SLIDING WEAR AND CORROSION RESISTANCE OF TRAIN OVERHEAD LINE CONTACT WIRE

Samrawit Abubeker and Daniel Tilahun

ABSTRACT

In this study, the mechanical sliding wear and corrosion resistance property of pure copper (Cu) and two copper alloys (CuAg ,CuNiSiCr) overhead contact wire were investigated by a pin-on-disc Tribometer which is designed and constructed as part of this thesis to simulate contact wire and collector (contact) strips contact, with mechanical and electro -chemical measurement. The copper alloys which were prepared in the form of pin, were forced to slide on stainless steel disc at temperature of 28^0c and unlubricated condition at a sliding speed of 80 km/hr under normal load up to 10.24 N without electric current. Corrosion test was also conducted in acid, rain, salt environmental condition and in notch stress. The worn surface, wear debris and the corrosion from the specimens were studied by metallurgical microscopes and the weight loss measured by analytical balance. Finally, the CuNiSiCr copper alloy has better wear and corrosion resistance property and also takes less purchase cost. Hence, the material is recommended for Addis Ababa light rail transit overhead line contact wire.

Keywords: *mechanical sliding wear, corrosion, a pin-on-disc, Tribometer, overhead line contact* wire

INTRODUCTION

There are many ways to generate electricity, of varying costs, efficiency and ecological desirability. A passenger train takes power through a third rail and lines. The fixed nature of a rail line makes it relatively easy to power EVs through permanent overhead lines or electrified third rails, eliminating the need for heavy on board batteries. Electric locomotives, electric trams/street cars/trolleys, electric light rail systems, and electric rapid transit are all in common use today, especially in Europe and Asia [2].

An Electric Vehicle (EV), also referred to as an electric drive vehicle, uses one or more electric motors or traction motors for propulsion. An electric vehicle may be powered through a collector system by electricity from off-vehicle sources, or may be self-contained with a battery or generator to convert fuel to electricity. EVs include road and rail vehicles, surface and under-water vessels, electric aircraft and electric spacecraft [2].

EVs first came into existence in the mid-19th century, when electricity was among the preferred methods for motor vehicle propulsion, providing a level of comfort and ease of operation that could not be achieved by the gasoline cars of the time. The internal combustion engine (ICE) has been the dominant propulsion method for motor vehicles for almost 100 years, but electric power has remained commonplace in other vehicle types, such as trains and smaller vehicles of all types.

Hence, the railway systems are becoming key-players in world-wide transport. Train transportation has several advantages over motorway transportation from the point of view of environmental impact, especially in terms of CO_2 emission, accident reduction, use of land, and time travel reduction [1]. The Addis Ababa Light Rail Project has started op-

Overhead line is a structure used in electric power transmission and distribution to transmit electrical energy along large distances using sliding contact with pantograph of rolling stock. It consists of conductors (contact wires) suspended by mast or poles. For certain applications, copper alloy conductors are preferred instead of pure copper, especially when higher strengths or improved abrasion and corrosion resistance properties are required [4].

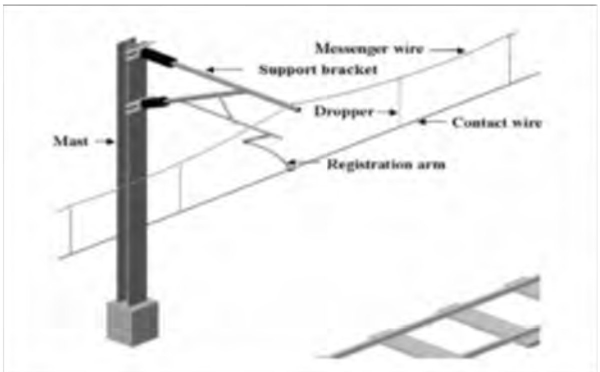


Figure 1 Parts of the overhead line systems [4]

Presently, Addis Ababa Light Rail Transit system is launched, i.e. it is new and uses the copper silver contact wire and pure copper supports, but their contact wire material has poor wear and corrosion resistance property relative to the copper alloy material that have good wear and corrosion resistance property elements or metals like chromium (Cr), nickel (Ni), silicon (Si), etc. [3, 5] and each element cost of CuAg alloy is expensive compared to elements mentioned above.

