Electrical connection for aluminium conductors in automotive applications

Prestudy of available solutions for electrical connection methods of aluminium cables

EMILIA HAMEDI
Abstract

Due to increasing weight of electrical component and wiring harnesses in a vehicle contrary to the demand of light constructed vehicles as well as the constantly increasing and fluctuating price of copper compared to aluminium’s stable and far lower price, the use of aluminium conductors as an alternative have been promoted.

This thesis work lay theoretical research of the available methods used for electrical connection of aluminium conductors in order to increase the knowledge about the available termination techniques.

Due to aluminium’s characteristics such as lower conductivity and strength, tendency to form oxides and relax over time, differences in thermal expansion coefficient and high potential for galvanic corrosion, there is a risk of deterioration and degradation of the connection if the termination of aluminium conductors is not done correctly without being aware of the challenges when it comes to aluminium connection.

The founded solutions are different welding and soldering techniques such as friction welding, ultrasonic welding, resistance welding, plasma soldering and many other modifications of conventional crimp.

A robust termination system that faces all those challenges and ensure a reliable connection during the entire life length of the vehicle and in order to inhibit corrosion different type of sealing of the contact interface will be required.

In order to evaluate the performance of the founded connection method, testing with evaluation of, tensile strength of conductor to contact attachment, tightness demand, corrosion resistance, vibration and heat evolution at the contact attachment have to be conducted.

Keywords: Connector, electrical contact, termination, aluminium conductor
Preface

This thesis work was performed at RECE- Electrical and electromechanical components group at Scania CV AB in Södertälje and at MSE- Material Science and Engineering department at KTH royal institute of technology in Stockholm. I would like to express my deepest gratitude to my supervisor at Scania Peter Li and group manager Hanna Lind who believed in me and gave me the opportunity to do my thesis at their group. I would like to thank all the people at RECE who did their best to help me and offered me a pleasant work environment. Also I want to thank all the help and assistance from RECT who always guided me and answered my questions.

I would like to express my special gratitude and thanks to my supervisor at KTH, Material Science and engineering department, Ander Eliasson who have supported and guided me during my work.

Emilia Hamedi

2017-08-17

Stockholm
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<tr>
<td><strong>Contact area</strong></td>
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<tr>
<td>Area of metal-to-metal attachment between the conductor and terminal</td>
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<tr>
<td><strong>Voltage drop</strong></td>
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<tr>
<td>Voltage across a conductor or component because of the electrical current flow</td>
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<tr>
<td><strong>Contact Resistance</strong></td>
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<td>Resistance at the contacting interface</td>
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<tr>
<td><strong>Alternator</strong></td>
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<tr>
<td>Converter of energy/power by transfer of engines mechanical work into electricity and recharging the battery</td>
</tr>
<tr>
<td><strong>Chassis</strong></td>
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<tr>
<td>Part of the vehicle which includes brake system, frame, electrical system, fuel tanks, suspension and wheels</td>
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<tr>
<td><strong>Cab</strong></td>
</tr>
<tr>
<td>An enclosed space in crew compartment, trucks and busses</td>
</tr>
<tr>
<td><strong>ISO</strong></td>
</tr>
<tr>
<td>The International Organization for Standardization</td>
</tr>
<tr>
<td><strong>Powertrain</strong></td>
</tr>
<tr>
<td>Power providing component which deliver to consumers that include gearbox, propeller shafts, engine and etc.</td>
</tr>
<tr>
<td><strong>Crimping</strong></td>
</tr>
<tr>
<td>Mechanically deformation and compression of splice, terminals or connectors to the conductor with the aim to ensure mechanical and electrical connectivity</td>
</tr>
<tr>
<td><strong>Welding</strong></td>
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<tr>
<td>Process for joining materials, usually metals by heating the surface to the melting point.</td>
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<tr>
<td><strong>Terminal</strong></td>
</tr>
<tr>
<td>A connecting device for termination of conductor and fixed to the cable for establishing an electrical connection</td>
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<tr>
<td><strong>Connector</strong></td>
</tr>
<tr>
<td>A device used to create electrical circuit and join electrical termination.</td>
</tr>
<tr>
<td><strong>Galvanic corrosion</strong></td>
</tr>
<tr>
<td>Electrochemical process when two metals are in electrical contact with each other and one metal have higher tendency to corrode</td>
</tr>
<tr>
<td><strong>Voltage drop</strong></td>
</tr>
<tr>
<td>Electrical current flow in a conductor or component resulting into voltage across the conductor or component.</td>
</tr>
<tr>
<td><strong>Thermal expansion</strong></td>
</tr>
<tr>
<td>Dimensional changes owing temperature changes or temperature shock</td>
</tr>
<tr>
<td><strong>Cycling</strong></td>
</tr>
<tr>
<td>Repeated process</td>
</tr>
<tr>
<td><strong>Serration</strong></td>
</tr>
<tr>
<td>Asperities on terminal surface with the aim to ensure additional contact area and fixed gripping of conductor</td>
</tr>
<tr>
<td><strong>CSA [mm²]</strong></td>
</tr>
<tr>
<td>Cross section area</td>
</tr>
<tr>
<td><strong>IACS</strong></td>
</tr>
<tr>
<td>International Annealed Copper Standards</td>
</tr>
<tr>
<td><strong>SEM</strong></td>
</tr>
<tr>
<td>Scanning Electron Microscope</td>
</tr>
<tr>
<td><strong>DC</strong></td>
</tr>
<tr>
<td>Direct current, electron flow in one direction</td>
</tr>
<tr>
<td><strong>AC</strong></td>
</tr>
<tr>
<td>Alternating current, when the electrons change their direction</td>
</tr>
<tr>
<td><strong>IDC</strong></td>
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<tr>
<td>Insulation displacement connection</td>
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IV
1 Introduction

The weight of electrical and electronic components and wire harnesses are increasing due to added functions such as safety and comfort in all type of vehicles. Weight and energy saving are the main driving force for development of alternative cables used in vehicles [1] [2]. It is estimated that an approximate weight reduction of 10 % of a passenger vehicle can contribute to 3-4 % less fuel consumption, and about 5 % less fuel consumption can be obtained for heavy vehicles such as busses and trucks if substituting heavy material by lighter materials [3].

The commonly used conductors and wiring harness systems are made of copper which compared to aluminium is expensive with volatile prices and heavier than aluminium. The demand for environmental friendly vehicles has led to research and development of high voltage wiring harness system that result into weight saving improved fuel efficiency, low carbon society and more cost efficient vehicles [4]. The average weight of wire harness system of a vehicle from 1960 is 3 to 5 Kg compared to 50 to 70 Kg in today’s vehicles. Although the weight of the wiring harness is about 30 Kg per vehicle, a weight saving of 30 % is possible if copper is replaced by aluminium. Cross sectional area of minimum 1.5 mm² enables weight reductions up to 48 % if the copper conductors are replaced by aluminium conductors [5]. An average passenger vehicle has potentials of weight reduction of 8.8 Kg if the current, copper made electrical system with CSA range 2.8-80 mm² is replaced by aluminium cables. Due to this the potential weight saving is expected to be higher in case of bigger vehicles such as busses and trucks.

It should be mentioned that aluminium conductors with large cross section area which support high current are mainly being used in battery cables aluminium conductors in cable uses is growing and being used in in many successful electrical power distributions. A variety of stranded wires and conductors are being used in modern vehicles, but high voltage wire harnesses with newly kind of electrical connection is being developed in order to meet the demand of weight reduction [6] [7]. In order to achieve a consistent conductance in the wire harness and a reliable electrical connection the different materials properties must be taken into account when developing a new electrical component.

1.1 Aim and objective of the study

Different areas of the vehicle are exposed to different environments which require a robust electrical connection that last the entire life length of the vehicle. The main objective of this study is to put forward state of the art regarding the available connection of aluminium cables used in vehicles. The objectives consist of:

- Investigate the available methods used for electrical connections of aluminium cables and if those methods are applicable solutions that fulfil requirements of Scania.
- Increase the knowledge about different aluminium conductors and the available electrical connection methods
- A comparison between those methods in order to list pros and cons of each approach

1.2 Outline of the Study

Scania has one of the world’s most sustainable transport solutions which always develop and optimize new solutions in order to meet the market demands and offer the most sustainable
solutions. When it comes to electrical and electromechanical components Scania have done some attempts to lower the average cable harness components by for instance a new interface design between the cab and chassis which may result into an average weight saving of 3.96 Kg. An approximate cost saving of 98 SEK based on today’s electrical system, current cable conductors and the present copper prices if a change to aluminium would be performed [3].

The electrical and electromechanical group at Scania are responsible for cable harness components such as cables, connectors, terminals and protection hoses for Scania vehicles. Development of new cable harness solutions in terms of weight saving, fuel economy, low carbon society and gas emissions, Scania is investigating the possibilities of replacing copper cables by aluminium cables and the challenges are to find a suitable electrical connection method that fulfil the requirements in different environment of the vehicle. Scania vehicles can be divided into three different zones for cable harness systems, namely chassis, powertrain and cab with different environment i.e. different vibration levels, operating temperatures and CSA. The battery is located in the chassis zone where the cables needs to cope with temperatures up to 100 °C, high vibrations and have higher current carrying capacity since it is the battery cable that carry the current which starts the motor, single core cables with large CSA is required for the chassis zone. Power train is the zone that has to cope with the highest temperatures and vibrations. Cables in this zone are both single core and multicore cables with size range of 25-125 mm². The cab zone is the area with lowest vibration and current carrying levels where the temperatures do not exceed 80 °C. The cables for cab zone are in the range of 0.5-6 mm² except the sensor cables which can have even lower CSA.

Due to this the cable harness system poses challenges when solving the electrical connection if the copper cables are replaced, the new type of connecting method must be robust enough and last the entire life length without breakdowns furthermore be easy to use in service and aftermarket. Evaluation of the consequences, performances and potential risks according to internal Scania product requirements needs to be done in order to be able to determine if it is possible to replace copper cables by aluminium cables.
2 Background

2.1 Automotive cables

Electrical cables in vehicles have to provide a compact and reliable method to transmit energy and power from alternator or energy accumulators (i.e. batteries) to consumers such as electrical panel and lightening system. It is also the connecting medium for the embedded system which distributes the power and signals within the vehicle [8]. Depending on where in the vehicle a cable is aimed to be used, the length, current carrying ampacity and acceptable voltage drop will vary. Those properties are given by

\[ G = \frac{\sigma A}{L} \]

Equation 1

and depend on, electrical conductivity \( \sigma \), cross section area \( A \) and length \( L \). Society of automotive engineers (SAE), standardize the cable sizes for different current carrying ampacity. A cable assembly consist of an electrical conductor with different insulating material depending on operating condition. Connection of those cable assemblies are done by different terminating connectors in solder or solderless condition [9]. Classification of the cables are done according to international standards and divided depending on their ability to withstand temperature range shown in Table 1 [10] [11].

<table>
<thead>
<tr>
<th>Class</th>
<th>Temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-40°C to 85°C</td>
</tr>
<tr>
<td>B</td>
<td>-40°C to 100°C</td>
</tr>
<tr>
<td>C</td>
<td>-40°C to 125°C</td>
</tr>
<tr>
<td>D</td>
<td>-40°C to 150°C</td>
</tr>
<tr>
<td>E</td>
<td>-40°C to 175°C</td>
</tr>
<tr>
<td>F</td>
<td>-40°C to 200°C</td>
</tr>
<tr>
<td>G</td>
<td>-40°C to 225°C</td>
</tr>
<tr>
<td>H</td>
<td>-40°C to 250 °C</td>
</tr>
</tbody>
</table>

There are two type of cables in which they can be divided into, solid cable which is a single stranded conductor or stranded cable which consist of a number of solid conductors that are twisted to a single conductor. The stranded cables are the most common cables used in vehicles due to their flexibility, long flex-life and reliability. The difference between single-core and multi-core cables are the core number of stranded cable. When the flexibility is not the prime priority, single-core cables are used, for instance as engine starter cables, battery cables and power cables, while multi-core cables are used for airbag release and antilock system, where the cables need to be customized for specific requirements and be accommodated in small installations. Double insulated multi-core cables can be used in trucks in order to increase reliability, vibration resistance and safety. The
shielded cables are used for components where protection from electrical noise and electromagnetic radiation without any effect on signals is essential. In addition to those cables, other cables like high-voltage cables, flat cables, data cables, ignition cables, coaxial cables and special cables are used in automotive vehicles. For instance special cables which need a special protection are used for communications within the vehicle i.e. pressure, temperature, gearbox and sensors while flat cables are used in areas where the installation space is limited but an intensive amount of devices have to be installed, for instance bumpers, door harnesses and roof liners dashboard.

When it comes to the insulating materials of the cables, the most commonly used materials are extruded electric type with core material component of, polyamide (PA), polyvinyl chloride (PVC), polytetrafluorethylene (PTFE), thermoplastic polyester (TPE), polyethylene (PE), polyethylene crosslinked (PE-X), polypropylene (PP ) etc. [12]. According to SAE standards, there are two main categories of cable insulators used in automotive vehicles, cross-linked and PVC. The difference between those two is the temperature range, PVC cables can be used in lower temperatures, up to 80 °C compared to cross-linked which can withstand temperatures up 125°C and is more resistant to aging, heat and abrasion. In addition to insulation material, when selecting the insulating layer one have to consider the required performance factors according to Table 2 [13]

<table>
<thead>
<tr>
<th>Performance factors</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal performance</td>
<td>Expansion and contraction</td>
</tr>
<tr>
<td></td>
<td>Compatibility with ambient</td>
</tr>
<tr>
<td>Electrical properties</td>
<td>Insulation resistance</td>
</tr>
<tr>
<td></td>
<td>Dialect constant</td>
</tr>
<tr>
<td>Mechanical characteristics</td>
<td>Tensile strength</td>
</tr>
<tr>
<td></td>
<td>Toughness</td>
</tr>
<tr>
<td></td>
<td>Abrasion resistance</td>
</tr>
<tr>
<td>Chemical resistance</td>
<td>Acids</td>
</tr>
<tr>
<td></td>
<td>Oils</td>
</tr>
<tr>
<td></td>
<td>Stability when exposed to flame</td>
</tr>
</tbody>
</table>

In addition to the SAE standards there are Japanese and Germany standards which are in accordance with international standards ISO 6722 which specify the automotive cables type and name, technical parameters, conductors and insulation materials.

For cable termination there are two main methods, solder type or solderless type where solderless types refers to mechanical termination and solder type is when the electrical conductor is fastened to a terminal and a strong electrical connection is provided. Crimping of stranded cables or solid cables is a simple installation method where the conductor is compressed and attached to a terminal. Crimping method creates an electrical path with high current carrying ability and low resistance while the electrical and mechanical connectivity depends on type of solder. Crimping termination compared to solder termination has the advantages of selecting terminal, cable and insulating
material without out weighting the thermal characteristics and the material effect on humans since the main concern of crimping method is to select the right tool for connectors/terminals and cables. However loosening of the terminal and disturbances of electrical path cannot be ignored since occurrence of stress relief, shock and vibrations of terminating point due to applied mechanical forces is possible.

2.2 Cable conductors

An assembly compromising of a conductor which is the current carrying part, protection, insulation, shielding and termination is a conductor system. The conductor can be a solid wire or strands which is a combination a wires that are not insulated from one another or a cable which is a combination of conductors insulated from one another with the main function to yield electrical current through the system while the insulation’s function is to restrain the current flow to the conductors in the system. The current carrying part is isolated from external influences by the protective part (example sheath) while the shielding’s function is reducing the effect of electric and magnetic field on the cable [14].

2.2.1 Conductivity

Conduction in terms of path of free electrons makes an element conductive and the larger number of free electrons the better conductor. In addition to that the degree of conductivity is affected by for instance plastic deformation, alloying elements, structural defects and reduction of the mean free path of electrons which result in heating. Resistivity, conductivity and physical changes are temperature dependent and the conductor materials property varies linearly with the temperature. These temperature dependent changes for a linear conductor can be expressed as

\[ R_T = R_0 [1 + \alpha_R (T - T_0)] \]  \hspace{1cm} \text{Equation 2}

\[ l_T = l_0 [1 + \alpha_L (T - T_0)] \]  \hspace{1cm} \text{Equation 3}

Where \( R_T \) is resistance, and \( l_T \) is the length of the conductor at a temperature \( T \), \( R_0 \) is the temperature at 20 °C and \( l_0 \) is the length at 20 °C, \( \alpha_R \) is the electrical resistance coefficient while \( \alpha_L \) is the coefficient for lineal expansion [14]. The electrical characteristic of a material and its ability to accommodate electrical charge is specified by electrical conductivity \( \sigma \). Reciprocal to conductivity is resistivity, a materials ability to resist electrical current flow, which convert the electrical energy into other form of energy, most commonly into heat. Materials which have high resistivity are good as insulators and for a material to be a good conductor it must have low resistivity with order of \( 10^{-8} \) Ωm. All metals and their alloys can be used as electrical conductors in different applications such as electrical contacts, power distribution lines, resistor and heating elements and electricity transmission. Electrical conductivity is usually stated as percentage of international annealed copper standards (IACS), where annealed copper conductivity is \( 5.8001 \times 10^7 \) S/m is 100 % IACS at 20°C. Gold, silver, copper and aluminium are considered as good electrical conductors where gold has a conductivity of 200 % IACS. The electrical resistivity of some solid materials is shown in Table 3.
Table 3. Electrical resistivity of solid materials at 20°C

<table>
<thead>
<tr>
<th>Material</th>
<th>Order of resistivity</th>
</tr>
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<tbody>
<tr>
<td>Gold</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Silver</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Copper</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>Aluminium</td>
<td>$10^{-8}$</td>
</tr>
<tr>
<td>Nickel</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Iron</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Glass</td>
<td>$10^{5}$</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>$10^{11}$</td>
</tr>
<tr>
<td>PVC</td>
<td>$10^{15}$</td>
</tr>
</tbody>
</table>

Conductivity and resistivity are properties that depend on the materials alloying elements, impurities, plastic deformation and temperature and are usually stated at room temperatures. The temperature dependency for instance can be expressed by

$$\rho_1 = \rho_2 \left(1 + \alpha (T_1 - T_2)\right)$$

*Equation 4*

Where $\rho_1$ and $\rho_2$ are resistivity at two different temperatures and $\alpha$ is temperature coefficient which is positive for conductors, meaning that resistivity is raised if the temperature is increased [14].

