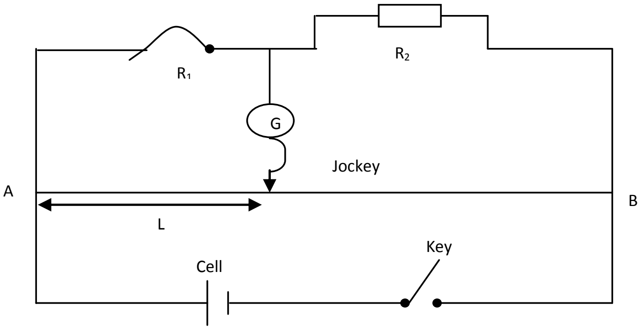
Table 1. General properties of aluminum (Higgins, 1971; Allen, 1983; Dieter, 1988; Polmear, 1995; Griffiths, 1998; Wikipedia, 2009)

Symbol, number	A1, 12
Group period, block	12, 3, p,
Appearance	Grey
Standard atomic weight	26, 9815386g/mol
Electron configuration	Is^2 2s^2 2p^6 3s^2 3p^1
Electron per shell	2, 8, 3.
Magnetic ordering	Paramagnetic
Electrical resistivity	(at 20^{0}C) 28.1 Ω/m
Thermal conductivity	(at 25^{0}C) 23.1 Nm. m^{-1} k^{-1}
Thermal expansion	(at 300k) 237 W.m^{-1} k^{-1}
Speed of sound (thin rod)	Groom temperature (rolled) 500m/s
Young's modulus	70Gpa
Shear modulus	26Gpa
Bulk modulus	76Gpa
Poisson ration	0.35
Mohs hardness	2.75
Vickers hardness	167Mpa
Brinell hardness	245.Mpa
Phase	Solid
Density (near room temperature)	2.70g/cm^3
Liquid density at melting point	2.375g/cm^{-3}
Melting point	933.47k (660.32^{0}C, 1220.58^{0}F).
Boiling point	2792k (2519^{0}C, 4566^{0}F)
Heat of fusion	10.7J/mol
Heat of vaporization	294.0kJ/mol
Specific heat capacity	(25^{0}C) 24.200J/mol.k.
Crystal structure	Face centered cubic (0.40494nm).
Electro-negativity	1.61 (Pauling scale)
Ionization energies	1st: 577.5k J/mol; 2nd: 1816.7k J/mol; 3rd: 2744.8k J/mol
Atomic radius	125 picometer (pm)
Covalent radius	118 picometer (pm)

Materials and methods

Five samples of aluminum cables available in Nigerian market were collected from various companies and tested:

Fig. 1. Meter bridge setup.



Sample J_1: Alind aluminum cable, *Sample J_2:* Curtix aluminum cable, *Sample J_3:* Moonlight aluminum cable, *Sample J_4:* Sunrise aluminum cable and *Sample J_5:* Newcon aluminum cable.

Chemical analysis

The samples were ground and sieved to 75μm particle size. 4g of the sieved sample was intimately mixed with 1 g of lithium tetra-borate binder ($Li_2B_4O_7$) and pressed in a mould under a pressure of 10-15 tons/in^2 to a pellet. The pressed pellets were dried at 110^{0}C for 30 min in an oven to get rid of absorbed moisture. The spectrometer was switched on and allowed to warm up and stabilize the optics and x-ray tube. It was then calibrated to determine the expected element present in the samples. Samples were run using the prepared calibration programs and the elements concentrations present in the samples were calculated and displayed after applying automatic statistics to the results by the spectrometer. These results are shown in Tables 2 and 3.

Electrical analysis

1. The meter-bridge was set up to determine unknown resistance for each sample of wire (J_1 to J_5) for varying lengths of 10, 20, 30, 40 and 50cm as shown in Table 4.
2. A graph of R against L was plotted for each sample and each slope was obtained using spreadsheet.
3. Resistivity and conductivity values of the samples were calculated and shown in Table 6.

Result and analysis

Results of chemical analysis using the x-ray fluorescence spectrometry are shown in Tables 2 and 3, while results of electrical analysis to determine resistivity and conductivity of sampled wires using meter-bridge are shown in Tables 4 and 6 respectively.

Discussion

The paper compared and assessed 5 different aluminum cables from different manufacturing industries namely, Alind, Curtix, Moonlight, Sunrise and Newcon-used in domestic electrification in Nigeria with a bid to assess the validity of failure rate usually associated to the use of aluminum cables. A common phenomenon is that

Table 2. Data from spectroscopy.