For tthis reason, we have to allow this technology with better performance and purchase cost of overhead line systems through improving property of overhead contact wire. As can be seen from few research papers, the main problems of contact wire are wear and loosing conductivity. Many engineers tried to solve this problem fully, but they could not. The only thing they have done is, specify the various types of copper and copper alloy conductors based on their advantages and disadvantages for a specific electrical application [3, 4]. Therefore, the researcher is interested in comparing and proving the result of Cu, CuAg and CuNiSiCr copper based alloy, in order to measure the performance of the alternative materials and suggest for Addis Ababa LRT overhead contact wire. In addition to this, to meet the aim of this research, design and construct pin - on -disc Tribometer machine for simulation of sliding contact of pantograph and contact wire was mandatory.

OVERHEAD CATENARY SYSTEM

Overhead Catenary constitutes an important traction system of electrical conductors used in conjunction with sliding pantograph current collectors to supply electrical energy to moving locomotives. The increasing speed of modern high-speed locomotives becomes a challenging problem in the design of electric traction systems all over the world. In recent technological developments of electric traction systems, major efforts have been devoted to speeding up locomotives, prolonging lifetime and reducing maintenance costs of the overhead Catenary and collector strips. To withstand the harsh service condition in real application, electric contact materials for the overhead Catenary and collector strips should possess high hardness and mechanical strength, high electrical sliding wear and corrosion resistance and excellent electrical conductivity [4].

C.T. Kwok [4] studies the service lifespan of the overhead catenary and collector strips essentially depends on (i) type of materials at contact; (ii) operating conditions such as sliding speed, contact force and current intensity; (iii) level of sparking and/or arching ; and (iv) environmental factors such as catenary in tunnels or in the open space. Conventionally, hard-drawn copper is often used as overhead Catenary for traction systems because of its excellent electrical and thermal conductivities and moderately low price but its limitations are low hardness, susceptibility to electrical sliding wear and atmospheric corrosion which lead to shortening of its service life, interruption of the system, and safety problems [4].

The S. G. Jia [15] group studied Cu–Ag–Cr alloy, as it is the latest and promising contact wire material for the high-speed electrified railway because of the wear mechanisms between the contact wire made of the Cu–Ag–Cr alloy and the strips which have not been systematically studied so far. Therefore, it is necessary to carry out such studies to explore the behaviour of Cu–Ag–Cr alloy for C.T. Kwok group [4]. Materials approved by researchers based on consideration of wear resistance, electrical conductivity and safety, Cu Cr Zr is a promising candidate as the contact wire material [4].

Corrosion is the electrolytic action of moisture and other dissolved ions of the atmosphere on the metals. The corrosive effects of the outdoor environments, for instance, salty coastal atmosphere, acid-rain and icing, the technological developments of electric railways, speedup of train and reduction of cost to maintain the facilities are strongly required. Major efforts have been devoted to solve these issues to meet the expectations of people. The contact wire is one of the factors, which can greatly affect the speedup of the train and the cost of maintenance. To improve the quality of the contact wire, new materials should be developed. The contact wire made with the new materials should have a low wear rate and an excellent combination of high strength and high conductivity.

Mostly, wear is composed of the several processes that occur in metal sliding situations. The processes possibly include metal transfer, film formation and removal, debris generation and cyclic surface deterioration. All of these affect the tribological behaviour and depend greatly on the sliding materials, the contact geometry, thermal effects (friction and the electric field), chemical environment of the contact and the mechanical parameters of the system [4].

Tribometer and its Type

In this research, the wear test is done through a pin-on-disc Tribometer machine which is designed and constructed as part of this research to simulate contact wire and collector (contact) strips contact.

A Tribometer (tribotester) is the general name given to a machine or device used to perform tests and simulations of wear, friction and lubrication which are the subject of the study of tribology. Often Tribometers are extremely specific in their function and are fabricated by manufacturers who desire to test and analyze the long-term performance of their products.