2.2.1.1 Effect of lattice imperfection on conductivity

Addition of alloying elements and impurities decreases the conductivity in the lattice much more than any other lattice imperfection. The degree of reduction depends on the metallurgical state of the impurities, type and concentration of them for instance the presence of impurities in solid solutions have larger conductivity reduction effect than as incorporated in, a second phase of the microstructure. Impurities in solid solution that result into disturbances in the lattice periodicity on atomic scale increase the electrical resistance more than perturbations caused by a second phase on a macro scale. For electrical purposes, purity of a solid conductor is essential since there is a linear relationship between electrical resistivity and concentration of the impurities even though there is a limit of solubility of the impurities. However, a high-purity conductor material is not the solution for prime quality conductors with low resistivity, since increasing the purity of conductor material lower the mechanical properties and increase processing cost significantly. Due to this limited addition of particular solutes may substantially enhance the mechanical response of the conductor without deteriorating its conductivity [14].

2.2.1.2 Grain boundaries

According to previous studies, grain boundaries and impurities species or segregated alloy at the grain boundary have a significant effect on the transport properties and performance of the conductors since electron scattering at the grain boundaries contribute to the resistivity. When an
electron crosses the boundary and enter a new region, it cannot continue in the same direction and
the same velocity which is due to anisotropy of elastic and electronic properties of the solid at the
grain boundary [14].

2.2.1.3 Vacancies
The concentration of vacancies in a solid conductor can be appreciated by rapid quenching from a
higher temperature and by irradiation with high energy particles. Produced vacancies by this method
enable pronounced effect on the electrical resistivity in pure metals [14].

2.2.1.4 Dislocations deformation
Plastic deformation leads to reduction of the metal ductility, harden the metal, increase its electrical
resistivity and tensile strength. For many types of conductors, an increase in tensile strength is useful
and is achieved by cold working. The increase in electrical resistivity in conductors is mostly caused
by plastic deformation when scattering of conduction electrons which is due to introduction of
dislocation into the lattice. The relation between, increasing in resistance $\Delta \rho$, due to plastic strain $\gamma$ is
given by

$$\Delta \rho = a \gamma^n$$  \hspace{1cm} \text{Equation 5}

Where $n$ and $a$ is characteristics of the conductor material. A plastically deformed conductors’
tensile strength and electrical resistance can be reduced by annealing which in turn increase the
ductility [14].

2.3 Conductor materials
Conductors used for cables should maintain high thermal and electrical conductivity, have good
wear and abrasion resistance, high melting point and low cost. Changes in voltage drop and power
losses when the temperature changes, requires low temperature resistance coefficient. A higher
resistance of conductor leads to voltage drop and increase of power loss which affects workability
and solder ability of the conductor which is essential for connection and termination of the
conductor.

In addition to this, cable conductors should maintain high corrosion resistance in order to avoid
degradation caused by corrosion; further a mechanical strength that withstand the thermal stresses,
mechanical load and vibration; likewise enough ductility and flexibility which enables them to be
drawn in different sizes and shapes. The most common material used for electrical conductors are
usually copper or aluminium because of their suitable properties such as conductivity, tensile
strength and accessibility of the raw material. Copper is one the most commonly used material for
electrical conductors in e.g. flexible cabling, high/low voltage power cables, wiring of
motors/alternators/transformers, underground cables while aluminium is used in domestic wiring,
overhead transmission lines and busbars. Basic properties of copper and aluminium conductors and
their applications are summarized in Table 4.
Table 4. Basic properties of Aluminium and Copper [14].

<table>
<thead>
<tr>
<th></th>
<th>Aluminium</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EC-0 (A)</td>
<td>Al-Mg (5005) (B)</td>
</tr>
<tr>
<td>Density (g cm(^3))</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Melting point (°C)</td>
<td>660.0</td>
<td>652.0</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td>2.34</td>
<td>2.05</td>
</tr>
<tr>
<td>(W cm(^{-1}) K(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linear Thermal</td>
<td>23.6</td>
<td>23.7</td>
</tr>
<tr>
<td>expansion Coeff.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10(^{-6}) K(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Electrical</td>
<td>4.46</td>
<td>4.03</td>
</tr>
<tr>
<td>Resistivity Coeff.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(10(^{-3}) K(^{-1}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrical resistivity</td>
<td>2.80</td>
<td>3.32</td>
</tr>
<tr>
<td>μΩ cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>83.0</td>
<td>200.0</td>
</tr>
<tr>
<td>(MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield Strength</td>
<td>28.0</td>
<td>193.0</td>
</tr>
<tr>
<td>(MPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>69.0</td>
<td>69.6</td>
</tr>
<tr>
<td>(GPa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Current Carrying</td>
<td>80.0</td>
<td></td>
</tr>
<tr>
<td>Capacity (%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Heat Capacity</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>(J/g/K)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hardness (×10(^2)N MM(^{-1}))</td>
<td>2.3</td>
<td>5.1</td>
</tr>
</tbody>
</table>

2.3.1 Copper and copper alloy as conductor material

Copper is a metal with high conductivity, solderability, weldability and formability. A variety of electrical products such as shaped and flat busbars, tubes, wires and sheets can be manufactured by drawing and rolling but in order to have high conductivity and be useful for electrical application electrolytic refining for removal of Au, Ag, Au, Sb and impurities have to be applied. Electrolytically tough pitch copper (ETP), or C11000 which is electrolytic refined copper are the most used in power industry. The embrittlement of ETP copper is the main deficiency which occurs when the metal is heated in hydrogen to temperatures above 370 °C since the present oxygen in the metal react with the hydrogen and build steam which leads to internal cracking, using copper with lower oxygen content prevent this problem. Phosphorus can be used as an effective copper deoxidizer but it is not suitable for electrical applications since it decreases the conductivity and due to this electrolytic slab that are melted and refined in oxygen free, inert gas and no metallic oxidizer process used instead. A 99.8 % pure copper with <0.005 % impurity called oxygen free high conductivity copper (OFHC) can be produced. The copper conductivity is set according to the international annealed copper standard (IACS), meaning % IACS is equal to 100 and IACS has a resistivity of 1.7241 μΩ cm. It is common to
define metals purity by ratio of resistivity at 5.2 and 273 K which varies between 150-500 for OFHC copper. Copper has high corrosion resistance under atmospheric conditions and at room temperature an oxide layer Cu₂O forms at the surface which prevent further oxidation and at higher temperatures an oxide layer of CuO forms at the surface when it is exposed to air. If copper is exposed to air containing chlorine or ammonia compounds a considerable corrosion of copper may occur. Improvement of the mechanical properties of copper is essential in order to be useful in electrical applications. This usually result into reduction of the electrical conductivity hence strengthening can be done by either additional alloying elements or cold working. By annealing the cold-drawn pure copper at temperatures of 200-325 °C, softening can be achieved but presence of impurities and the previous cold deformation may alter the annealing range. Additional alloying elements or presence of impurities rises the annealing temperature while high degree of prior cold deformation requires lower annealing temperature range. The effect of alloying elements and impurities on coppers electrical conductivity is shown in Figure 1 [14].

---

*Figure 1. Effect of alloying element and impurities on conductivity of copper.*
Addition of alloying elements such as Mg, Ni, Ag, Cr and Mn and further treatment such as annealing and hard drawing, makes the copper conductors usable in various applications. For example the hard drawn conductor have higher mechanical strength than annealed copper, hence more suitable for voltage cables, overhead transmission lines and underground cables, while annealed copper have higher ductility and flexibility can be used as low voltage power cables and serve bending without failure [15].

The main advantages of copper and the properties that makes it suitable as conductor material is high electrical and thermal conductivity, low voltage drop and resistivity which compared to other metals provide better voltage quality and less voltage losses for the same cross section. It has higher chemical stability and corrosion resistant which helps avoiding oxidation accidents even though copper is usually by nickel, tin and silver. High tensile strength flexibility and anti-fatigue enable withstanding mechanical loads, long flex life, high stress levels, and high fatigue strength value of 62 MPa for annealed copper. Due to coppers low thermal expansion coefficient, it will not go through many contraction and expansion cycles which minimize the stresses in terminating joints and this makes copper conductors one of the most preferred electrical conductors and it has a wide field of applications.

2.3.2  Aluminium and its alloys as conductor material

Due to aluminium’s light weight, availability, moderate cost, relatively good thermal and electrical properties it has been considered as an alternative to copper for conductor applications in electrical systems in recent years. [14]. Aluminium is normally not used in its pure state, alloying elements such as Mg, Mn, Cu, Fe and Zn is usually added in order to enhance different properties. Aluminium alloys are categorized as either cast alloys or wrought alloys where casting as treatment is used for cast cat alloy to determine their shape while wrought alloyed are extruded, forged and rolled into shapes such as foil, plate and sheet products. The wrought alloys are usually differentiated by a four-digit number as shown in Table 5 where the first number stands for a series that is characterized by the main alloying element. A prefix, EN AW (European standard) or AA (Aluminium association) is used to denote the standards. There are eight different series with different physical, mechanical and corrosion properties hence different behaviour and properties during service forming, welding and surface treatment.

By heat treatment processes of the alloys, different properties can be achieved and the aluminium alloys are also differentiated by being heat-treatable or non-heat-treatable alloys. Heat treatment strengthens the alloy and the elements get homogenously distributed which changes the microstructure and age hardening or precipitation may occur. The non-heat-treatable alloys can be strengthened by cold-working during forging, rolling or annealing. Further, mechanical deformations at ambient temperatures increase the metal resistance and strengthen it. Formation of vacancies and dislocations in the structure which inhibit the atom movement and strengthen the alloy [3].
Table 5. Main properties and application of aluminium alloy series.

<table>
<thead>
<tr>
<th>Series No.</th>
<th>Primary alloying elements</th>
<th>Heat treatment</th>
<th>Properties</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1xxx</td>
<td>None</td>
<td>Non-heat-treatable</td>
<td>Excellent workability and corrosion resistance, high electrical and thermal conductivity</td>
<td>Transmission, power grid, lines (1350)</td>
</tr>
<tr>
<td>2xxx</td>
<td>Cu</td>
<td>Heat-treatable</td>
<td>No atmospheric corrosion resistance, good combination of high toughness and strength</td>
<td>Aircraft alloy after cladding with 6 b xxx series or painting for higher corrosion resistance (2024)</td>
</tr>
<tr>
<td>3xxx</td>
<td>Mn</td>
<td>Non-heat-treatable</td>
<td>Good workability and enough strength</td>
<td>Heat exchangers, beverage cans, cook utensils (3004)</td>
</tr>
<tr>
<td>4xxx</td>
<td>Silicon</td>
<td>Non-heat-treatable</td>
<td>Lower melting point</td>
<td>Brazing alloys, welding wires</td>
</tr>
<tr>
<td>5xxx</td>
<td>Mg</td>
<td>Non-heat-treatable</td>
<td>Good weldability and corrosion resistance in marine environment, moderate to high strength</td>
<td>Pressure vessels, storage tanks and marine applications (5083), constructions and building (5005), in electronics (5052)</td>
</tr>
<tr>
<td>6xxx</td>
<td>Mg and silicon</td>
<td>Heat-treatable</td>
<td>Highly formable and weldable, high strength and corrosion resistance</td>
<td>Marine frames and trucks (6061), structural and architecture applications (6010)</td>
</tr>
<tr>
<td>7xxx</td>
<td>Zn</td>
<td>Heat-treatable</td>
<td>High strength alloy</td>
<td>Aircraft industry (7050 and 7075)</td>
</tr>
<tr>
<td>8xxx</td>
<td>Other than the other series</td>
<td></td>
<td>Depend on the alloying element; e.g. 8006 (Al-Fe-Mg): a combination of strength and ductility at both room temperature and higher temperature 8001(Al-Ni-Fe): High corrosion resistance at higher pressure and temperature</td>
<td>Domestic wiring(8177), bearing alloys in trucks and cars (8280 and 8081), Al-Li alloys for aerospace applications, power generation (8001)</td>
</tr>
</tbody>
</table>

### 2.3.3 Aluminium as an electrical conductor

For the same length and resistance, aluminium conductor should have 60% larger cross section area compared to copper, while the weight of aluminium conductor is 48% of copper with a current carrying capacity of 80% of that of copper conductor. Aluminium is ductile, it is softer than copper and can be rolled into several µm thin foils with relatively high electrical and thermal conductivity.
Since aluminium’s mechanical strength is low it cannot be drawn into extremely thin wires. The purity of aluminium and grade of cold work affect mechanical durability and resistivity. Commercial aluminium has a resistivity of 2.78 µΩ cm whereas that of high pure aluminium (99.999 %) has a resistivity of 2.635 µΩ cm at 20°C. The commercial aluminium contains <0.015% Ti, Cr, Mn, V, <0.1% Si and <0.02 boron. Addition of Ti and V minimize the effect of impurities on conductivity while adding boron leads to transformation of those impurities into borides with low effect on electrical conductivity. Alloying elements is essential for improvement of creep and tensile strength when the metal is hard-drawn, since pure aluminium results into insufficient mechanical properties. The most common used alloys for electrical applications are Al-Mg-Si or Al-Mg containing Co or Fe. The drawbacks of aluminium conductors, preventing wider usage is their lack of a reliable and economically viable termination. Oxidation of aluminium occurs immediately when it is exposed to oxygen which generate oxide layer, Al₂O₃ on the surface which are an electrical insulator. The oxide layer weakens the terminal and conductor connection which leads to a softened surface layer and a significant weakened metal to metal contact which results into separation of the layers in long term. The main challenges due to nonconductive surface are therefore to strand conductivity to the terminal, the strand to strand conductivity and intermediate wire size [5]. Different methods such as ultrasonic welding, friction welding, plasma welding, plating and brazing have been established in order to overcome this problem. Most of those methods are either too expensive or require bigger operator care with marginal mechanical or electrical operations in some cases [14].

Disadvantages of aluminium conductors can be summarized as:

- Overheating of the connections may occur because of connection problem that generate heat under electrical load.
- Oxidation on the surface of the conductor.
- The insulating layer increase overheating which challenges the safety and reliability of connection.
- Loosening of the terminal due to aluminium’s tendency to cold flow under pressure.
- Thermal expansion owing coupling of dissimilar metals.
- Aluminium should have larger gauge than copper for the same current carrying capability.

The weight and price of aluminium metal are the primary factors that make aluminium attractive as conductor material. The advantages of aluminium are summarized as:

- Aluminium compared to copper is available in ample supply while copper is resource limited. This result into constantly stable and lower price of aluminium.
- The conductors retain its intrinsic qualities after removal of the insulation material since it does not adhere to aluminium which facilitates the recycling treatment.
- Aluminium conductor unlike copper conductor has no effect on compound containing rubber since no stearates is produced even under presence of oils.
- Corrosion is attributed to the oxide layer formed at the surface of the conductor and usually traced to connection joint between two different metals when it is exposed to air or moisture. This targeted point can be approached by different protection methods.
- Aluminium is a light metal with a mass of 2700 Kg/ m³ and for equal electrical conductance as copper, two times less relative weight of aluminium is required. This weight reduction
results into reduced fuel consumption, hence reduced CO₂ emissions. Even the logistic processing and installation operation benefits from a weight reduction.

- Even though pure aluminium is 65 % IACS, aluminium’s conductivity in relation to the same weight as copper is two times larger.
- Aluminium is ductile with low melting point which enables customary processing and excellent workability such as bending, machining, stamping and forming with a variety of surface treatments.

2.4 Comparison of aluminium and copper conductors

A conductor’s capability to carry current can be calculated by conductivity, resistivity, length and CSA of conductor metal expressed by resistance formula:

\[ R = \frac{\rho L}{A} \]

Where \( \rho \) is resistivity, \( L \) is length and \( A \) is area of the conductor. Since copper’s conductivity is greater than aluminium, about 1.5 times conductive as aluminium a larger cross-section area of aluminium is required for the same current carrying capacity. The raised volume owing the bigger CSA of conductors results into increased weight of armouring and insulation materials which are one of the main drawbacks of aluminium conductors and have to be considered when comparing and calculating weight reduction of the assembly. Additionally, the need of larger cable accessories, for instance cable straps, cable ties and cable tapes results into the need of another installation processes since the grater size of aluminium cable require larger space for a greater bending radii and installation of cable assembly. The bending radii of aluminium cables increase with 58 % which requires 27 % more space for installation of the cable [16]. This means that it is not only characteristics differences between these two cable materials, one have to consider how the whole system and other components might be influenced by replacing copper with aluminium.