Sample J_1	% Al	% P	% S	% Si	% K	% Ca	% Ti	% V	% Cr	% Mn
	99.33	0.08	0.09	0.10	ND	0.10	0.006	ND	0.004	0.01
	% Fe	% Ni	% Cu	% Zn	% Se	% Ba	% As	% Ga	% Pb	
	0.15	0.003	0.01	0.01	ND	0.03	ND	0.008	ND	
Sample J_2	% Al	% P	% S	% Si	% K	% Ca	% Ti	% V	% Cr	% Mn
	99.10	0.12	ND	0.26	ND	0.19	0.01	ND	0.01	0.007
	% Fe	% Ni	% Cu	% Zn	% Se	% Ba	% As	% Ga	% Pb	
	0.14	0.002	0.03	0.01	ND	ND	0.002	0.02	ND	
Sample J_3	% Al	% P	% S	% Si	% K	% Ca	% Ti	% V	% Cr	% Mn
	98.50	0.34	ND	0.50	ND	0.28	ND	0.01	0.008	0.01
	% Fe	% Ni	% Cu	% Zn	% Se	% Ba	% As	% Ga	% Pb	
	0.24	0.01	0.04	0.004	0.004	ND	0.01	0.01	0.03	
Sample J_4	% Al	% P	% S	% Si	% K	% Ca	% Ti	% V	% Cr	% Mn
	99.20	0.11	0.06	0.11	0.03	0.13	0.01	ND	0.005	0.01
	% Fe	% Ni	% Cu	% Zn	% Se	% Ba	% As	% Ga	% Pb	
	0.21	0.004	0.02	0.006	ND	0.02	ND	0.007	ND.	
Sample J_5	% Al	% P	% S	% Si	% K	% Ca	% Ti	% V	% Cr	% Mn
	98.80	0.13	0.10	0.08	0.04	0.31	0.009	ND	0.006	0.01
	% Fe	% Ni	% Cu	% Zn	% Se	% Ba	% As	% Ga	% Pb	
	0.25	0.007	0.01	0.02	ND	0.33	ND	0.006	ND	

Table 3. Percentage chemical composition of samples.

Chemical elements	Samples (%)				
	Sample J_1	Sample J_2	Sample J_3	Sample J_4	Sample J_5
Al	99.33	99.10	98.50	99.20	98.80
P	0.08	0.12	0.34	0.11	0.13
S	0.09	ND	ND	0.06	0.10
Si	0.10	0.26	0.50	0.11	0.08
K	ND	ND	ND	0.03	0.04
Ca	0.10	0.19	0.28	0.13	0.31
Ti	0.006	0.01	ND	0.01	0.009
V	ND	ND	0.01	ND	ND
Cr	0.004	0.01	0.008	0.005	0.006
Mn	0.01	0.007	0.01	0.01	0.01
Fe	0.15	0.14	0.24	0.21	0.25
Ni	0.003	0.002	0.01	0.004	0.007
Cu	0.01	0.03	0.04	0.02	0.01
Zn	0.01	0.01	0.004	0.006	0.02
Se	ND	ND	0.004	ND	ND
Ba	0.03	ND	ND	0.02	0.33
As	ND	0.002	0.01	ND	ND
Ga	0.008	0.02	0.01	0.007	0.006
Pb	ND	ND	0.03	ND	ND

ND=Not detectable

of cable failure leading to cables melting under loads it is expected to handle conveniently.

Summary of chemical analysis

The percentage chemical composition of each cable was obtained chemically using the XRFS test at national metallurgical development centre (NMDC), Jos. The chemical analysis; showed that J_1 has the highest percentage purity of aluminum- 99.30%. After which is J_4-99.20%, J_2-99.10%, J_5-98.80% and J_3-98.50%. Also J_1 has the highest percentage of copper which improves its strength and conductivity (Davis, 1999). The results also showed the chemical constituents of the aluminum cables to include; Phosphorus (P), Sulphur (S), Silicon (Si), Potassium (K), Selenium (Se), Vanadium (V), Calcium (Ca), Titanium (Ti), Chromium (Cr), Manganese (Mn), Iron (Fe), Nickel (Ni), copper (Cu), Zinc (Zn), Barium (Ba), Arsenic (As) Gallium (Ga) and Lead (Pb) but not all of these are contained in all the cable samples.

Sample J1 does not contain As, K, Se, V, Pb; Sample J_2 does not contain S, K, V, Se, Ba, Pb; Sample J3 does not contain S, K, Ti, Ba; Sample J4 does not constitute V, Se, As, Pb and Sample J5 does not constitute V, Se, As, Pb. According to Davis (1999) the constituent elements can

Table 4. Measured values of balance points & unknown resistance of sampled wires.

Sample	Length, Y (CM)	Balance point, *L*	Unknown resistance, R_1 $R_1 = \dfrac{LxR_2}{100-L}$ (Ω)
J_1	10.0	5.76	0.122
	20.0	6.10	0.130
	30.0	6.50	0.140
	40.0	7.00	0.150
	50.0	7.40	0.160
J_2	10.0	4.70	0.099
	20.0	5.40	0.144
	30.0	6.30	0.135
	40.0	7.30	0.158
	50.0	8.30	0.181
J_3	10.0	12.70	0.291
	20.0	13.20	0.304
	30.0	14.90	0.350
	40.0	15.20	0.360
	50.0	16.10	0.386
J_4	10.0	5.50	0.116
	20.0	5.80	0.123
	30.0	6.20	0.132
	40.0	6.80	0.146
	50.0	7.50	0.162
J_5	10.0	6.20	0.132
	20.0	7.10	0.163
	30.0	7.80	0.169
	40.0	8.60	0.188
	50.0	9.50	0.210

Table 5. Values of length & unknown resistance for various samples (Used for spread sheet).