Different types of pin-on-disc tribometer observed from different literature-based on their function and for this research model of the machine is taken from literature [11] by its simple design, but the load application and position adjusting system are different.

A. Tribometer TPD-04

Tribometer TPD-04 enables simulation of different contact and test types. A special device enables pin-on-disk, circular and linear reciprocating test types. The main purpose of tribometer was investigation of friction and wear of polymer materials with or without lubricant according to appropriate standards [11].

B. Friction oscillations with a pin-on-disc Tribometer

Oscillations on friction force tracings recorded during pin-on-disc experiments were found to be a result of non-uniform surface features and lubrication conditions along the circular wear track. The oscillations were not due to stick slip. Spacing between peaks and valleys on the tracings were observed to correspond directly to the rotations of the disc specimen.

Characteristics of the friction force oscillations were more clearly revealed when the chart speed was increased or when the disc rotation was slowed. The amplitude of the oscillations changed with continued sliding. Results indicated that the coefficient of sliding friction for the materials tested under boundary or unlubricated conditions should more properly be reported as a range of values rather than one single nominal value. Reporting a range of values provides additional information on the stability of sliding conditions and the uniformity of lubrication for the tribosystem [11].

C. Tribotronic system on Pin-On-Disc (POD)

Tribometer Focusing on friction measurement using load cell. The analysis conducted using MATLAB software to measure Coefficient of Friction (COF) of 2 sample types in order to prove the validity of the measurement. The 2 samples are lubricant (Shell Helix Fully synthetic oil) and lubricant (Shell Helix Fully synthetic oil) with additive. It is revealed that the measurement of the lubricant with additive shows better COF (0.006) than lubricant without additive, COF of 0.02[11].

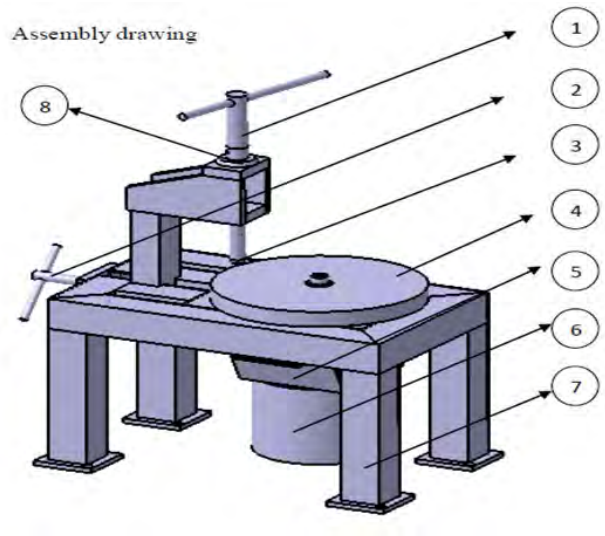


Figure 2 Model of pin-on-disc Tribometer machine by Catia v5, which is constructed here+

No.	Part name (main component)
1	T-bolt (pin holder)
2	T-bolt (direction adjuster)
3	Pin
4	Disc
5	Motor Support
6	Motor
7	Supporter (frame)

Overall dimension

Length=346mm,

Width=211mm, height=450mm

Figure 2 Model of pin-on-disc Tribometer machine by Catia v5, which is constructed here

Figure 3 Photograph of pin-on-disc Tribometer at AAIT mechanical workshop

EXPERIMENTAL DETAILS

1. Sample material preparation

For this research the industrial grade materials are taken from manufacturing industries and consider the impurities like the amount of iron in the material. For example, to get pure silicon, 45%FeSi (45% silicon in FeSi) have been collected, Then calculate the amount of pure silicon to add to the composition to be melted.