When substituting copper to aluminium one should take into account their differences in e.g. mechanical strength, resistivity and density, physical properties etc., a comparative characteristics of aluminium and copper are expressed in Table 6.
Table 6. Properties of Aluminium and copper conductors [17], [18] [19]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Copper</th>
<th>Aluminium 1350 (Hard drawn)</th>
<th>Aluminium 8000 (half hard)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight for the same conductivity</td>
<td>100</td>
<td>54</td>
<td></td>
</tr>
<tr>
<td>Cross section for the same conductivity</td>
<td>100</td>
<td>164</td>
<td></td>
</tr>
<tr>
<td>Electrical resistivity (µΩcm)</td>
<td>1.72</td>
<td>2.83</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus (KN/mm²)</td>
<td>118 (annealed) 118-132 (half hard)</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Tensile strength (N/mm²)</td>
<td>200-250 (annealed) 260-300(half hard)</td>
<td>169-200 85-100</td>
<td></td>
</tr>
<tr>
<td>Mass density (g/cm³)</td>
<td>8.89</td>
<td>2.705</td>
<td>2.710</td>
</tr>
<tr>
<td>Modulus of rigidity (torsion) at 20°C (Shear Modulus) (KN/mm²)</td>
<td>44 (annealed) 44-49 (half hard)</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>0.2 % proof strength annealed (N/mm²)</td>
<td>50-55 (annealed) 170-200 (half hard)</td>
<td>20-30</td>
<td></td>
</tr>
<tr>
<td>Fatigue Strength (N/mm²)</td>
<td>62 (annealed) 115 (half hard)</td>
<td>35 (annealed) 50 (Half hard)</td>
<td></td>
</tr>
<tr>
<td>Fatigue No of cycles</td>
<td>300 x106</td>
<td>50 x106</td>
<td></td>
</tr>
<tr>
<td>Coefficient of expansion(/°C) (20-200°C )</td>
<td>17.3 x 10-6</td>
<td>23 x 10-6 (alumina 7.6 x 10-6)</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity at 20°C ( W/mK)</td>
<td>397</td>
<td>230</td>
<td></td>
</tr>
<tr>
<td>Temperature coefficient of electrical resistance</td>
<td>0.00393 (annealed, 100 % IACS ) 0.00381 (fully cold worked, 97% IACS)</td>
<td>0.00429a</td>
<td></td>
</tr>
<tr>
<td>Temperature for creep of 0.22%/1000h under typical termination stress</td>
<td>150 °C</td>
<td>20°C</td>
<td></td>
</tr>
<tr>
<td>Specific heat(J/kgK) at 20°C</td>
<td>386 (at 20°C) 393 (at 100°C)</td>
<td>900</td>
<td></td>
</tr>
<tr>
<td>Thermal diffusivity (mm²/s) at 300K</td>
<td>117</td>
<td>98.8</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (Wcm/cm²K)</td>
<td>3.94 (at 20°C) 3.85 (at 100°C)</td>
<td>2.05</td>
<td></td>
</tr>
<tr>
<td>Corrosion (Zero potential at 20°C)</td>
<td>+0.34V</td>
<td>-1.67V</td>
<td></td>
</tr>
<tr>
<td>Surface oxide film</td>
<td>Cu2O (conductivity 10s/cm) copper sulphate conductance</td>
<td>Al₂O₃ (conductivity 10-7 s/cm)</td>
<td></td>
</tr>
<tr>
<td>Conductor price (May,2016) USD/Kg</td>
<td>4.98</td>
<td>1.67</td>
<td></td>
</tr>
</tbody>
</table>

*a Approximated value for high conductivity hard drawn aluminium or pure aluminium

b Values for annealed conductor
The mechanical properties, stress-strain relation of a conductor metal are expressed by Hooke’s law:

$$\sigma = E \varepsilon$$  \hspace{1cm} \text{Equation 7}

Where $\sigma$ is stress, $E$ elastic modulus is the stress-strain curve in the elastic deformation zone which can evaluate the stiffness behaviour. The stress produced by shear stress, called shear modulus is expressed by:

$$\tau = G \gamma$$  \hspace{1cm} \text{Equation 8}

The metal can return to its previous dimension in the elastic deformation zone without being permanently deformed after unload. The higher stiffness of a conductor the higher load it can resist without fracture or necking. Therefore, a conductor with less stiffness and bending radii require more caution during installation. The conductor stiffness is affected by its flexibility class, a smaller bending radii is required for conductors with high flexibility class. As shown in Table 6, conductors having less stiffness than copper with respect to their elastic modulus values require cautions during installation. If the minimum bending radii is exceeded, unwanted and unmovable kinks with hot spots and potential weakness forms and remains in the aluminium conductor. Equivalent creep occurs at 20°C for aluminium conductors and at 150°C for copper conductors while the creep rate at 0.022 % occurs at much higher temperatures for copper conductors compared to aluminium where aluminium’s tendency for creep is higher at normal operating temperature and room temperature. Creep is a deformation that is irreversible and affects conductor termination by decreasing contact pressure with potential overheating issues. Likewise, cold flow which is a permanent deformation of the material when exposed to force or pressure during mechanical termination. Creep coupled with cold flow is a factor challenging termination of aluminium conductors. Due to this aluminium should have its own regulations and standards for torque settings for terminals, connection and terminating methods.

A metal’s ability to conduct heat is defined as thermal conductivity. Metals with high thermal conductivity have a better heat dissipation which results into less temperature rise and hot spots at terminating joint. The specific heat is the conductor’s ability to absorb heat while the heat generated by joule effect is stored in the conductor and expressed by

$$J = I^2 R t$$  \hspace{1cm} \text{Equation 9}

Where $R$ is resistance, $t$ is the time period the conductor conduct heat which is equivalent for conductors with same length and resistance value and the temperature rise owing heat storage is expressed by

$$\Delta T = \frac{J}{c m}$$  \hspace{1cm} \text{Equation 10}

Where $c$ is the conductor metal’s specific heat value. Comparison of copper and aluminium’s temperature rise shows that the temperature rise for aluminium conductor is smaller than copper conductor. Due to this, thermal diffusivity which indicates the capability to conduct relative store thermal energy, aluminium conductors with lower thermal diffusivity has a higher tendency to absorb thermal energy while copper favours thermal conductance.

As indicated in Table 6, aluminium has larger thermal expansion coefficient than copper, this may result into incompatible expansion between the terminal and conductor. Brass and copper is the typical terminal metals used for copper conductors which have much lower thermal expansion coefficient than aluminium. Using those metals as terminal metals for aluminium conductors will result in connection problems where the connection tends to loosen over time owing the different
expanding degrees. Loosening of the connections results into increased contact resistance which in turn leads to arcing and overheating.

Regarding the mechanical properties of conductors shown in Table 6, required stress for 0.2 % plastic deformation before losing elasticity is defined as proof stress and copper conductors ability to withstand proof stress is about 3 to 6 times higher than aluminium conductors. This means that copper conductors have lower risk of breaking or necking during processes where mechanical pulling is employed. It is more likely for aluminium cables to neck-down or stretch when exposed to high pulling forces resulting in reduction of CSA, worsen current carrying capacity and overheating issues. Pulling force serve greater mechanical deterioration and irreparable stresses on multicore cables consisting few small sized cables which limit application of aluminium based cables with small CSA or diameter.

With respect to corrosion issues indicated in Table 6, aluminium conductors have higher tendency for corrosion owing its low zero potential. Connecting aluminium with metals having higher zero potential results into galvanic corrosion. Formation of insulating Al₂O₃ is one of the most damaging factors since it inhibit current flow, consumes the conductor metal and cause formation of hot spots in the contact spots.

In addition to those properties, the constantly increasing and fluctuating price of copper compared to aluminium’s stable and far lower price, about one third or copper makes this to one of the main differences between these conductor materials.

2.5 Application of Aluminium wires in automotive industry

There are many suppliers in the market offering aluminium wires in different dimensions which can be used with conventional terminals where copper made lugs are used as connection method. Aluminium in combination with copper leads to potentials of galvanic corrosion [7].

Earlier studies have shown that the weather conditions have a significant role when it comes to degree of corrosion, since galvanic corrosion occurs when the metal comes in contact with electrolysis for instance snowmelt salt, chloride and squalls depending on whether the vehicle is used in North America or Middle East for instance. Due to this development of corrosion protection and different solution is essential in order to prevent corrosion and provide wires with electrical connections that last the entire lifetime of a vehicle.

Although there was no international standards for regulation of aluminium cables characteristics in automotive applications, usage of aluminium cables in automobiles started in 2000. An non-ISO standard, LV122-2 developed by German car manufactures for aluminium cables in automotive was released, until 2013 when the international standard ISO 6722-2 was created where standardization of CSA conversion with the aim to minimize the impact on termination system. The standard includes aluminium cable size with a range of 0.75-120 mm², including specification of battery cables and primary cables for equivalent current carrying capacity [20]. The investigation of using aluminium cables in automobiles started in Europe followed by the Japanese automakers who expected a weight reduction of 40 kg by replacing copper cables with aluminium cables [21] [22]. The larger cable being replaced, the more weight saving, according to a study done for battery cables [21], a 6 m long cable with CSA of 95 mm² and insulated by PVC would require an aluminium cable with 150 mm² for equivalent current, even though this results in 22.9 % increased cable diameter, a weight saving of 46.3 % is possible. As indicated in Figure 2, the Japanese and European automakers have implemented aluminium cables such as battery cables and power cables where large sized cables represent cables with CSA larger than 25 mm².
The issues related to larger cable size of aluminium are fatigue life, flexibility and strength of stranded conductors since next generation of automobiles demand reduced size of cable conductors and according to a study done by Kuypers [23], application of cables for high voltage systems e.g. 48 V are not recommended if the vibration cannot be relieved and if the short circuit cannot be protected. Development of aluminium cables started for more than 30 years ago where it was used in aircar where large sized cables was firstly used before development of small gauges signal cables. Due to this the small sized cables which counts for major part of cable harness weight, cables with small CSA have been investigated by [24] [25] [26] [27]. Those studies recommended substituting aluminium cables with CSA range of 0.5-15 mm$^2$, in areas where high vibration is not present for instance replacing copper conductor by aluminium conductors in engine compartment with presence of high vibrations is not recommended. Apart from this, aluminium cables with large CSA for instance battery cables are being used on a mass production basis but the termination techniques faces some challenges and have to be improved. When it comes to the further usage of aluminium cable harnesses in automobiles, battery cables and cables with CSA over 15 mm$^2$ will reach a wider use, while signal cables with small CSA and midsized cables (2.2 mm$^2$-8 mm$^2$) need further investigation before being recommended [3]. The difficulties of aluminium conductors is to provide an stable and reliable termination and the challenges as indicated in Table 6 owing aluminium’s characteristics which represent incompatibility with the terminal, corrosion potentials and high thermal expansion which challenge termination and reliable connection of aluminium cables. The challenges regarding application of aluminium cables in automobiles are summarized as:
- The increased diameter of aluminium conductor requires larger volume and space which may affect the present termination system and parameters that are standardised and the strategies of cable harness makers have to be in agreement with terminal makers.
- A greater diameter and bending radii of aluminium cables challenge the installation of the cable harness and is controversial to minimization trend that claim high flexibility and lowered volumes.
- Aluminium conductors may face some mechanical strength issues, especially the small sized conductors where fracture crack or kinks during service or installation may occur, in fact reduced flex life and break strength lead to cable failure, hence, cables with smaller CSA than 0.75 mm² is not recommended in current vehicles.
- A reduction of contact pressure under termination and crimping owing the applied force result into non-gastight contact interface where corrosion and oxidation can occur even if the termination joint is sealed. This lead to loosening of mechanical connection and increased contact resistance which generate heat and further creep and cold flow of the conductor.
- The surface of aluminium tends to quickly oxidize and form an electrically resistance layer when exposed to external atmosphere. This surface layer worsens the metal to metal contact and if a conventional termination technique, as shown in Figure 3 is used, the insulating layer will prevent current flow and as a result, higher contact resistance and unacceptable heating of the joint can occur.
- Galvanic corrosion which occurs when two dissimilar metals are in contact with each other and in presence of an electrolyte is another issue that affect the contact behaviour, weaken the conductor and lead to contact failure.
- Using different metals at the termination join hampers handling high temperature, high vibration conditions and thermal shock since aluminium have high thermal expansion coefficient which along with those conditions generate incompatible thermal expansion of the terminal and conductor which in turn deteriorate the connection with a failure as result.

![Copper crimped](image1) ![Aluminum crimped?](image2)

*Figure 3 Comparison of conventional crimping of copper and aluminium [28].*

### 2.6 Current load capacity

Due to characteristics of aluminium a larger cross section of aluminium is required compared to copper. A comparison between aluminium and copper, in terms of cross section area for the same current carrying capacity, is shown in Table 7 below [5].
Table 7. The relation between aluminium and copper for the same current carrying capacity [2].

<table>
<thead>
<tr>
<th>Wire cross section of aluminium</th>
<th>Wire cross section of copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 mm²</td>
<td>1.5 mm²</td>
</tr>
<tr>
<td>4.0 mm²</td>
<td>2.5 mm²</td>
</tr>
<tr>
<td>6.0 mm²</td>
<td>4.0 mm²</td>
</tr>
</tbody>
</table>

Equation 11 describes the cross section needed for aluminium cables to get the same equivalent electrical current as in copper. Since the cross section of the conductor is reversely proportional to electrical conductivity, the aluminium conductors have to be 1.6 times larger than copper in order to carry the same current [5].

\[
\frac{\text{Cable cross section}_{\text{Al}}}{\text{Cable cross section}_{\text{Cu}}} = \frac{\text{Specific Conductance}_{\text{Al}}}{\text{Specific Conductance}_{\text{Cu}}} = \frac{58.5 \text{ S/m/mm}^2}{35.5 \text{ S/m/mm}^2} \approx 1.6 \quad \text{Equation 11}
\]
3 Current electrical connection methods

3.1 Contact physics

The conduction of electricity occurs at asperity point even called $\alpha$-spots which raise the contact resistance. The contact resistance can be described by:

$$R_c = \left(\frac{\rho^2 \eta H}{4F}\right)^{1/2}$$

Where $\rho$ is resistivity, $\eta \approx 1$ is empirical coefficient of surface cleanliness, $H$ is the metal hardness and $F$ is the contact force. In the case of connector application, a stable and low contact resistance is required during the entire life of the connector. The contact material determines the hardness and resistivity while the contact force is a design factor. The degree of surface corrosion, contaminations in the surrounding environment and type of protection determine surface cleanliness $\eta$. In general a material with low $H$ (soft material), and low resistivity $\rho$ and great contact force $F$ provides larger $\alpha$-spot size. There are challenges regarding connectors with low cost, small size, light weight and operating in extreme environment but those challenges can be faced by different approaches [28].

3.2 Contact area

All solid surfaces, on a microscale are rough and this roughness consists of variation in high and geometrical characteristics that depend on details of surface generation process [29]. Contact between two bodies occurs at discrete spots that are produced by mechanical contact of asperities on two surfaces shown in Figure 4.

![Surface A and B](image.png)

*Figure 4. Bulk Electrical interface and constriction of electric current.*

The true contact for a material is a small fraction of a nominal contact area for a range of contact load [29]. The real surface of the contacting area is not flat and contains many asperities, shown in Figure 5, deformation of those contacting asperities can plastic, elastic or a mix of plastic-elastic deformation depending on the stresses in the local mechanical contact and on the materials properties, for instance the hardness and elastic modulus of the material.
The contact surface of metals in an electrical interface is often covered with electrically insulating layers or oxides. In general a surface is electrically conductive when metal to metal contact spots is produced, which is possible if the insulating film is displaced at the asperities of contacting surface or getting ruptured. Due to this the real area of electrical contact in an electrical junction is smaller than the area of mechanical contact. The electrical current lines in an electrical junction become distorted when the contact interface is approached and the flow lines together passes through the contact spots (or “α-spots”) [30]. The apparent contact area, shown in Figure 6 include, real contact area, oxides, contaminant films and the α-spots which provide the conductive paths for electrons and is formed by small cold welds.

As shown in Figure 6 the α-spots which are the physical contact area, where the passage of electrons occurs are much smaller than the real contact area. The properties of those α-spots are related to the contact metal material and environmental dependent. The electrical resistance increases since constriction of electrical current by α-spots reduces the volume of the material. This increase in interface resistance is defined as constriction resistance and often, presence of contaminant films on the contacting surface, increase the resistance of α-spots. The interface contact resistance in turn is determined by total interface resistance owing the constriction and film resistance [30]. The relation between apparent contact area $A_a$ and applied normal load $F_c$ and hardness is given by

$$F_c = \varepsilon HA_a$$  \hspace{1cm} \text{Equation 13}
where $\varepsilon$ is pressure factor that is determined by the amount of asperities on the contact areas and $H$ is the hardness of a metal with estimated ability to resist deformation under pressure load up to three times of yield stress ($H = 3\sigma_y$).