Length (cm)	Unknown Resistance, R_1 (Ω)				
	Sample J_1	Sample J_2	Sample J_3	Sample J_4	Sample J_5
10.0	0.122	0.099	0.291	0.116	0.132
20.0	0.130	0.144	0.304	0.123	0.163
30.0	0.140	0.135	0.350	0.132	0.169
40.0	0.150	0.158	0.360	0.146	0.188
50.0	0.160	0.181	0.386	0.162	0.210

Table 6. Resistivity & Conductivity Values of Sampled Wires.

Sample	Mean resistance, R (Ω)	Resistivity ρ (Ωm) $\pi(d/2)^2$x slope	Conductivity $(\Omega m)^{-1}$ $\sigma = 1/\rho$	Standard value of resistivity (Ωm)
J_1	0.140	2.324×10^{-9}	430.29×10^{6}	2.82×10^{-8}
J_2	0.137	3.921×10^{-9}	255.04×10^{6}	2.82×10^{-8}
J_3	0.338	2.689×10^{-9}	371.89×10^{6}	2.82×10^{-8}
J_4	0.136	2.614×10^{-9}	382.56×10^{6}	2.82×10^{-8}
J_5	0.170	2.890×10^{-9}	346.60×10^{6}	2.82×10^{-8}

be regarded as alloy impurities which have the following positive or negative effects when present or absent in the cables:

1. Impurity alloys like Cu, Zn Mn, Fe, Cr, Ni, As and P increase the strength and hardness of the cable, while Cu, Se, Ti, V, and Cr improve the electrical conductivity in cables; and Silicon lowers the melting point of the cable.
2. Mn, P, Ti, Ni and Pb improve the cables' non-corrosive nature and increase the electrical contact properties for high yield point and sufficient flexibility for use under difficult conditions in unfavourable atmosphere.
3. Sulphur and manganese should be in negligible quantity because they make the cables brittle.
4. Iron reduces the ductility, while gallium increases the electrical resistivity of the cables thereby reducing its conductivity.

Summary of electrical analysis

Sample J_1 has a low resistivity, ρ value of 2.324×10^{9} Ω m and a high conductivity value of 430.29×10^{6} $(\Omega m)^{-1}$. It is followed by J_4 with resistivity value of 2.614×10^{-8} Ω m and conductivity of 382.53×10^{6} $(\Omega\ m)^{-1}$. It is closely matched by sample J_3 with a resistivity value of 2.689×10^{-9} Ω m and conductivity value of 374.89×10^{6} $(\Omega\ m)^{-1}$. The next is J_5 which has resistivity and conductivity values of 2.890×10^{-9} Ω m and 346.046×10^{6} $(\Omega m)^{-1}$ respectively and sample J_2 with a high resistivity and a low conductivity of 3.921×10^{-9} Ω m and 255.036×10^{6} $(\Omega m)^{-1}$ respectively. Judging from the electrical test J_1 has the lowest resistivity and highest conductivity compared to the other cables, and so it is the best as a conductor cable.

Conclusion

The results from the chemical analysis and the electrical test show that sample J_1 is the best cable to be used in electrical domestic electrification. Having the highest percentage of aluminum (99.30%) it retains most of the properties that makes aluminum an excellent conductor. It also contains the highest percentage of copper (0.01%) which is one of the most important alloy in aluminum cables for improved strength and conductivity. Hence, it can be concluded that J_1 meets up to the standard to be used for domestic electrification. This is followed by J_4, J_3, J_5 and J_2. Also considering the results from the chemical analysis in Tables 2 and 3, J_1 is also the cable with the highest percentage purity of aluminum and also the highest percentage of copper. It can be concluded therefore, that J_1 is the best aluminum cable to be used in domestic electrification.

We suggest that further work should be carried out on other aluminum cables to determine the source of impurities in cables and more extensive research their effects on cable performance. Furthermore, research should be intensified to upgrade the aluminum cables and reduce incidences of electrical fire outbreak in aluminum cables.

References

1. Allen DK (1983) Metallurgy theory and practices. American Technical Society, Chicago, U.S.A.
2. Davis JR (1999) Corrosion of aluminum and aluminum alloys. ASM International.
3. Dieter GE (1988) Mechanical metallurgy, McGraw Hill, NY
4. John E (2001) Aluminum, nature's building blocks. An S-Z guide to the elements, Oxford University Press, Oxford.
5. Higgins RA (1971) Engineering metallurgy (3rd edn.), English Universities Press, London, U.K
6. Larson BF (2008) Centre for non-destructive evaluation. Lowa State University U.S.A. www.ndt.ed/org.
7. Polmear IJ (1995) Light alloys: Metallurgy of the light metals. Arnolds, USA. 2nd Edition.
8. Shakhashiri BZ (2007) Chemical analysis of the weak Aluminum. McGraw Hill, NY.
9. Tipler P (2004) Physics for scientists and engineers: Electricity, magnetism, light and elementary modern Physics. McGraw Hill, NY (5th Edition.).
10. Wikipedia (2009) www.wikipedia/allelectricalproducts. com