Cost of materials from the market

The cost taken during the study is from Micron International Trading House PLC: Cu = 680 Birr/500 gram, Ag=70Birr/1gram, Ni=460Birr/500gram, Si=600Birr/100gram; Cr=450Birr/100gram; and when comparing the cost per one pin, which is equal to 15.461gram, the cost calculation shows in pure copper and two alloys: Cu = 20.985 Birr, Cu Ag=21.748Birr and Cu Ni Si Cr=20.562 Birr. Therefore, the Cu Ni Si Cr copper alloy takes less purchase cost from pure copper (Cu) and Cu Ag alloy. After the melting process, in order to know the chemical composition of the specimen, the spectrometer machine is used; and the average result taken after three tests and to compare the pure copper and alloy materials results, the cu, Cu Ni Si Cr, and Cu Ag alloy pins are prepared by 13 mm diameter and 13 mm length, this size adapted from actual contact wire size and also the material has been chosen by the consideration of their good wear and corrosion resistance properties. Stainless steel disc (316L) of 200 mm diameter will prepare, this size taken to have different wear truck and the material chosen by consideration of copper alloy have to test by great hardened material (i.e. the alloys will perfect for carbon brush and other material).

2. Manufacture and wear test procedure of sample materials

- The two copper alloys Cu Ni Si Cr, Cu Ag and pure copper are considered
- Manufacture the pin alloys and pure copper of diameter of 13mm and length of 13mm and 200mm diameter stainless steel disc using manufacturing process.
- Check the hardness and material composition using hardness and spectrometer respectively, before test.
- Weight the specimen by electronic balance
- Then, the wear test conduct using pin-on-disc Tribometer by copper alloy pins are forced to slide against stainless steel disc driven by an electric motor in workshop temperature of air unlubricated condition at constant sliding speed of 80 km/hr the hardness of stainless disc is 151 HV.
- Normal forces of 5, 7.86, 10.24 N and dc current intensity 0A were applied during the test. The motor was connected to the power supply to rotate the motor

The test duration was one minute and the weight loss Δw (in gram) of the specimen in wear time t (in minute) was recorded by an electronic balance. The volume loss Δw (in mm^3) was calculated by the following equation; Where ΔV1000ΔW/ρ is the density of the alloying/cm^3. The wear rate w (in mm^3/h) and the worn surface and wear debris of the selected specimen is characterized by metallurgical microscopy. Finally, put the conclusion about the materials by comparing each other

Corrosion test procedure of sample material Copper alloying

- Wash the specimen by 100 ml distilled water and 0.5 hydrochloric acid (HCl) for 15 minutes in order to remove corrosion initiators compound
- Dry the specimen thoroughly in warm oven at maximum temperature of 70 degrees

Figure 4. Specimen in corrosion studies kit (AAIT environmental laboratory)

After knowing the composition, the corrosion test was conducted and the corrosion resistance was calculated by gram loss that is tried to show on Figure 4.

- Each sample must be weighed by an electronic balance before being immersed in the solution and must be carefully labelled to later identify its initial weight

- Fill the Vickers with proper amount of water
- Make 3.5% NaCl solution, acid-rain solution with 5PH, rain water and pure distilled water for stress test in each Vickers for each specimen
- Leave the specimen for 5 days
- After the experiment has been completed, wash the specimen by HCl like before test or brush the specimen with running water and dry it with warm oven and then reweigh.
- Put the gram difference which indicates the corrosion part.

RESULTS AND DISCUSSIONS

Corrosion behaviour

The corrosion test of the sample materials for five days result under 3.5% NaCl, PH5 Acid- rain, rain water and stress corrosion media is summarized in **Table 1** and shown in **Figure 5.**The high weight loss indicates that a high corrosion rate property of the material. The ranking of corrosion resistance property in descending order in 3.5% NaCl corrosion media is: CuAg>CuNiSiCr> Cu; PH5 Acid rain: CuNi-SiCr>CuAg>Cu; rain water: CuNiSiCr>CuAg>Cu; stress: CuNiSiCr>CuAg>Cu. Hence, the corrosion effect has been seen high in pure copper and less in CuNiSiCr. The total weight loss after corrosion in each media implies: 0.3545 in 3.5%Nacl, 1.967 in PH5 Acid-rain, 0.3684 in rain water and 0.0806 in stress .The result indicating that high corrosion effect is observed in PH5 Acid-rain.