The constriction resistance of a single $\alpha$-spot is given by

$$R_s = (\rho_1 + \rho_2)/4a$$  \hspace{1cm} \text{Equation 14}

Where $a$ is the radius of a $\alpha$-spot, $\rho_1$ and $\rho_2$ are electrical resistivity of conductor and connector which means that a minimum constriction resistance can be obtained if the contact metals are the same, i.e.,

$$R_s = \rho/2a$$  \hspace{1cm} \text{Equation 15}

If greater force $F$ applied, the radius of the contact area increases which in turn lower the constriction resistance. Other factors contributing to resistance of electron movements are the sulphides, oxides and inorganic layers that form at the surface. The total contact resistance is the sum of film resistance $R_f$ ($R_f = \sigma/\pi a^2$) where $\sigma$ is resistance per area of the film and $R_s$ which is constriction resistance. During formation of contact spots, mechanical breakage of the films occurs hence resistance contributed by film resistance is almost unneglectable [3].

Taking operating temperature into consideration, the contact resistance value can be expressed as Wexler resistance

$$R_w = \frac{4\rho}{3\pi a^2} K + \frac{\rho}{2a} \Gamma(K)$$  \hspace{1cm} \text{Equation 16}

Where $\Gamma(K)$ is the temperature related function and $l = l/\rho$, $l$ is the mean free path of electrons [31].

The formation of insulating intermetallic compounds on the contact interface result into increased resistance that continues increasing if hardness of the formed layer is higher than the contacting material and current conductivity is possible only when this film layer is broken. Due to this coatings for electrical material is used in order to prevent formation of this insulating film layer, mechanical wear and corrosion, decrease the hardness and promote conductivity. Using tin and nickel as plating material for aluminium conductors leads to that, the thickness of coating and $\alpha$-spot’s diameter and their conductive ratio affect the contact resistance. [3]

Contact resistance is the most important characteristics of electrical contacts and changes in contact resistance cause significant drawbacks since it might be greater than the previous value owing to considerably differing with variables in contact pressure load, real contact area and resistive film which is an fatigue indicating factor since accumulation of strain leads to fatigue behaviour, this means that an increased resistance results into fatigue behaviour and high voltage drop that is directly measurable in a DC potentiometers [32].

### 3.3 Automotive Connector contacts

The use of electrical devices in modern vehicles has grown tremendously. A vehicle in 1940s needed a 6Volt DC electrical system for providing the required power for ignition, starter motor, wiper and lighting circuit while vehicles today require currents up to hundreds of amperes and multiple voltage levels. Typical voltage level in a vehicle is described in Table 8. An electrical connection is required
for all these electrical systems which have to withstand performing in extreme environments where the temperatures varies between -40°C in arctic conditions and up to 150°C at engine mounted sensors [28]

<table>
<thead>
<tr>
<th>Type</th>
<th>Circuit</th>
<th>Current (A)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power</td>
<td>Appliance/commercial/residential</td>
<td>10-100</td>
<td>120-240 ac</td>
</tr>
<tr>
<td>Lightening</td>
<td>Appliance/commercial/residential</td>
<td>&gt;10</td>
<td>120-240 ac</td>
</tr>
<tr>
<td>Control</td>
<td>Appliance/commercial/residential</td>
<td>&lt;2</td>
<td>24-36 ac</td>
</tr>
<tr>
<td>Power</td>
<td>Automotive</td>
<td>&gt;1</td>
<td>12-36 ac</td>
</tr>
<tr>
<td>Power</td>
<td>Automotive, Electric Drives</td>
<td>~300</td>
<td>~300 ac, dc</td>
</tr>
<tr>
<td>Control</td>
<td>Automotive</td>
<td>&lt;1</td>
<td>5.12 dc</td>
</tr>
<tr>
<td>Low power</td>
<td>Electronics</td>
<td>&lt;1</td>
<td>5-12 dc</td>
</tr>
<tr>
<td>Signal</td>
<td>All</td>
<td>0.1</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

3.4 Cable Termination

Cable termination is a non-separable connection between the terminal and the cable where mechanical (crimped or soldered) or metallic joint provide the mechanical and electrical connection. The interface between the terminal and cable is permanent, it provide the mechanical and electrical link between the terminal and the cable. Further it has the main role in, performance and assembly of the terminal which is a part of the connector. Degradation of cable or terminal interface result into degradation of female or male terminal contact interface. The mostly common terminal-cable interfaces used for appliances and automotive wiring is barrel crimps and F-crimps, shown in Figure 25. The termination process consist of, stripping the wire insulation, insertion of the bare section into the barrel region or crimp wing where the crimping tool rolls the wing and deform or press the barrel which deform the wire, loosen the surface oxides, induce metal flow which forms a tight bundle and create electrical and mechanical bonding. The assembly is under high compression, so when the tool is released, the assembly rebounds. The barrel or crimp wing are relaxed which makes the metal to bounce back from the compressed state. This in turn reduces the contact force between the crimp wing and the wire so the crimp should be designed in a way where back bouncing with remaining residential force is allowed and low contact resistance with suitable mechanical joint can be obtained [33] [34].
The highest mechanical strength and the most optimum electrical performance do not take place at the same crimp connection level since a crimp with optimal electrical performance might have poor mechanical strength while a crimp connection with high mechanical strength lead to poor electrical stability. Due to this a trade-off where the best combination of long-term mechanical strength (pull strength) and electrical stability have to be found. A combination of best electrical performance and mechanical strength and their relationship is shown in Figure 8. At different crimp compaction level, the pull strength (shown with the dashed line in the figure) varies while the electrical performance (shown as solid line in the figure) varies with crimp compaction. Discernment of different compaction levels is performed at various environment conditions with SAE USCAR-21 as a good environmental exposure reference where crimped connections in automotive are specified [35]. With respect to Figure 8, at compaction levels, tighter than highest pull strength point, occurs the best combination of mechanical and electrical performance. A controlled crimping process is essential for reliable wire termination where in the case shown in Figure 8 it is ± 50 microns. Therefore, terminal manufacturers select material, coating, tool geometry, gauge, pressing force profile, internal barrel surface serration and final crimp deformation wisely in order to maximize the operating range [34]. Crimping is not suitable for small gauge wires since it will be subjected to high operating temperature which makes the crimp unreliable, hence alternative termination such as soldering or welding which are more expensive can be used since it provide higher mechanical strength and stable electrical interface.
3.4.1 Crimping

The connection of a cable to a terminal have a structure shown in Figure 9 below where a crimped wire with a terminal is inserted to a pair of connectors, male or female connector which provide the electrical connection between wire harness and equipment/component.

To ensure the retention force, crimping as a connection method is being used; the wire with stripped insulation is crimped in the terminal. A special press tool is used in order to achieve a deformation that is predefined and a mechanically strong electrical connection between the connection element and conductor is achieved. The crimping condition i.e. the strength of the crimped area affects the
retention force and the electrical connection, generally the retention force decreases when the crimping force increases and the electrical connection stabilize. Due to this the manufactures have to take into account the required range of electrical connection and retention force in order to fulfil the standards. [37]. During crimping the cable and the connection element material is exposed to high mechanical pressure which leads to exceeded yield point. Crimping is correctly executed when the metal flow is mutual which means that the combination of connection element and cable area has to be suited with the crimping tool being used [38].

Crimping connection method is being used for copper wires but the property differences between copper and aluminium leads to challenges that require improvements and other solutions in order to enable the method for electrical connections of aluminium wires. The aluminium surface is covered by an insulating oxide film which has the biggest detrimental effects in the crimping properties and according to previous studies the electrical connection might be improved if the insulating oxide film layer is removed. In one of the study’s experiment a conductor wire was pushed against the terminal and the contact resistance were measured while load was applied. The results showed that in order to stabilize contact resistance, aluminium required more load than copper. In order to stabilize the contact resistance for aluminium wires, a higher crimping compression compared to copper wires is required. The wire retention force is then lower since stabilization of aluminium wire requires higher crimping compression than copper, the retention force lowers which means that the contact resistance needs to be improved at lower compression or improve the wire retention force at higher crimping compression which enables electrical connection of aluminium by crimping. A comparison of contact resistance, crimping strength and wire retention force between copper wires and aluminium wires is shown in Figure 10 [6].

![Crimping property of copper wire](image1)

![Crimping property of aluminum wire](image2)

*Figure 10. Contact resistance, crimping strength and wire retention force of copper and aluminium*

Few modifications of the terminal design and connection technology crimping is essential for enabling use of aluminium cables.
Inside the core crimp the geometry is knurled which together with the flowing characteristics of aluminium ensures that the surface oxide layer is broken and the terminal can strand conductivity electrical connection is achieved [5].

The strand to strand conductivity is achieved by ultrasonic welding of single aluminium strands to each other before crimping the wire to a terminal. A cable geometry called “nugget” with electrical strand to strand connection that can be crimped to a terminal is then provided. The nugget geometry will result into a more robust mechanical characteristic due to prevention of movement of the strands. A crimped, nugget that can be connected to a terminal is shown in Figure 11.

Figure 11. An ultrasonic welded cable with "nugget" shape that can be crimped to a terminal [5].

3.5 Welded connectors
Connections with all type of copper or aluminium conductors can be done by welding which is a highly accepted method since it creates an efficient, permanent electrical connection which is economical with a good appearance and most suitable for connection of two members with different cross sections. From the electrical standpoint, a joint that is properly welded is the most reliable joint since the contact resistance will be reduced which in turn prevent heat generation from high current [39]. There are different welding techniques for different applications but the most commonly used for power connections are thermite (exothermic) welding, friction welding, explosion welding, and resistance welding and ultrasonic welding and resistance brazing.

3.5.1 Thermite (exothermic) welding
Fusion process where two metals are heated and the overheated metal undergoes an aluminotermic reaction and the metals become bonded is called thermite welding. The melted metal from the reaction between aluminium and metal oxide acts as metal filler and make a molecular weld since it hangs around the conductor. The advantages of the thermite connections are that a high mechanical strength and good corrosion resistance can be achieved; the current carrying capacity of the connector is greater than the conductor’s capacity and a high stability during repeated short circuit current. Disadvantages of this process is the intense heat anneals the conductor which lead to that, the thermite connectors is not suitable in tension applications [14].

3.5.2 Friction welding
A combination of different nonferrous metals can be welded by a technique called friction welding. It is a solid state welding process where mechanical energy is converted to thermal energy at the contact interface without any external heat or energy. The wire is prepared by crimping the aluminium made sleeve on the striped wire before cutting the end of the sleeve and getting a clean surface. A rotating work piece is in contact with a non-rotating piece under pressure until the welding temperature is reached at the interface. A friction between the pieces generates frictional
heat which rises the temperature at the interface. When the interfaces are in contact with each other, atomic diffusion occurs and metallurgical bond between two pieces forms [14]. In order to ensure a surface without any pollution with residues of coating or aluminium oxide, a thin layer of the end of the connector is removed by a turning tool [7]. Both annealing of the carrier and segregation of metal oxides which occurs during melting when welded by other techniques can be minimized by this welding process. Production practicality and economics of this process have limited usage of this contact welding to low volume application [40]. A high voltage aluminium conductor welded to aluminium connector by friction welding technique is shown in Figure 12.

![Image](image.png)

Figure 12. Aluminium connector welded to an aluminium conductor by friction welding [7].

3.5.3 Resistance welding
Welding process where heat is generated by resistance to the electrical current flow through the conductors under force by electrodes and are held together and varying surface are joined by heat that is generated by a shot time pulse of high amperage current and low voltage which forms a fused nugget of welded metal. The electrode force is preserved when the current flows ceases and weld metal cools and solidifies. The resistance of materials weldability by this process is inversely proportional to its thermal and electrical conductivity.

3.5.4 Resistance brazing
A resistance welding process where a filler material is inserted in-between two pieces that are heated locally and melted by the heat from resistance to the electrical flow through the joint is called resistance brazing. An efficient localized heating method can be provided by using of high resistivity electrodes. In order to minimize or provide oxidation of the joint during heating a flux which provide a coating is used, in addition to that it dissolves the present or formed oxide during heating and assist the filler metal to promote capillary flow [14].

3.5.5 Resistance butt welding
Wires with various materials and cross section area can be welded by resistance butt welding but is usually used for wires of the same type. The material is melted by the electrical flow on both joint partners and the pollutions are flushed by pressing them together. A sleeve with base metal of aluminium needs to be crimped in order to ensure reliable electrical contact and clamp the wire, for a cleaner and more flat surface, the face side of the wire is cut off. This welding technique results into less damages in coating compare to other welding techniques but as in friction welding the end of the cable is cut of and cleaned before welding in order to get a clean and flat surface. According to previous studies it seems to be possible to weld similar wires without any sleeve where a connector can directly be joined to a wire. An example of a resistance but welded connector to conductor is shown in Figure 13 [7].
3.5.6 Ultrasonic welding

For years the only method to make a splice of wires was the clip and dip method where a metal terminal was applied over the wire strands in order to hold the wires together, which then was dipped in a cleaning solution to remove oil and oxidation. It was dipped in molten solder and shaken, to remove the extra solder and then cooled in neutralizer acid, a cleaning agent and dip-solder. The disadvantages of dip soldering are the introduction of acid and limited quality control. An more accurate method is ultrasonic welding where high frequency sound or ultra sound causes rapid vibration within the wires that is welded, the vibrations which can be up to 20 000 vibration per second causes the wires to rub against each other. This friction rises the surface temperature and sets the condition for the wire to form a molecular bond to one another and splices the wires. No terminal, no acid and no solder are used and important parameters such as wire quantity, gage, orientation to the weld, weld height before and after the weld, width of the weld, required time to make the weld, pressure, amplitude and energy put in to weld are monitored in a software used together with the ultrasonic welder which control welding parameters and ensure that they are repeatedly accurate. A tool compress the wires, then a ultrasonic are applied and when the tooling is opened a splice nugget of solid aluminium with fixed and durable connection after the ultrasonic splice is made it is covered with tape or rubber mould according to purchasers specifications [41] [42]. This welding process might damage the structure of contact material during welding and is sensitive to surface conditions, due to this coating and predefined cable head geometry is required while the oxide layer and coating from the surface have to be removed before processing in order to avoid unbounded and broken areas, an example of an ultrasonic welded aluminium cable is shown in Figure 14 [7].
3.6 Parameters affecting the power connections performance

According to previous studies a reliable connection of aluminium cannot be achieved by established methods and applications for joints with copper conductors. The difficulties with aluminium is that whenever two dissimilar metals are in contact to each other, due to their differences in mechanical, metallurgical and physical properties and reaction of those under different conditions determine their degree of compatibility [14]. The interface between the conductor and its terminal is the electrical contact interface where a good metal to metal contact is essential in order to assure continuity of electricity [3]. This requirement for aluminium is not easily achieved owing to the insulating oxide layer that is ever-presented at the surface. In addition to the external factors that affect the electrical conductivity, the microstructure of the connector metal also have an important role on electrical conductivity. Several phenomena related to the electrical contact interface such as temperature distribution, deterioration in contact which may result into increase in electrical contact resistance [3]. Aluminium’s propensity to undergo stress relaxation and creep, high tendency for galvanic corrosion and having a large thermal expansion coefficient that may result into fretting at the contact interface can result into failure of the connection and should be an awareness of [14]. A course of a cycle describing the complexity of failure mechanism is shown in Figure 15 [14].

![Figure 15. Schematic of degradation mechanism in aluminium power connections.](image)

3.7 Parameters affecting the contact area

Parameters such as shape and size of the contact surface, contact resistance and pressure, protection against external environment all together effect if the current can cross through the contact interface without being interrupted. A continuous passage of electrical current can be measured and there are three way, as shown in Figure 16, for improving the contact performance in order to ensure a reliable passage of current.

- Improvement of contact design
- Developing new contact material, lubricants and coatings
- Involving the state and structure of the interface
The stiffness of contacting members, the current density through the contact and the applied force are generally factors that define the contact area and a sufficiently large contact area can prevent a temperature rise of the interface under different conditions. The contact temperature itself on the other hand is an effect rather than a cause that occurs in a joint as a function of the contacts geometrical dimensions, current density and voltage drop throughout the contact. The temperature of the contact interface can increase more than the connector or conductors bulk temperature without making the contact interface electrically instable. On the other hand an increase of contact voltage even if to moderate values cause increase of contact temperature above that of connector or conductor bulk temperature. Due to this, the changes in voltage and contact temperatures with the connector operating time have to remain small <10 mV. This requirement can be met if, the real contact is large enough regardless deterioration and there are still enough of contact spots (α-spots) which guarantees that overheating in the joint is not reached. Previous studies [43] [44], have shown that lubrication and mechanical abrasion (brushing) of aluminium is one of the most simple and efficient method for achieving large number of contact points. Brushing together with application of a contact aid compound (grease) to the contact interface prevent oxidation of the metal. In order to ensure a large contact surface area between the conductor and connector, serration of the connector contact surface for splicing conductors can be used [45] [46].

3.8 Factors affecting the reliability of power connections

The probability of a process or equipment to function for a given period, without failure when operated correctly under stated conditions is the definition of a reliable connection. The discrete nature of the interface is one of the main problems when providing reliable electrical contacts. An electrical contact within the contacting interface in the discrete region is formed between the slides. It is the formation of conductive contact areas that control the efficiency and reliability of electrical contacts which in turn is dependent on several interrelated or independent factors. Those factors can be divided into factors determined by contact units’ fabrication characteristics, design-
technological factors, or the performance factors that are dependent on operating conditions which are divided into external or internal groups shown in Figure 17 [14].

The external factors are variation in time, temperature, atmospheric pressure, humidity which are uncontrollable while the internal factors are electric, (operating voltage, strength and type of current) mechanical contact load and characteristics and type of motion such as, the sliding velocity. The performance factors affect the surface films and the contact materials properties. If chemical or physical process occurs in the contact zone, formation of wear particles influencing the interface, the contact resistance and finally the reliability of electrical contact [14]. The effect of design-technological factors on the quality and reliability of electrical contacts are show in Figure 18.
The selected contact material, geometry, the intermediate layer that separate contacting surfaces, the contact surface microrelief and quality of selected coating all together determine the number, size and distribution of contact spots that influences the real electrical contact area, surface film resistance and the reliability of contact area [14].