Table 1 Weight loss of material after corrosion test

Corrosion media	material	All are with 21% oxygen 3.5%Nacl	PH5 Acid	Rain water	stress
Gram of specimen in each medium before corrosion	Cu	15.7244	17.4234	12.6748	14.5748
	CuAg	24.5663	19.7050	25.7145	23.3757
	CuNiSiCr	15.0532	14.7038	14.7664	15.1376
Gram of specimen in each media after corrosion	Cu	15.5888	16.5843	15.6294	14.3512
	CuAg	24.4632	19.0521	25.7096	23.3747
	CuNiSiCr	14.9374	14.2287	14.7622	15.0977
Weight loss after corrosion in gram	Cu	0.1356	0.8391	0.2236	0.0454
	CuAg	0.1031	0.6529	0.1049	0.031
	CuNiSiCr	0.1158	0.475	0.0399	0.0042

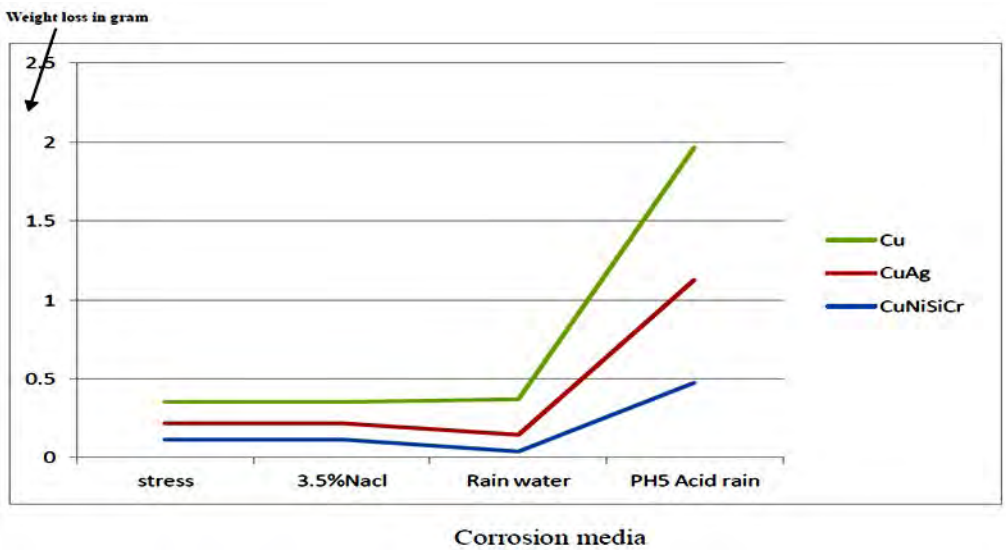
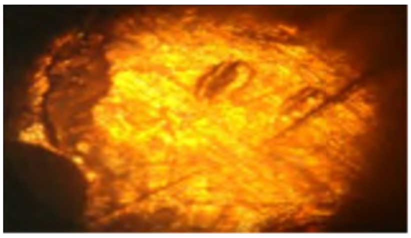


Figure 5 Weight loss after five days of corrosion test vs corrosion media

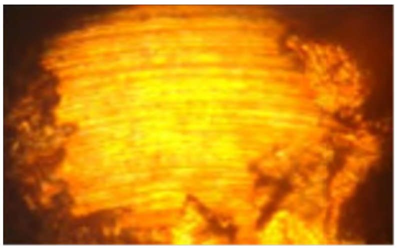
Sliding wear behaviour and Effect of normal force

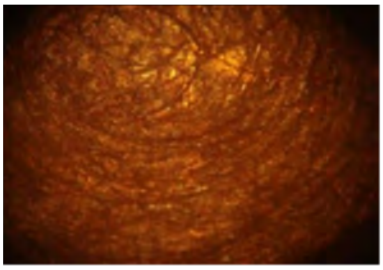
After sliding contact of the specimen with disc or mechanical sliding wear in pin-on-disc Tribometer machine, worn surface or macro structure of specimen with 10 x100 magnifications was analyzed by a metallurgical/optical microscope in the mechanical workshop at Addis Ababa Institute of Technology. The worn surface in descending order that was observed in the microscope is Cu> Cu Ag > Cu Ni Si Cr under normal forces of 5N, 7.86N, 10.24 N and 0A DC current intensity.



(a)

(b)





(c)

Figure 6 worn surfaces of (a) Cu; (b) Cu Ag and (c) Cu Ni Si Cr with load 10.24 N and without current and 10x100 macroscopic image by optical/metallurgical microscope

On micro-scale, asperities of the harder surface, with plastic flow of the softer surface occurring around the harder asperities. For adhesive wear, the asperity junction of the sliding surfaces of counter parts under normal contact force adhere together through solid phase welding of asperities. Subsequent detachment from the surface of the weaker phases resulted in loss of material [4]. The graph below shows the wear resistance property of each material versus applied load; when the force increases, the wear resistance property of all materials decreases, because of high friction that happened at the contact surface and the ranking of mechanical sliding wear resistance at 5N, 7.86N, 10.24 N and 0A in descending order which is:CuNiSiCr>CuAg>Cu. Therefore, the wear resistance value of Cu Ni Si Cr is greatest from CuAg and Cu.In Figure 7, the wear rate of materials increase proportionally with the increase in the normal forces (5 to 10.24N) at constant sliding speed of 80 km/hr with 0A current intensity.

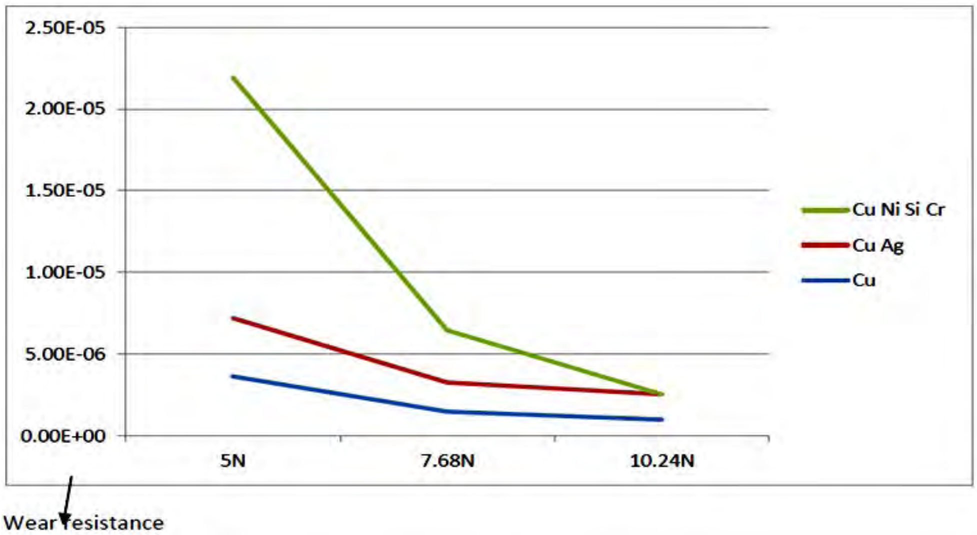


Figure 7 Wear resistance of each material vs applied force

The researcher recommends for the future further investigation to be done on electro-mechanical wear, machine capacity and analysis of wear and corrosion property of material using related software.

CONCLUSIONS AND RECOMMENDATIONS

In this study, the properties of materials for train overhead line contact wire are determined under different load and environmental conditions. Based on the experimental result, the following conclusions are made:

- The Cu Ni Si Cr has the greatest corrosion and wear resistance property than Cu, CuAg and also take less cost to purchase from market
- Figure 6. Indicates that, when the normal load increases, the wear rate also increases
- High corrosion effect is observed in PH5 acid-rain corrosion media that comes from harmful gases of industries and cars.
- Literatures and microscopic image show the dominant wear mechanism during the mechanical sliding wear processes is Adhesive Wear [4].