3.8.1 Plastic and elastic deformation of power connectors
Plastic deformation of asperities occurs if the contact force is higher than few Newtons and formation of α-spots occurs. For lighter contact forces elastic deformation of asperities occurs instead and for some regions of contact force a combination of elastic-plastic deformation takes place [47] [48].
3.8.2 Corrosion
An electrochemical or chemical reaction between a metal and its surrounding environment leading to significant changes and deterioration of the material properties and function is the definition of corrosion. It starts with a progressive change in the geometry without any change in the materials microstructure or other chemical composition. Degradation starts with formation of a corrosion product layer and continues till one of the reactants can sustain a reaction and spread through the layer. The characteristics and the composition of the corrosion product layer have a huge influence on corrosion rate and the most common that could have an effect on metallic component of power equipment are localized, atmospheric, pitting, dust and galvanic corrosion [14].

3.8.2.1 Galvanic corrosion
Galvanic corrosion is an electrochemical process where the differences in materials properties such as electrode potentials and the presence of electrolyte is the basis of galvanic corrosion. Galvanic corrosion is considered as one of the most dangerous degradation mechanisms in a bimetallic system [49]. The voltage differences between two metals is the driving force behind electrons flow where the direction is dependent on which of the metals is more active. The less noble metal is more active and become anodic, corrosion occurs and the other metal that is less active becomes cathode [14]. A power source starts when moisture comes in between the metals and an electrode potential of at least 5 mV is required in order to start a current flow [49]. In the case of copper-aluminium connections, the most non noble metal aluminium behave as anode, dissolves and deposited at copper in a complex hydrated aluminium oxide form while hydrogen forms at cathode copper. This degradation process continues until all aluminium is consumed and as long as an electrolyte is present although the erosion rate at the surface is limited by the corrosion products. Corrosion can affect aluminium to copper connections in two ways, either a mechanical failure caused by a severely corrosion of the connector or an electric failure caused by a drastic reduction of contact area [14]. Galvanic corrosion of aluminium and copper is shown in Figure 19.

![Figure 19. Galvanic corrosion of aluminium and copper [36].](image)

3.8.2.2 Localized corrosion
Localized corrosion have an relatively fast attach rate with a small affected area which is hard to quantify and detect since the surface defects tends to be small and a good indication of the extent of those defects is hard.
3.8.2.3 Atmospheric corrosion
Altering of a material or gradual degradation of a material when it gets in contact with e.g. water, oxygen, vapour, carbon dioxide, chloride and sulphur components presented in the air is called atmospheric corrosion. Degradation is accelerated considerably by a thin film of water owing the electrolytic nature of corrosion. Even though the corrosion rate is dependent on the temperature, humidity, sulphate and chloride levels, it is not constant over time, it decrease when exposure time increases [14].

3.8.2.4 Pitting corrosion
Degradation of a metal surface confined to a small area or localized to a point that forms cavities are pitting corrosion. Those pits have an irregular shape and may get filled by corrosion products. Coated metals are usually affected by pitting where the pits forms at a weak spots where the coating is mechanically damaged and cannot self-repair. Metals such as aluminium, copper, cobalt, chromium, and their alloys are prone to pitting corrosion. A local breakdown of surface corrosion films, initiates pits which accelerate the corrosion rate, those pits are commonly observed in H₂S and CO₂ environments. The corrosion products are usually black in colour and adhering to the metal surface [14].

3.8.2.5 Dust corrosion
Dust corrosion have been investigated by Zhang [50], occurs because of the presence of water soluble salts in dust that comes in contact with the metal. Zhang indicated that one the most influencing factors on dust corrosion is humidity and pH factor. As shown in Figure 20, corrosion of dust particles increases linearly with humidity. Typical product appearing around the dust particle is shown in Figure 21 [14].

![Figure 20. Corrosion ratio of dust particles having different PH, as a function of humidity.](image1)

![Figure 21. SEM picture of corrosion product around dust particle.](image2)

3.8.3 Thermal expansion
Thermal expansion is another degradation mechanism caused by differences in thermal expansion coefficient between two different contact metals. In the case of aluminium to copper connections,
when the connector is exposed to increase in temperature, aluminium expands at a higher rate than copper which results into lateral movement in the metal-contact bridges zone with a reduced contact area, or plastic deformation of contact interface. This lead to increase in contact resistance which rise the connection temperature but a matrix recovery where the stresses are relieved is feasible at higher temperatures. However, those thermal stresses build up again when the material is cooled and further plastic deformation and interracial shearing with small recovery possibilities occurs since potentials for matrix recovery and stress relieves at lower temperatures are small. If this process is repeated and if the generated thermal stresses are higher than aluminium’s yield stress, plastic deformation in the contact zone occur which accelerate degradation of the connection until failure. If the metals are annealed, the thermal stresses in aluminium can be assumed to be negligible and an estimation of magnitude of the maximum generated elastic stresses in aluminium-copper connections in thermal cycles, at peak temperatures can be calculated by

\[ \Delta d = \varepsilon_t \Delta T \]  

Equation 17

Where \( \Delta d \) is the amount of contraction for both copper and aluminium when cooled, \( \varepsilon_t \) is the thermal expansion coefficient and \( \Delta T \) is the change in temperature. The differential strain because of the constraint is then described by

\[ \Delta d \varepsilon = \Delta T[\varepsilon_t(AI) - \varepsilon_t(Cu)] \]  

Equation 18

Aluminium- copper contacts differential strain at 100 °C, 150°C and 200 °C, are 6.8, 10.2 and 13.6×10^{-4} (1/°C), since for copper \( \alpha_t=17.2\times10^{-6}(1/°C) \), and for aluminium \( \alpha_t=24.0\times10^{-6}(1/°C) \). The elastic modulus of aluminium is 70 GN/m² and the tensile yield strength is 55 MN/m², which gives a yield strain of 7.8×10^{-4} (1/°C). Those values compared to the calculated differential strain values, indicates that during cooling of contact, aluminium should yield [14]. In addition to this, thermoeelastic ratcheting is another consequence of great thermal expansion of aluminium where excessive tightening of bolts in aluminium to copper joints can deform the conductor plastically during heating cycles and cannot regain their original shape after cooling cycles. Due to this loosening of the joint occurs after repeated heating and cooling cycles which in turn increase contact resistance and joint temperature [51].

3.8.4 Creep

A metals plastic deformation during creep is related to the viscous diffusion flow and dislocation dynamics phenomenon. At temperatures close to the melting temperature occurs viscous diffusion. The creep rate gradually decreases and vanishes at low applied stresses and medium temperatures, which can be described by the logarithmic law:

\[ \varepsilon = \varepsilon_0 + \alpha \ln(\beta t + 1) \]  

Equation 19

Where \( \varepsilon_0 \) is the initial deformation, \( \alpha \) and \( \beta \) are constants and can be used for studying the rate of plastic deformation of metals which is valid for materials with different type of crystals and at temperatures below 0.2-0.3 \( T_m \). At lower temperature, creep is mainly affected the dislocation mechanism that is result of applied stresses and thermal fluctuations which unhamper the motion of dislocations through the lattice. Klypin [52], studied creep of metals under the influence of electrical current and founded that creep rate is strongly affected by the electrical current and the creep rate increase significantly when current is applied. The growth of creep in connectors and consequent process occurring in the contact is shown in Figure 23.
3.8.5 Creep and stress relaxation

Cold flow or creep in a metal occurs when it is exposed to constant external force over time. Creep is higher for aluminium than copper and the rate depends on temperature and stress. Even stress relaxation depends on temperature, time and stress but in contradiction to creep it does not result into dimensional changes. Stress relaxation occurs at higher stress levels and metallurgical structure changes result into reduced contact pressure. Failure of contact joint occurs when the elastic strain changes to plastic strain which reduce residual contact pressure significantly which in turn increase the contact resistance. Acceleration of initial contact pressure loss occurs when the temperature is raised which shorten the time of contact area loss. Due to this, high stresses owing the connector system and deformation of the conductor. If no residual mechanical loading is provided for the contact interface, an acceleration of stress relaxation resulting in to failure of contact joint will occur [14].

Farrell [53] [54] investigated the effect of temperature and metallurgical state on copper and aluminium’s strain relaxation and the result showed that an increased hardening and temperature increase the rate of stress relaxation and that metal forming, stress relaxation, and flow stress is affected by the flow of the electrical current and the interaction between dislocations and electrons.

3.8.5.1 Effect of electrical current on stress relaxation

Silveira and co-workers [55] investigated the effect of metals mechanical properties on electrical current and founded that, stress relaxation rate of polycrystalline copper and aluminium near 0.5 Tm (melting temperature) can be increased by applying 1.6 A/mm² continuous AC or DC current. It was
found that DC current changed the arrangement of dislocation in copper specimens which restructured the structure of the cells while no changes in dislocation structure were found for aluminium. Application of current increases the stress relaxation rate considerably, Braunovic [56] studied the differences of aluminium conductors stress relaxation at room temperature and low initial stresses (20 N), when influenced by low-density current (3 A/mm²) and conductors at higher initial stresses (260N) at a higher temperature (150°C), it was clear that aluminium’s stress relaxation under cycling conditions and at higher temperatures is similar. It means that a wires contact force (initial force $F_i=20N$) under current cycling decreases at the same rate as if the wire would be exposed to stress relaxation at 150 °C and higher force, $F_0=260N$.

It is not only the effect of temperature that justify the effect of current cycling on stress relaxation since the temperature difference owing passage of low current density is about 2-3°C. one explanation to this phenomenon could be that thermal fatigue in aluminium wires is caused by current cycling which reduce the materials overall durability and increase the rate of stress relaxation. Additionally, the contact zone that is under compression during cycling, work-hardens because of the wires thermal expansion which increases the contact stress and it is known that the rate of stress relaxation is increased by work hardening, hence the rate of stress relaxation can augment.

A metals stress relaxation is usually related to its structural defects for instance solutes, grain and subgrain boundaries, impurities, precipitates etc. so when the electrical current passes through the wire, it will cause heating, weakening of the binding forces between the dislocations and obstacles that prohibit the motion of the dislocation. This increases the density of dislocations and alters their arrangement. Repeated current cycling in the wire reduce the dislocation density, enhance mobility and free the dislocations from pinning defects which in turn increase the rate of stress relaxation [14].

3.9 Fretting

Fretting is an accelerated damage of surface that occurs at the contacting interface when exposed to small oscillatory movements produced by mechanical vibration, load relaxation, differential thermal expansion of contacting metals and junction heating when the power is switched on and off. This kind of fretting damage includes fretting corrosion, fretting fatigue and fretting wear. Fretting is a time related process and the effect of it is not easily recognizable since a power connections failure is usually associated with contact zones’ destruction by arcing [14]. Factors affecting fretting can be divided into environmental conditions, material properties and behaviour and contact condition, those factors and how they affect each other are schematically illustrated in Figure 23 [57].
Those factors can interact and influence each other which have an impact on degree and nature of fretting, for instance under some conditions the environmental effect can be neglected from the contact area, hence have no strong effect on fretting.

Fretting is one of the factors that contribute to electrical instability and joint failure, it is one of the major deterioration mechanism in dry connections and appears in conductor and contact materials such as copper, aluminium, tin, nickel and silver [58] [59]. Fretting of aluminium made connections is of considerable importance since the aluminium oxide particles degrade the metal which initiates oxidation and accumulation of fretting products [60].

3.10 Intermetallic compounds

Usage of bimetallic welds of aluminium to copper by for instance pressure welding, friction welding and ultrasonic welding. Frequent current surges; generate conditions for nucleation and growth of intermetallic at the interface which decrease the mechanical strength and electrical stability due to the intermetallic lower mechanical strength and higher electrical resistance. Previous investigations of aluminium to copper joints have shown that if the intermetallic phase’s thickness exceeds 2-5 μm, the joint loses its mechanical integrity. Figure 24 shows microstructure of intermetallic phases formed at Al-Cu contact interface owing thermal gradient.
The process of diffusion can be described by

\[ D_1 = D_0 e^{-Q/RT_1} \]
\[ D_2 = D = D_0 e^{-Q/RT} \]

**Equation 20**

Where \( D_0 \) is a constant, \( R \) is the universal gas constant and \( Q \) is the required activation energy for diffusion. Aluminium’s activation energy for diffusion is \( Q = 40 \text{ Kcal/mole} \) and diffusion at a temperatures \( T_1 \) and \( T_2 \) (\( T_2 = T_1 + \Delta T \)) is,

\[ D_0 e^{-Q/RT_2} D_2/D_1 = e^{Q/R} \left( (1/T_1 - 1/T_2) \right) \]

**Equation 21**

Due to current constriction, development of \( \alpha \)-spots may occur at higher temperatures with diffusion rate than in the bulk. Required temperature rise \( \Delta T \), to double diffusion rate \( D_2/D_1 = 2 \) at \( T_1 = 60^\circ\text{C} \) gives \( \Delta T = 4^\circ\text{C} \). If the \( \alpha \)-spots is assumed to form at \( T_2 = 300^\circ\text{C} \) and the bulk at \( T_1 = 60^\circ\text{C} \) will result into diffusion rate of \( \alpha \)-spot is \( 10^{12} \) faster than in the bulk, this means that formation of intermetallics is likely to occur under these conditions. The characteristics and composition of common intermetallic phases formed in aluminium to copper joints are shown in Table 9.
### Table 9. Characteristics and composition of intermetallic phases formed in aluminium-to-copper joint

<table>
<thead>
<tr>
<th>Phase</th>
<th>Symbol</th>
<th>Composition</th>
<th>Cu (wt %)</th>
<th>Al (wt %)</th>
<th>Hardness $x10^2$ (N/mm$^2$)</th>
<th>Resistivity (µΩ cm)</th>
<th>$D_0^2$ (cm/s)</th>
<th>Q (Kcal/mole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>$\Gamma_2$</td>
<td>Cu$_2$Al</td>
<td>80</td>
<td>20</td>
<td>3.0</td>
<td>14.2</td>
<td>3.2X$10^{-2}$</td>
<td>31.6</td>
</tr>
<tr>
<td>Phase 2</td>
<td>$\delta$</td>
<td>Cu$_3$Al$_2$</td>
<td>78</td>
<td>22</td>
<td>18.0</td>
<td>13.4</td>
<td>2.6X$10^{-1}$</td>
<td>33.5</td>
</tr>
<tr>
<td>Phase 3</td>
<td>$\xi_2$</td>
<td>Cu$_4$Al$_3$</td>
<td>75</td>
<td>25</td>
<td>62.4</td>
<td>12.2</td>
<td>2.7X$10^6$</td>
<td>61.2</td>
</tr>
<tr>
<td>Phase 4</td>
<td>$\eta_2$</td>
<td>CuAl</td>
<td>70</td>
<td>30</td>
<td>64.8</td>
<td>11.4</td>
<td>1.7X$10^6$</td>
<td>19.6</td>
</tr>
<tr>
<td>Phase 5</td>
<td>$\theta$</td>
<td>CuAl$_2$</td>
<td>55</td>
<td>45</td>
<td>41.3</td>
<td>8</td>
<td>9.1X$10^{-3}$</td>
<td>29.3</td>
</tr>
</tbody>
</table>

### 3.11 Degradation of connectors

The electrical connections should have a sustainable operating condition over a long period of time. Their life span, age and life cycle management are affected by operating conditions, design criteria, manufacturing process, safety consideration and maintenance procedure. The fluctuations in humidity and temperature, the reactive gaseous composition, seasonal changes and the different environment within the vehicles are all together parameters affecting the degradation mechanism. Their remaining life can be calculated by measuring the total damage and analysing their history. The connectors expected remaining life, is the time period after which probability of failure is unacceptably high.

The “bathtub” curve, shown in Figure 25 is a reliability curve by which a components life expectancy and usefulness can be expressed. As shown in Figure 9 the failure rate during the first operation time (Break-in period) is high, this is usually because of installation or manufacturing problems. The probability of failure is then constant during “normal life” until it sharply increases during the wear out time. The original design life may not match the sum of expected remaining life and operating life time hence an expected remaining life which is a probability distribution will still be more precise. When a component of an electrical system approaches to its end of operating life span, failure of the component is likely to occur. The design and manufacture of an electrical component determines its lifetime which affected by service conditions. The useful life of a component is shortened at a high rate if the operating condition of a component becomes more serve [14].
Additionally, one of the most dangerous degradation mechanisms is oxidation of metal to metal contacts within the contact interface occurring in mechanical connectors. A chemical process where the oxygen content of the base metal increases and results into losing its electrons is oxidation process that is considered as the most dangerous degradation mechanism in mechanical connectors [14].

Degradation mechanism is a less likely mechanism in the case of aluminium contacts since growth of oxides is self-limiting. For aluminium it reaches 10 nm thickness which is much less than the contact spots diameter, after a short period of time. When the bare aluminium surface is exposed to air or moisture, the oxide forms as a duplex film that consist porous bulk layer on top. A maximum thickness of the barrier layer is reached within microseconds since it is temperature dependent while the bulk film is dependent on both temperature and relative humidity is developed more slowly. Oxidation kinetics of the most comment contact materials is described in Table 10 [14].

Table 10. Oxidation kinetic of common electrical contact material.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Ambient</th>
<th>Product</th>
<th>Characteristic Features</th>
<th>At</th>
<th>Thickness (Nm) $\times 10^3$ hr</th>
<th>Thickness (Nm) $\times 10^5$ hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Air</td>
<td>Cu$_2$O</td>
<td>Temperature dependent, Oxide forms immediately, Initially slow growth rate</td>
<td>100 °C</td>
<td>15.0</td>
<td>130.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20 °C</td>
<td>2.2</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20 °C</td>
<td>4.2</td>
<td>6.1</td>
</tr>
<tr>
<td>Al</td>
<td>Air</td>
<td>Al$_2$O$_3$</td>
<td>Humidity and temperature dependent, Oxide forms immediately (2 nm in s)</td>
<td>Self-limiting growth</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sn</td>
<td>Air</td>
<td>SnO</td>
<td>Self-limiting, Weak temperature dependency</td>
<td>20 °C</td>
<td>1.6</td>
<td>15.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100 °C</td>
<td>25.0</td>
<td>36.0</td>
</tr>
<tr>
<td>Ni</td>
<td>Air</td>
<td>NiO</td>
<td>Weak temperature dependency</td>
<td>100 °C</td>
<td>3.4</td>
<td>34.0</td>
</tr>
</tbody>
</table>
The formed oxide on aluminium’s surface provides a corrosion protection up to melting point of aluminium. Aluminium oxide have a resistivity of $10^{24} \mu \Omega \text{ cm}$, it is adamant, hard brittle and transparent which means that even the clean appearance of aluminium conductors does not assure low contact resistance without a suitable surface prep. The oxide film can either be broken mechanically or electrically, thick oxide film is broken by fritting at high voltages. In the case of aluminium, particularly if both contact members are aluminium based, rupture of the oxide film is essential for enabling current flow. While in the case of copper, a continuous oxidation of metal to metal contacts occurs when it is exposed to oxygen, this results into increase of contact resistance. The copper oxide grow and flake of the base metal and from 40 °C to 200 °C in air the, a continuous thickness growth of Cu$_2$O that is temperature dependent grows and above 200 other copper oxides that consume the metal forms. Copper oxide is softer then aluminium oxide which easier gets disrupted by applied contact force [14].

It is known that making electrical contact through Al$_2$O$_3$ is more difficult than forming a metal to metal contact through Cu$_2$O$_3$, because of the aluminium oxide’s hardness. According to Tylecote [61], cold welded aluminium require lower deformation for initiating welding in aluminium compared to cold welded copper and that for cold-forged metals a lower deformation is needed for initiating welding. It is generally known that annealed metals have higher ductility and larger α-spots can be formed since plastic flow through fractures in oxides occurs easier. Deformation is more concentrated in under plane-strain conditions which leads to larger cracks in the oxide if aluminium I scold-worked.

A study done by Braunovic [62], showed that thermal cycling in aluminium containing 0.5 at % magnesium cause segregation of impurities to free surface and have a considerable effect on contact resistance, resistivity and hardness. He suggested that vacancies that are formed near metal-oxide interface, diffuses into the metal and start a solute flow, moving from the metal to the surface which results into higher magnesium content in the oxide. It is known that this flow of solute lowers the contact resistance but there are other unknown, complex reactions such as clustering of vacancies, polygonization and dislocations that could occur at the same time and affect the electrical and mechanical properties [62].

The quality of distributed power is a function of equipment’s characteristics, supply system and end user system. The equipment should be designed so it can withstand variation in power quality variations. An crucial prerequisite for maintain a reliable power connector with structural integrity all through their service life is to control their aged-related degradation which can be accomplished by a systematic management process of age-related degradation consisting of:

- Understanding of failure mode
- Inspection, monitoring and assessment
- Minimizing degradation
- Replacement, maintenance and repair
- Utility development of maintenance program

3.11.1 Economical consequences of contact degradation

Properties of connector material may deteriorate due to influence of deterioration mechanism or aging in-service which reduce the margin of operating safety or useful lifespan. Using an old
connections beyond their originally expected life enable economic benefits. An evaluation of the connectors remaining useful lifetime has to be done in order to guarantee that the structural integrity and safety are held even during the extended operating time. A continuous and valid monitoring of a reliable extended life of the critical equipment is required. If an error and its evolution is discovered and monitored then the defects severity can be measured where decisions on what action should be taken, can be considered [63]. Early detection of faults, evaluating and monitoring a fast developing defect and its progress provide necessary information which can be used for reacting on time and reducing the overall damages. Power components are susceptible to different deterioration modes and ageing, the cause, potential impacts and their cost are shown in Table 11 [14].

### Table 11. Power components susceptible to ageing [14].

<table>
<thead>
<tr>
<th>Application</th>
<th>Cause</th>
<th>Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductors</td>
<td>Broken conductor strand</td>
<td>Conductor strands broken- overheated-overhead line could come down</td>
</tr>
<tr>
<td>Circuit breakers</td>
<td>Overheating, overloading</td>
<td></td>
</tr>
<tr>
<td>Splices</td>
<td>Loose/ corroded/ improper connection and splices</td>
<td>Replacement safety consideration and expensive repair</td>
</tr>
<tr>
<td>Power distribution</td>
<td>Poor breaker connections</td>
<td>Overheating, burning, fire, arcing</td>
</tr>
<tr>
<td>Disconnect switches</td>
<td>Loose/ corroded/ improper connection and splices</td>
<td>Replacement safety consideration and expensive repair</td>
</tr>
<tr>
<td>Miscellaneous power components</td>
<td>Loose/ corroded connections, poor contacts</td>
<td>Overheating, burning, fire, arcing, 25 % of all power equipment failures are caused by loose electrical connections</td>
</tr>
<tr>
<td>Switches breakers</td>
<td>Overheating, overloading</td>
<td>Expensive replacement and cost of repair</td>
</tr>
</tbody>
</table>

3.11.2 Prognostic models for contact remaining life

Estimation of a components, for instance a connectors life time can be done by prognostic model where data collection of the components performance from initiation to the final stage is an important prerequisites. Development of those prognostic models requires derivation and validation since a statistically valid model provide subjective predictions. Models that are based on genes, related to the component performance are likely to be correspondingly predictive in other context as well while simple models are likely to be integrated into predictive practices and utility maintenance with nominal disruption.
In the case of remaining life a connection, the contact interface is assumed to be homogenous with circular shaped \( \alpha \)-spots, as shown in Figure 26 [64]. Additionally it is assumed that oxygen intrusion and growth of oxide film is the main factor affecting conductivity of the surfaces. A calculation of the contact life time as a function of time and variation of contact resistance is shown in Figure 26.

*Figure 26. Circular shaped contact spot [14].*
4 Study of electrical connection, connectors and termination techniques

This chapter is state of the art of different electrical connection methods, connectors and termination techniques. The principles and most essential aspects affecting the electrical contacts are discussed in this chapter. The current connectors, terminals and termination techniques that are used today are discussed in 4.2-4.3 while termination techniques for aluminium conductors are discussed in chapter 4.5. This is a literature study based on information from patents, books, reports, articles and presentations at companies working with electrical conductors and connectors.

4.1 Electrical connections made of aluminium

The electrical connection of an aluminium cable can either, as mentioned earlier be by conventional terminals with different copper made lugs but, in order to reduce the chemical potentials and corrosion potentials between copper and aluminium, a fully aluminium based connector for electrical connection of aluminium cable can be used. Implementation of new electrical connection requires that one take into account that different environment may affect in different way if another material or method is used. A study done for high voltage connectors made of aluminium based their requirement on electrical hybrid vehicles EHV, where the ambient temperature in the engine can be up to 140 °C while the temperature limit for insulating polymers used is about 180 °C. Due to this, the maximum allowed temperature increase in the connector is about 40 °C which means that testing of artificial ageing and effect of creep should be considered at this temperature. There are other requirements such as electrical safety, electromagnetic compatibility, assembling and manufacturing that have to be considered when implementing new electrical connection method [7].

4.1.1 Aluminium wiring connection

Due to coppers high conductivity, high corrosion resistance and good strength, it has been used for most wiring in vehicles. Additionally the electrical connection of copper is relatively easy, with mechanical means, welding, brazing, soldering and crimping. The need of reducing vehicle weight and coppers violate prices makes aluminium as an attractive alternative to copper even though aluminium faces challenges related to aluminium’s properties such as conductivity, strength properties of electrical contact and low resistance to corrosion. As mentioned earlier aluminium wires conductivity is about one-half of copper which means that a larger diameter of aluminium for the same current carrying capacity as copper will be required. Further aluminium’s density is about one-third of copper which means that even if larger diameter is used, the mass will still be less than copper. Increasing the diameter of the conductor require a bigger connector housing and packing of those in an already limited space, in modern vehicle is difficult. Another factor that has to be considered when replacing copper cables by aluminium cables is corrosion resistance since aluminium is prone to galvanic corrosion when it is connected to dissimilar metals in presence of electrolyte. A crimped connection between aluminium conductor and copper alloy terminal before and after corrosion is shown in Figure 27, part of the cable strand have corroded away after a severe corrosion. Sealing of the copper terminal from electrolytes can be used as a protection method for this type of corrosion [28].
4.2 Types of connectors

The purpose of an electrical connection is to permit passage of electrical current across the contact interface which requires a good metal to metal contact in order to achieve an uninterrupted electrical current passage. Although the function of a connector is to complete the circuit by providing electrical interconnection, complex processes such as degradation of the contacting interface which is due to changes in temperature, load and contact resistance occurs in the contact zone and effect the contact behaviour. Different factors such as physical and electrical properties of connector material, contact area, mechanical properties, oxidation tendency of the contact material and contact pressure affect the contact resistance. In addition to that, the type of connector or connection system is determined by non-electrical factors, for instance the size, shape, mating and unmating force, mounting and frequency have to be considered. Environmental factors such as temperature cycles, humidity, contaminants, vibration and shock require a complicated selection process. In order to have a reliable performance of a connector during its service life and meet the electrical and mechanical requirements and sustain a specific operating condition different type of connector devices have been developed. In general it is accepted that a good mechanical joint also is a good electrical joint but there are other operating conditions, deterioration mechanism and design features of a particular connector have an impact on connection performance [65].

Depending on complexity of the electrical system, different type of connectors such as device connectors, junction splices, in-lines, headers and separable contacts with male and female terminals used. The “architecture of the wiring harness, determine the number and location where the circuits will be connected. Design and application of a connection needs consideration of where the devices is going to be connected in which determine the voltage and current level; and the functional, mechanical, electrical and environmental requirements which determine the connection system used. For instance if the connection is directly to the motor then a sufficient retention force is required to withstand the vibration, while a ribbon cable require a large-gauge round cable from
a power feed line. Connectors can be classified according to their functional operation and current-carrying capacity into three groups: light, medium and heavy duty connectors [65].

**Light duty connectors** are devices operating at voltages up to 250 V and carrying at flows below 5 A. A stable and low contact resistance and right connector material is essential for a successful operation of the connectors.

**Medium duty connectors** operates at voltages up to 1000 V and carries currents above 5 A, the electric wear is prime importance.

**Heavy duty connectors** operate at voltages up to hundreds of kV and carry currents up to tens of kA.

### 4.2.1 Plug-and-socket connectors

This type of connector compromise contact base and contact finish material intended for quick engagement and disengagement of electronic units which have to maintain satisfactory operation over period of time. The selection of connector material is based on requirement to sustain mechanical flexibility, rigidity, electrical, contact force deflection and contact design. The most common connectors that are frequently used in automotive applications are, rack and panel, terminal-terminal and plug and receptacle.

When one part of the connector is fixed or stationary and the other part of the connector is removable, *rack and panel* connectors for mounting of equipment used. The connector is mated since the removable part is installed on the “rack” and in order to ensure alignment of contact terminal, a floating connector is mounted which in turn prevent damages due to position variations during insertion. An example of rack and panel connector is shown in Figure 28 [66].

![Figure 28. An example of rack and panel connector [66].](image)

The simple *terminal-terminal* connector requires manual connection and no insulation is present to protect the terminal and is used within an enclosure for instance appliance’s housing. Low contact resistance even with the non-noble coatings is provided by a sufficient contact force and the adequate mechanical force prevent the contacts from parting. A simple blade-box connector is shown in Figure 29 [14].
The most widely used type of connector is **plug and receptacle**, it requires manual installation which is used in vehicles where complex circuits and harnesses require flexibility in order to support the large number of functions and electrical features. Since this type of connector is manually installed mating can be difficult, due to this some type of mechanical assistance e.g. bolt-screw is incorporated. Figure 30 is an example of plug and receptacle connector [66].

**4.2.2 Common features of connectors**

The design of the connectors varies depending on type of application it will be used for but the necessary parts of a connector are: cable or wire termination, contact terminal, enclosure and line insulation.

*Cable termination:* An inseparable connection between the terminal and the cable conductor is provided by termination where a mechanical or metallic joint (welded, soldered or crimped) provide a permanent mechanical and electrical connection which is the link between the cable and the terminal.

*Contact terminal:* It is the conducting members which consist of female and male terminals where the mated current passes. The terminal is attached to the contact interface on the one end and the cable on the other.
Enclosure: Connector parts are assembled into a housing where mating is done by joining connector enclosure together to and. The enclosure protects the internal parts and provide mechanical guide for mating.

Line insulation: It is a part of plastic enclosure which serves to ensure the alignment and location of the terminal. This kind of insulation is essential as electrical insulation, multiple lined connectors and isolation between adjacent lines.

4.2.3 Electrical Terminals
Electrical contacting points are provided by the electrical terminals where a stable and low electrical resistance during the connector’s service life at different operating conditions are required. Contact force, contact material and wire terminations are the most important parameters. Depending on what application it is going to be used in, different combination of terminal configuration such as form of termination, alloying material, type of crimp, coating, cladding and spring members varies. Additionally the selected material and terminal design have to consider the connector assembly and overall fabrication process. The most common terminal types are summarized in Table 12 [28].

<table>
<thead>
<tr>
<th>Type</th>
<th>Contact form</th>
<th>Base material</th>
<th>Coating</th>
<th>Typical current (A)</th>
<th>Termination</th>
<th>Common usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Press-fit</td>
<td>Pin-hole</td>
<td>Cu-alloy</td>
<td>Sn, Solder</td>
<td>≤5</td>
<td>Crim or solder</td>
<td>Commercial automotive</td>
</tr>
<tr>
<td>Bump-flat</td>
<td>Butt</td>
<td>Cu, Cu-alloy</td>
<td>Sn, Pd, Ag, Au</td>
<td>≤2</td>
<td>None or solder</td>
<td>Commercial automotive</td>
</tr>
<tr>
<td>Pin-hyperboloid</td>
<td>Wire-pin</td>
<td>Cu, Cu-alloy</td>
<td>Sn, Ag, Au</td>
<td>≤2</td>
<td>Crim, IDC or solder</td>
<td>Commercial</td>
</tr>
<tr>
<td>Pin-sleeve</td>
<td>Multiple beam</td>
<td>Cu-alloy</td>
<td>Sn, Ag, Au</td>
<td>≤10</td>
<td>Crim, IDC or solder</td>
<td>Commercial, appliance, automotive</td>
</tr>
<tr>
<td>Blade-leaf</td>
<td>Beam</td>
<td>Cu-alloy</td>
<td>An, Ag, Au, Ni</td>
<td>≤30</td>
<td>Crimp or solder</td>
<td>Automotive appliance, commercial</td>
</tr>
<tr>
<td>Blade-box</td>
<td>Row</td>
<td>Cu-alloy</td>
<td>None, Sn, Ni</td>
<td>≤40</td>
<td>Crimp or solder</td>
<td>Appliance, automotive</td>
</tr>
<tr>
<td>Tuning fork</td>
<td>wire-blade</td>
<td>Cu, Cu-alloy</td>
<td>None</td>
<td>≤20</td>
<td>None or crimp</td>
<td>Commercial automotive</td>
</tr>
<tr>
<td>IDC</td>
<td>Wire-blade</td>
<td>Cu, Cu-alloy</td>
<td>None</td>
<td>≤20</td>
<td>None or crimp</td>
<td>Commercial automotive</td>
</tr>
<tr>
<td>Plug-screw or Wire-screw</td>
<td>Flat-flat or wire-flat</td>
<td>CU, Al</td>
<td>None, Sn</td>
<td>≤100</td>
<td>None or crimp</td>
<td>Household wiring/appliance</td>
</tr>
<tr>
<td>Wire-wire twist</td>
<td>Multiple wire-wire</td>
<td>Cu, Al</td>
<td>None</td>
<td>≤20</td>
<td>None</td>
<td>Household wiring</td>
</tr>
</tbody>
</table>
Pin-sleeve terminals have reduced size where the contacts are smaller with low contact force and high circuit density. These types of terminal are used for appliance, automotive and commercial electronics. Metal coating of terminal might be required since those terminals control circuits and deal with all or some electronic signals. A female and male pin-sleeve terminal is shown in Figure 31.

![Figure 31. Female and male pin-sleeve terminals](image)

Blade-leaf terminals, shown in Figure 32 evolve from blade-box type and are used in automotive where high circuit density and low insertion force is required. Smaller blades cannot be accommodated in the “box” if the connection density increases but various leaf designs are possible. There are challenges regarding connector component used in vehicles since they are exposed to fluids from lubricating oils, mechanical vibrations, high pressure washer jets and extreme temperatures

![Figure 32. Blade-leaf terminal](image)

The blade-box terminals have a robust construction and have ability to carry a wide range of current. These types of terminals are usually used for commercial electrical circuits and appliances and can be applied for high current range due to its large contact area. Large contact areas in combination with high contact force these terminals are resistant to high vibration and if a suitable coating is selected, the contact is gas-tight, hence resistant to gas corrosion.