Based on wear and corrosion resistance property and each material purchase cost, the researcher recommends that the Addis Ababa Light Rail project use Cu Ni Si Cr alloy for overhead line contact wire. By making further investigation and from PH5 acid-rain corrosion media result, it is necessary to suggest for the future that Addis Ababa have a protected environment beyond the contact wire material property.

ACKNOWLEDGEMENTS

The work described in this paper was fully supported by the Ethiopian Railways Corporation (Railway Engineering Centre), Akaki Metal Factory, Mekelakeya Engineering (Hibret), ELSEWEDY CABLES (Dukem), Micron International Trading House PLC, AAU Science Faculty, Environmental Engineering Laboratory and the Mechanical workshop of AAiT.

REFERENCE

[1] Addis Ababa E-W & N-S (Phase I) Light Rail Transit Project, 2013, "*Professional Technical Standard for Contact Line, China Railway Group Limited LRT Project"*, Ethiopian Railways Corporation, Addis Ababa, Ethiopia.

[2] Bellis, M., "*The Early Years", The History of Electric Vehicles*, About.com, retrieved 6 July 2006

[3] Copper development association, "*A guide to working with copper and copper alloys*", collection of scientific research from 1990-2009, New York.

[4] C.T. Kwok, P.K. Wong, H.C. Man and F.T. Cheng, Sliding Wear and Corrosion Resistance of Copper-based Overhead Catenary for Traction Systems, *IJR International Journal of Railway* Vol. 3, No. 1 / pp. 19-27, The Korean Society for Railway.

[5] China railway publishing house, *"Copper and copper alloy contact wires for electric railway",* TB/T 2809-2005, china.

[6] C.R.F. Azevedo and A. Sinatora, "*Failure anal ysis of a railway copper contact strip*", De partment of Mechanical Engineering, Escola Politecnica, Universidad de S~ao Paulo, Bra zil.2004

[7] Daniel T. Redda, Tsutomu NAKANISHI and Gang DENG, Surface durability of developed Cr-Mo-Si under Rolling-Sliding Contact, *Advanced mechanical design, system and manufacturing journal* volume 2, No.2, 2008, University of Miyazaki, Japan.

[8] Delhi Metro Rail Corporation Ltd, "*Power Supply and Overhead Catenary System*", Pre Feasibility Report 2011.

[9] Didacta, 2002, IC136D, "*Corrosion studies kit-code 998100, user manual and exercise guide, edition one*", Italia. http://www.didacta.it

[10] Goran Matijasevic, Lutz Brandt, "*Conductive materials, wires, and cables*", ELECTRICAL ENGINEERING-Vol. II Page13, university of California -, Irvine, USA.

[11] Instruments of CSM, "*Advance mechanical surface testing by Tribometer's*", 2012, http:www.csm-instruments.com,switzerland.

[12] Industrial and Traction Technology, "Carbon Sliding Strips for Pantographs and Trolley Pole Systems", 2004, www.schunk-group.com, germen.

[11]

[13] Arnar Kári Hallgrímsson, "*Dynamic behaviour of contact lines for railways with laboratorial model setup according to Norwegian conditions*", 2013, Norwegian University of Science and Technology.

[14] Koji Kato, "*Wear in relation to friction (a review)*", Wear 241_2000, pp151–157, Laboratory of Tribology, School of Mechanical Engineering, Tohoku University, Japan.

[15] S.G. Jia a, P. Liua, F.Z. Rena, B.H. Tian a, M.S. Zheng b, G.S. Zhoub, "*Sliding wear behaviour of copper alloy contact wire against copper-based strip for high-speed electrified railways*", School of Materials Science and Engineering, Henan University of Science and Technology, China. Wear 262 (2007) 772-777, www.elsevier.com/locate/wear

LIST OF ABREVIATIONS AND ACRONYMS

Cu - copper

Ni - nickel

Si - silicon

Cr - chromium

Ag - silver

LRT - light rail transit

COF - coefficient of friction

Zr - zirconium

HCl - hydrochloric acid

Nacl - sodium chloride

SEM - scanning electron microscopy

P - power of motor in kw

Δw - weight loss

W - wear rate