Insulation displacement connection terminals (IDC) are used for connecting an insulated wire to a device in a single operation which eases the installation but the design of the terminal is sensitive to gauge. A suitable strain relief should be a part of the terminal design in order to avoid disconnection and maintain wire-slot orientation. Since the wire-blade contact is usually small, the current an IDC can carry is limited and therefore not suitable for high current connectors but.

Tuning fork type is similar to IDC terminals and due to its groove design, it can be used in a wider range of contact force.

The plug-screw and wire screw are designed for manual mating of circuits. It is for connecting an equipment or device to a wire where the wire is crimped to a lug. The current carrying capacity of
this type of terminals are high due to high contact force that might be applied but changes in vibration, thermal contraction or expansion and relaxation under stress lead to drop of contact force to significantly lower levels.

The wire-wire twist terminals are used for joining the electrical wiring in household. The low contact resistance is provided by copper-copper contacts. High number of contacting point ensure a durable and reliable connection and the formed oxides are fritted through a voltage supply. Even though it is difficult to establish good electrical contact for aluminium based wires, owing the formed oxides on the surface, it is still acceptable for similar applications.

4.3 High power connectors
An average vehicle with internal combustion engine and a 12-volt electrical system have a peak for high-power electrical circuit under 2 kW. The charging circuit carries about 100 A during some conditions while the starter connection hundreds of amperes during few seconds at a time and simple bolted ring terminals are usually used for connection of those. Electric and hybrid vehicles have to operate at hundreds of volts during some conditions where some of the circuits carry hundreds of amperes during extended period. Hence the connections have to retain a stable and resistance over time with additional requirements. In order to protect the nearby electronic components from being influenced by the high power circuits, an electromagnetic shielding of the connection is required. Additionally an environmentally sealing of the connector which prevent dielectric breakdown between circuits where a high isolation resistance between the neighbouring circuits is essential. Electric motors, DC/AC inverters, DC/DC converters, and battery packs all require reliable connections that can perform in demanding environments within the vehicle. A typical high power connector used in vehicles is shown in Figure 33. Special features such as HVIL (high voltage interlock circuit), electromagnetic shielding and isolated terminal cavities are highlighted. The purpose of HVIL is to protect from hot disengagement of contact and avoid damage of contact terminal and the operator [28].

4.3.1 Improvement of electrical connection
In order to narrow the contributing factors affecting the crimping connection of aluminium wires and enhance the electrical connection, cause and effect diagram shown in Figure 34, with respect to serration can be used. An asperity on the terminal wire barrel that is usually formed by three grooves and contributes to stability of the mechanical and electrical connection is called serration.
The surface oxide film is usually broken at serrations which prevent the wire coming off after crimping since it is caught in the serration after crimping [36].

Serration contribute to stabilization of electrical connection which enhance crimping properties of the terminal. Deformation of the wire at the serration occurs during crimping which leads to breakage of the surface oxide film. Applying more load to this section result into formation of the surface, tin adheres to aluminium and bond the wire and the terminal which establish the electrical connection. Due to this, increasing the volume of serration will result into increased bonding section of the wire and terminal which improve the electrical connection.

The retention force of the wire is another affecting factor that have to be taken into account and improved in order to enable aluminium wire connection by crimping method which can be done by crimping at a higher compression. If the serration can be modified so the finest aspiraties is spread over a broad range and if a sufficient serration edges is secured, both the wire retention force and the electrical connection can be improved with a reliability equivalent to the copper wires used in vehicles [36].

4.3.1.1 Anti-corrosion of the crimped section
Deep corrosion can be caused by slight amount of electrolysis solution which means that the best way to protect the crimped section from corrosion is to protect it from coming in contact with electrolysis solution which means preventing moisture from entering crimped sections. As shown in Figure 35, moisture may enter through either from path 1, 2 or 3, therefore it is important to protect the end part of the terminal to avoid any clearance except the exposed section of the conductor.
With respect to reasons mentioned above, R&D laboratories at Sumitomo Electric group company [36] have developed a mould structure as anti-corrosion technique shown in Figure 36, that covers the whole crimped section with optimized resin material regarding heat resistance, adhesion to the terminal and assuming actual use in vehicles.

4.3.1.2 Corrosion protection

In order to protect the crimped area from corrosion different type of protection can be used depending on where the cable is going to be installed. A vehicle can be divided into three different zones depending on degree of required corrosion protection. Figure 37 shows the location of each zone were zone 1 include for instance the instrument panel and without any need for corrosion protection since the zone is considered as “high and dry” while zone 2 and 3 are interior and exterior compartments which demands corrosion protection. Selective metal coating, SMC is a treatment method for the terminals which accidentally can be exposed to corrosion atmospheres while applications located in wet areas are protected by connector housing with a single seal design [5].
4.3.1.3 Selective metal coating (SMC)

Galvanic corrosion protection of an aluminium cable connection to a copper terminal can be done by selective metal coating SMC, where a layer of electroplated brass (CuZn) with an overlying layer of tin is coated at the punched edge of the terminal at the core crimp which mainly is formed of copper based lead material and is located next to the aluminium wire as well as on hot dip tin that is copper based material. Figure 38 below shows an example of SMC protection layer [7].

The SMC protection is then tested by sodium chloride solution that is used as an electrolyte where chloride is the element promoting the corrosion. Dissociation of sodium chloride into a conductive Na\(^+\) and Cl\(^-\) ions solution which is a requirement for galvanic corrosion occurs. When aluminium dissolves formation of hydrogen gas H\(_2\) which increase pH level in sodium chloride solution and accelerate dissolution of aluminium. Chloride which is the reactive element reacts firstly with aluminium and zinc and then with more noble metals i.e. copper and tin, and then dissolves these metals. Inspection of reflection electron microscope (REM) pictures from the end of the corrosion
test shown in Figure 39, shows that chloride diffuses into the CuZn intermediate layer, react with zinc and dissolves it slowly. Chloride will also diffuse homogeneously into the outer Sn layer, but not beyond that [5].

![Figure 39. REM picture of Selective metal coating protection layer after the corrosion test.](image)

The connection between the terminal and aluminium cable have an electrochemical potential, $\Delta E$ (mV) that initiate the galvanic corrosion and is the electromotive force (EMF) of the corrosion. According to a study done at Delphi Deutschland [5], the $\Delta E$ between aluminium and copper is measured to 435 mV where the SMC protection layer have a potential to reduce $\Delta E$ by 306 mV and in order to prevent galvanic corrosion, a direct contact between the aluminium, copper and chloride should be avoided by for instance SMC coating and avoiding the conductive contact between aluminium and copper [5].

4.3.1.4 Tin layer

According to previous study where a corrosion test were performed test at Delphi Deutschland [5] the galvanic corrosion slows down if the terminals e.g. at the copper punched edges are re-tinned, since copper and ten tends to form intermetallic phases such as, Cu$_6$Sn$_5$ and Cu$_3$Sn which can diffuse into the outer layer of tin. The copper base material can be protected by the intermetallic CuSn phase, due to the electronegativity differences between copper and CuSn, penetration of chloride from the outside into tin can be prevented [5].

4.3.1.5 Additional corrosion protection

Only pre-tined as corrosion protection is not enough for preventing contact corrosion, a layer of brass (CuZn) on the copper, as an additional corrosion protection can be used. Earlier study done at Delphi Deutschland shows that if a 5 µm thick layer of tin is deposited on copper and on brass as shown in Figure 40 and stored in 25 days at a storage temperature of 170 °C, the layer on the copper interlayer will dissolve due to tin’s diffusion behaviour with brass and copper. The diffusion of copper from brass into tin is slower than pure copper into tin, since the endeavour of the copper
from the brass to alloy with tin is significantly lower than concentrated copper to tin. The CuZn interlayer slows the diffusion of copper in the overlaying tin and there is no formation of intermetallic phase of zinc and ten. It takes about 60 days to dissolve the copper layer, as shown in Figure 40 below [5].

4.3.2 Electrical connections made of aluminium
The electrical connection of an aluminium cable can either, as mentioned earlier be by conventional terminals with different copper made lugs but, in order to reduce the chemical potentials and corrosion potentials between copper and aluminium, a fully aluminium based connector for electrical connection of aluminium cable can be used. Implementation of new electrical connection requires that one take into account that different environment may affect in different way if another material or method is used. A study done for high voltage connectors made of aluminium based their requirement on electrical hybrid vehicles EHV, where the ambient temperature in the engine can be up to 140 °C while the temperature limit for insulating polymers used is about 180 °C. Due to this, the maximum allowed temperature increase in the connector is about 40 °C which means that testing of artificial ageing and effect of creep should be considered at this temperature. There are other requirements such as electrical safety, electromagnetic compatibility, assembling and manufacturing that have to be considered when implementing new electrical connection method [7].

4.4 Other parameter of electrical contacts
Even thought contact resistance and terminal design are the most important parameters affecting the contact performance there are other parameters such as pressure, bulk resistance, force, wipe, coating and plating that are important as well. The frictional force that holds the mated terminal together is provided by the contact force. Contact force together with wipe remove non-conducting particles and film of the surface and provide a cleaner surface at mating which is necessary for low initial contact resistance. The amount of required wipe force depends on contact material, type of
surface film and contact geometry. For example the surface film of bare copper is thick and hard to remove, hence the required for removal will be several Newton with a wipe distance of several millimetres while tin-coated contact with soft tin and hard tin oxide require a wipe force less than 1 N with wipe distance of tenths of a millimetres [67]. The contact force is usually distributed over the available asperity points but if the asperities are concentrated in small area the contact pressure increases significantly, hence one have to consider the pressure in contact material when designing small contacts so the deformation in the contact does not affect the performance of the contact.

A terminals bulk resistance is particularly important for high current ratings. The bulk resistance is in the range of few micro ohms to tens of micro ohm in relation to the contact resistance which have to be 10-100 times larger. When the wiring harness is attached to a device that generates heat, for instance a light source or a motor, the terminal and the wire forms a major heat sink at the attached part of the circuit. The terminal should not be a heat source and cause heat flow into the wiring. Imbalance of heat flow may rise the contact temperature considerable in some circuits which result into degradation owing stress relaxation of the contact and shortened life or failure of the contact as result [28].

4.4.1 Connections in high-vibration environments
Multiple of sensors such as knock sensors, positioning sensors and temperature sensors are directly mounted on the engines and supply the needed information for an optimum performance of the engine. Connections to the sensors have to tolerate vibrations for the life of the engine where a good performance can be achieved if the influence from the vibrations on the contact interface can be eliminated. Using suitable lubricant and plating of the contacts in high-vibration environments and relief of the strain in wiring harnesses are important factors for reducing vibrations and relative movement at the contact interface.

4.4.1.1 Wire connectors
Devices for connecting cables and wires to electrical equipment, the wire connectors can be crimped or thermos compression bonds, wrapped or screwed joints, soldered or welded. The most used are straight coupling types, clamp-on types, lugs, splices, crimps, compression-screw lugs, binding-head screw terminals and eyelets.

4.4.1.2 Requirements on the aluminium made connectors
A new high voltage aluminium connection method that fulfil the requirements mention above have been developed and patented by German institute of metal forming and casting [7]. The connector’s essential part is the symmetrical wedge with an angle $a$ amplify the external force $F$ and ensure an enough contact force for a minimal contact resistance. The external force is kept constant while an extra distance $d$ is kept in order to compensate the creep effect during the connector’s lifetime. Different welding techniques $\omega$ can be used in order to connect to the cable $c$. Figure 41 below is an schematic illustration of an high voltage aluminium connection [7].
Since aluminium is not an optimum material for elastic spring at higher temperatures, an external steel made spring and housing where the reaction force of the spring is carried out by the housing is used. Due to high voltages which can be above 400 V, a protection against electrical shock hazard is provided by slots in contact area with an extra space for insulating fins. As shown in Figure 42 below, the width of the fins is half of the slots which mean that it can be connected from both parts and all the touchable areas are covered by either insulating material or housing [7].

4.4.1.3 Manufacturing high voltage connectors made of aluminium

The connectors are manufactured by extrusion moulding which is an economically favourable process for high quantities. The extruded bars are made of an AlMgSi alloy that is suited for machining and extrusion moulding with a proof stress of 215 MPa that is high enough for mechanical loads that may appear in the application and an electrical resistivity of 32-36 nΩ/m. Required geometries can be achieved by adjustment of sawing, milling and welding techniques used. The components are deburred by vibratory grinding after the machining and prepared for further coating. The coating is done in order to lower electrical resistivity which is due to the oxide layer on the surface of aluminium and can lead to high contact resistance. Nickel and silver is used as coating materials, 20 µm of nickel is for diffusion barrier to aluminium but since nickel is a hard and brittle material with high contact resistance, a 10µm layer of silver is coated on nickel in order to keep the contact resistance low at higher temperatures as 180 °C. After the coating, the connector can be welded to the conductor by different welding techniques [7].
4.4.1.4 Alloy composition

Pure aluminium with purity of 99.6% have an enough high conductivity of 62% IACS (international annealed copper standards) while the tensile strength is about 70 MPa which is quite low and have to be improved by for instance designing an more suitable alloy for usage in wiring harnesses. The electronics and material R&D laboratories at Sumitomo Electric group company [36] has developed a new aluminium alloy that is suitable for wiring harnesses in vehicles and fulfil the IACS.

The alloy elements where selected by using misfit strain (MS) which is an index that specify the degree of deformation due to atomic rearrangement in the base metal which occurs due to dissolution of an solid element. MS is based on first principle calculations by which materials physical properties can be calculated using the basic law of quantum mechanics and the solubility of a solid element at room temperature. The solid solution state in this case is when Mg or Fe is melted in the base metal Al, in an atomic state. The conductivity decreases while the strength is improved significantly and MS can be used as an index for indicating the strength improvement effects since the larger MS becomes, the bigger strength improvement effects. This means that the alloying element with large MS and small solid solubility will result into improved strength and conductivity which is required for wiring harnesses in vehicles. The research done at R&D laboratories at Sumitomo Electric company examined the solid solubility and MS of different elements and founded that Fe is the most suitable element and at least 1.5 mass % Fe is required for the eligible properties, the variation of tensile strength and conductivity with the amount of Fe is shown in Figure 43 and the relation between MS and solid solubility of different elements are shown in table 13 [36].

![Figure 43. Relation between material property and Fe content [36].](image)
Table 13. The relation between misfit strain and solid solubility of different elements [36].

<table>
<thead>
<tr>
<th>Element</th>
<th>Misfit strain</th>
<th>Solid solubility (mass %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>3.9</td>
<td>0.03</td>
</tr>
<tr>
<td>Mn</td>
<td>3.5</td>
<td>0.62</td>
</tr>
<tr>
<td>Cr</td>
<td>3.2</td>
<td>0.62</td>
</tr>
<tr>
<td>Ni</td>
<td>2.9</td>
<td>0.37</td>
</tr>
<tr>
<td>Sn</td>
<td>2.2</td>
<td>0.00</td>
</tr>
<tr>
<td>W</td>
<td>2.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Mo</td>
<td>2.0</td>
<td>0.06</td>
</tr>
<tr>
<td>Pt</td>
<td>1.8</td>
<td>0.00</td>
</tr>
<tr>
<td>Cu</td>
<td>1.6</td>
<td>2.48</td>
</tr>
<tr>
<td>Ti</td>
<td>1.0</td>
<td>0.70</td>
</tr>
<tr>
<td>Mg</td>
<td>1.0</td>
<td>18.60</td>
</tr>
<tr>
<td>Li</td>
<td>0.7</td>
<td>14.00</td>
</tr>
<tr>
<td>Si</td>
<td>0.6</td>
<td>1.50</td>
</tr>
<tr>
<td>Zn</td>
<td>0.4</td>
<td>67.00</td>
</tr>
<tr>
<td>Au</td>
<td>0.3</td>
<td>0.60</td>
</tr>
<tr>
<td>Ag</td>
<td>0.2</td>
<td>23.50</td>
</tr>
</tbody>
</table>

If the regular continuous billet casting and extrusion method is used for manufacturing, crystallization of coarse Al-Fe compounds occur and lead to brittle and poor in processability. Another continuous casting and rolling system called the Properzi method where the aluminium alloy is cooled after casting and sent to continuously hot rolling without any need of reheating. Precipitation of fine form compounds resulting into exceptional processability is enabled by this method. However, further research showed that processability of the wire decreased if Fe content is more than 1.2 mass %, therefore Fe have to be partly replaced by another alloying element. A comparison of the elements in Table 13 shows that an element with large solid solubility which enhances the strength and small MS since processability is lowered if MS is large, should be suitable as a second additive, for instance Mg. The study showed that an alloying composition of Al-1.05 % Fe-0.15 % Mg would fulfil the required processability and result into a conductivity of 60 % IACS and tensile strength of 120 MPa which is the eligible, predetermined target [36].

Wiring harnesses flexibility is essential for processability and mountability in vehicles, therefore annealed materials are usually used since annealing decrease hardness and increase ductility. Annealing can either be done by batch annealing or continuous annealing. Batch annealing is when the wire reel is placed in a furnace with temperature about 350 °C, held for approximately 4 hours and then slowly cooled while continuous annealing is when the wire from the reel passes through a furnace with temperatures about 500 °C or higher and then rapidly cooled.
Inspection of transition electron microscope (TEM) pictures, shown in Figure 44 have shown that, if the metal is heated up to 500 °C or higher temperature and then rapidly cooled, considerable precipitation of Al-Fe compounds occur in comparison to annealing temperature is around 350 °C and slowly cooled where Al-Fe compound precipitate in fine form. At higher annealing temperatures Fe supersaturates, exceed the solid solubility and lower the conductivity. The effect of different annealing condition on conductivity is shown in Figure 45. Due to this batch annealing is preferable in order to obtain suitable properties for conductors used in vehicles [36].

Figure 44. Transition electron microscope pictures of different annealing treatment [36].

According to the result of the study done at Sumitomo Electric Group Company it is possible to manufacture aluminium wires that can be used for wiring harness in vehicles using methods mentioned above and thereby replace the copper wires with wires made of aluminium alloy if the CSA is larger. The effect of weight reduction by replacing copper wires by aluminium wires are shown in Table 14 [36].

Figure 45. Effect of different annealing condition on conductivity [36].
Table 14. Effect of replacing wires by available aluminium wires [36].

<table>
<thead>
<tr>
<th>Cooper</th>
<th>Aluminium</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Size (mm²)</td>
</tr>
<tr>
<td>Ultra-thin wall</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
</tr>
<tr>
<td>Thin Wall</td>
<td>2</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Size (mm²)</th>
<th>Weight (g/m)</th>
<th>Weight reduction (g/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultra-thin wall</td>
<td>0.75</td>
<td>3.1</td>
<td>2.3 (43%)</td>
</tr>
<tr>
<td></td>
<td>1.25</td>
<td>5.0</td>
<td>2.6 (34%)</td>
</tr>
<tr>
<td>Thin wall</td>
<td>2</td>
<td>9.1</td>
<td>4.0 (31%)</td>
</tr>
<tr>
<td></td>
<td>2.5</td>
<td>11.7</td>
<td>9.5 (45%)</td>
</tr>
</tbody>
</table>

4.5 Termination technique of aluminium cables

A reliable and effective metal-to-metal contact between the terminal and conductor where corrosion or deterioration of the contact is prevented is essential for a good termination. Conventional termination techniques that are used for copper conductors are not suitable for aluminium conductors since aluminium have high tendency for galvanic corrosion and is vulnerable to oxidation when two dissimilar metals are in contact with each other. Due to this, other solution such as welding, soldering or modified conventional crimp where the oxide layer is cracked overtime by arranges morphology of the surface or by additives needs to be adapted. Welding and soldering is probably the preferable solution even though conventional crimping is still being used. Additionally coating with copper, tin and nickel as treatment before crimping is used as corrosion protection of termination joint, such as using sleeve or shrinkable tube for additional corrosion resistance. Yuichi [68] tried to improve the conventional crimping, by means of crimping one portion to the conductor and the other portion to the insulation where the conductor is protected from being exposed to humidity environment. The difficulty of this method is to crimp onto insulation where moisture might still enter through formed gaps.

Later, Sakaguchi [69] invented another solution where sealing was applied in order to protect the crimp and connect the crimping portions and fully integrate both parts. Other methods such as sleeve or shrinkage tube which is similar to application of sealer have been adopted in order to protect the conductor in connection part from being exposed to external environment.

Nölle and lietz [70] invented a copper made terminal with adopted aluminium sleeve where the aluminium conductor can be connected to brass or copper in for instance cable lug or battery terminal applications. The purpose of the sleeve was to enable welding with a suitable fitting which can be regarded as extension of the cable at termination point and increase the connection point.

Hino [71], suggested use of tubular joint terminal where cables can be injected into the tubular joint and then mechanically pressed in order to form a metallic bond.

Takashima and co-workers [72] designed a new connection structure where the uninsulated portion were inserted into the terminal where molten solder was injected in order to pressure bond with the terminal and caulk the conductor. Galvanic corrosion can be prevented by this method. In the case of battery terminals, an electrically conductive adhesive can instead of the molten solder be filled
between the conductor strands and the terminal in order to seal and prevent galvanic corrosion. However, those approaches do not work for dissimilar metals being in contact with each other since galvanic corrosion might still occur then [73] [74]. Applying protective sleeve and conductive adhesives in termination have shown to offer an optimized termination of aluminium conductors. Termination method by applying conductive adhesives is shown in Figure 46 [21].

Further, another approach invented by TE connectivity [75] involves, sealing before crimping and using an additionally intermediate cape that is made of the same material as the terminal in order to shield the exposed aluminium strands. This method is quite complicated, expensive and only suitable for larger cables. Therefore they redesigned the connecting structure and used a crimp terminal which includes an insulation barrel and wire barrel which ensure pressure bonded contact between the conductor strand and the terminal. This method is applicable for cables with small CSA, about 2.5 mm$^2$.

Termination of aluminium conductors is challenged by the formed oxide layer which must be broken, TE connectivity [75] developed a crimp barrel solution for connection of aluminium conductors where the surface have the same properties as F-crimp barrel but it is featured with a “shark fin shaped serration”, shown in Figure 47. The surface oxide layer is broken by the serration, during crimping and electrical contact is further established by cold welding.

The connectors in this case is made of copper and their study showed a crimping connection between an aluminium conductor and copper connector is mechanically stronger than connection between aluminium conductor and aluminium connector. For example, a wire with CSA of 1.5 mm$^2$
has pull-out strength of 80 N and a residual surface crimp pressure of 180N/mm² with no existing condition that could cause creep. In order to prevent corrosion, additional material such as sealing agent is rolled into the front end of the crimp barrel [75].

4.5.1 Terminal with integral oxide breaker
As mentioned before aluminium oxidize when it is exposed to moisture and build an oxide layer on the surface which does not flake off and protect the non-oxidized aluminium from corrosion which is an problem when using aluminium as conductor since the conductivity decreases and the metal to metal contact is deteriorated. Due to this the connection between for instance power strips, lug or terminal and the wire end have to be ensured in order for the interface to be able to efficiently conduct the electricity that the cable is meant to carry. High resistance at the interface leads to inefficient conductance and overheated interface and since the fastening of the wire to the terminal usually is done by a heat process such as soldering or welding which in turn may deteriorate properties in the area where an efficient metal to metal contact is essential for ensured conductivity. The terminal can also be mechanically fastened to the aluminium conductor and to ensure a proper electrical contact the insulation on the wire, in the area in which is going to be mechanically crimped firstly removed or penetrated. Due to aluminium oxidation and corrosion, crimping of aluminium wire compare to copper wires is more complicated and requires that one have to consider how to get good electrical conductivity and resistance of air infiltration and moisture between the aluminium wires. In addition to this the cable have to be smooth and straight in order to avoid stress concentrations, further provide a wire and terminal combination with a coherent and strong geometry [76].

A patented invention shown in Figure 48 with a shape known as a CRN terminal in the industry. It is based on a one piece integral electrical terminal made of aluminium which have a mount portion B and a wire receiving portion A, that is cylindrical shaped but can be made of a variety of shapes and an aluminium stranded wire C, with an insulating sheath D, an abrasion sheath with two holes where the terminal can be fastened. The receiving portion has a sealing portion with an integral seal ring that work as sealing [76].

![Figure 48. Aluminium terminal with integral oxide breaker [76].](image)

The contact portion with an integral oxide breaker with several tapered protrusions that breaks through the oxide layer of the conductor strands and the receiving portion have a seal portion with integral sealing for protection of the insulator on the wire [76].
4.5.2 Favourable electric connection of wire harnesses in automobiles

A Japanese invention relates the excellent electrical connectivity of a crimped contact of a stranded aluminium wire or aluminium cable end structure for electrical connection of wire harnesses such as battery cables in automobiles. An aluminium cable is composed by aluminium stranded wire which is the electrical conductor and a crimped contact is used as the connection part. The crimped section is then equipped with a connection terminal at each end of the cable in order to be able to connect it to different electric instruments. The contact shown in Figure 49, has a U-shaped cross section 1 with a bolt fastening part 4, in the inner crimping section 1, the serration 3, is formed of several concave grooves which prevent the stranded wires from coming out since the stranded wires are fitted into the grooves 2 of the serration 3. A hole 5 in which bolt can be pierced is drilled in the fastening portion 4 [77].

![Figure 49 Crimp contact for an aluminium stranded wire [73].](image)

The stranded wire is inserted into the crimping portion 1, the side walls 6, are pressed from the outside which crimp the wire and the crimping portion to each other.

Good electrical connection is achieved when the oxide film on the stranded wire is broken. In order to improve the electrical contact between the crimped contact and aluminium stranded wire and prevent the aging deterioration in electric connectivity and mechanical connectivity. A crimp contact with a serration in an inner face of a crimping portion, of the crimp contact with a d/e ratio of at least 0.33, in which e represent the diameter of the wire while d represent the depth of a groove forming the serration with 3 or more grooves in order to achieve a stable electric connectivity and low contact resistance. The properties of a copper or copper made alloy crimping portion of the crimping contact, made for aluminium wires is shown in table 15 [77]

<table>
<thead>
<tr>
<th>Table 15. Properties of a copper made crimping contact.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress relaxation</td>
</tr>
<tr>
<td>Electrical conductivity</td>
</tr>
<tr>
<td>Tensile strength</td>
</tr>
<tr>
<td>Vickers Hardness</td>
</tr>
</tbody>
</table>
4.5.3 Plasma soldering of copper connector to an aluminium conductor

A patented method by Gebauer & Griller for connecting a copper or copper alloy made connector to an aluminium made conductor is based on coating the surface of the connector by nickel and then welded to aluminium conductor by way of zinc, therefore a direct contact of aluminium and copper can be avoided. It is known that if aluminium conductors is welded or soldered to a terminal and in particular cable lugs they get adhesively bonded by means of electrically conducting plastic material which connect them to one another in a locking manner by compression or deformation. Due to this it is necessary that the aluminium conductor is not in direct contact to the copper terminal since presence of a liquid act as an electrolyte that effects the connection, as an electrochemical process takes place and break the mechanical and electrical connection. The terminal and conductor can be connected by different methods such as plasma welding and crimping. The present zinc will fuse into the conductor when the terminal and conductor is connected by plasma welding process. If the terminal has a sleeve where the conductor is fitted onto, zinc is applied at the end face of the conductor, the conductor and sleeve can be connected by mechanical deformation of the sleeve or by crimping the sleeve. Due to this, zinc will fuse both to the conductor and terminal element [78].

4.5.4 Compression

An electrical connection method patented by Mecatraction proposes a terminal made of aluminium for electrical connection that include a tubular shaped shank and a recess that partially is filled with contact grease with a stopper which keep the grease in recess. The grease volume is chosen to correspond with the free volume of the recess after cable insertion and crimping. The crimping portion can be deformed radially and the stopper has a transverse membrane that can be torn by the electric cable when it is inserted into recess and have one portion placed in crimping portion and the grease is filled in bottom of membrane and recess. The grease enable breakage of the aluminium film formed on the surface of the recess that is exposed to air and the recess’s opening is then sealed by silicon. The purpose of the stopper is to retain the grease and work as sealing to prevent water penetration, silicon as sealing material [79]. An example of compression as crimping method and how the cross section in the cramped area changes after crimping is shown in Figure 50.

![Figure 50. An example of compressed terminal](image-url)
5 Methodology for testing electrical connectors in Scania trucks and busses

Evaluation of the connector’s performance and behaviour is one of the most essentials for reliability and stability control of electrical contact in order to assess potential risks of failures. The chemical, thermal, mechanical and electrical effect on the electrical connectors have to be tested in order to guarantee high conductance between cable and connector and a good electrical contact which fulfil the requirements of ISO standards. Testing methods for assessment of electrical connector’s behaviour are proposed with respect to ISO 8092:2005 that is an international standardization test method in which testing methods and performance requirements for single and multi-pole connections used with electrical wiring harnesses in vehicles are specified.

The requirements and main assessments principles of electrical connectors used in vehicles is summarized as follows:

- Reliability and life-cycle durability of electrical connectors
- Corrosion resistance and tightness test for sealed interfaces in order to prevent galvanic corrosion.
- Good metal to metal contact between the conductor and connector to ensure continuity of electricity.
- High mechanical tensile strength that meet the demand of handling connectors, plugs and terminals.
- Ensure that the terminals and the conductor is in contact to each other during thermal shock cycles which is due to the thermal expansion which may lead to increased resistance and heat.
- Stress relaxation and creep, relaxation over time may result into higher resistance.

All the testing are performed with respect to internal, general regulation that take into account the requirements for environmental factors affecting electrical and electromechanical devices with additional product description information that is need which all, is in accordance to ISO standards.

5.1.1 Tensile strength of conductor to contact attachment

Mechanical tensile strength of the conductor to contact attachment is done using a test apparatus operated at a constant speed with a range 25-100 mm/min. Each sample is attached to corresponding cable as specified by connector manufacturer and if more than one cable is attached the force applied should be according to Table 16 in which the minimum tensile strength of conductor crimp with non-specified nominal cross sectional area can be determined by interpolation.

The isolation of the cable should be mechanically ineffective so the test is performed on the contacts and the conductor crimp should withstand the minimum tensile strength of conductor crimp specified in Table 16 [81].
Table 16. The minimum tensile strength of conductor crimps [81].

<table>
<thead>
<tr>
<th>Nominal cross section area of cable [mm²]</th>
<th>Minimum tensile strength [N]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.22</td>
<td>30</td>
</tr>
<tr>
<td>0.35</td>
<td>50</td>
</tr>
<tr>
<td>0.5</td>
<td>60</td>
</tr>
<tr>
<td>0.75</td>
<td>90</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>1.5</td>
<td>150</td>
</tr>
<tr>
<td>2</td>
<td>175</td>
</tr>
<tr>
<td>2.5</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>260</td>
</tr>
<tr>
<td>4</td>
<td>310</td>
</tr>
<tr>
<td>5</td>
<td>355</td>
</tr>
<tr>
<td>6</td>
<td>360</td>
</tr>
<tr>
<td>10</td>
<td>380</td>
</tr>
</tbody>
</table>

5.1.2 Tightness demand and corrosion resistance

If the connectors are sealed and used with one part that is attached to a component, the testing condition is then exposing the connector and the component to submersion in water. The requirement is that no intrusion of water is allowed and the leakage current at a 48 V applied voltage should not exceed 50 µA which is measured during the last exposure cycle when the connectors are in water. Current leakage is then measured according to ISO 809 where the samples are immersed into deionized water with 5 % NaCl, 0.1 g/l wetting agent and a temperature of 23 ±3 °C. A colouring agent is included in order to visualize and check the ingress of liquid into the sample after the electrical test [82] [81].

If the connector is permanently attached to a component, both the connector and the component is exposed to corrosion test with respect to the requirements set for the component otherwise corrosion resistance testing of all the connectors is done for 500 hours in 40°C with a humidity of ≥ 93 % but if the component is known to withstand exposure to corrosive environment the testing can be reduced to 240 hours. Salt spray test is applied for sealed connectors in 168 hours and then placed in a temperature chamber at +80°C for 48 hours. The salt spray is a sodium chloride solution with a concentration of 50 g/l and a conductivity of 20 μS/cm is used in order to simulate a corrosive environment. The corrosive behaviour of the connector metal is evaluated and measured by morphological approaches such as SEM/EDS or metal loss. The requirement on the connectors is that no corrosion on the pins is allowed and it should be possible to un-mate the connector after test termination. No water intrusion is allowed in the sealed connectors and an insulation test to be performed after the termination of the corrosion test [81].
5.1.3  Thermal aging and contact resistance
In order to test the voltage withstand and contact resistance an voltage of 1600 V DC is applied at a 
humidity of 45-75 % for 1 minute across the contacts with the requirements that, no dielectric flash- 
over or break down is allowed, different conductive demands depending on usage purpose of the 
connector, for instance contact resistance of ≥ 2 mΩ for low conductive demands while 0.02-0.05 
mΩ is a typical contact resistance value for ring bolted connections in Scania [82].

5.1.4  Vibration and temperature
If the connector is permanently attached to a component, then the connector together with the 
components is exposed to a vibration test. Otherwise the connector is exposed to random vibration 
type at different frequencies and levels depending on if the if the connector is aimed to be used in 
chassis, cab or power train. The temperature range is -25 to + 85°C with a temperature change range 
of 1-5 °C/min and a exposure time of 72-210 hours depending on if the connector is going to be used 
in the cab, chassis or powertrain [82].

5.1.5  Heat evolution at the contact attachment
The conductor to contact attachment’s tensile strength is evaluated by attaching the sample to the 
corresponding cable or the cable specified by the connector manufacturer and then then tested at a 
constant speed within the range 25-100 mm/min. the effect of cable insulation should be 
mechanically rendered and the test should be performed on the contact only. If more than one cable 
is attached to the connector, the applied force should be according to Table 16, by using different 
samples [81][82].

5.2  Experimental procedure
Testing of the tensile strength of conductor to contact attachments has been performed. The tested 
aluminium cables were from TE connectivity [75] as described in section 4.5, it is a modified crimp 
featured with “shark fin shaped serration”. The tests were carried out at Scania laboratory and the 
result is evaluated according section 5.1.1. Tensile strength test were performed on cables with CSA 
of 2.5 mm² and 4 mm². The result showed that the 2.5 mm² cables had 18 % lower tensile strength 
than the minimum tensile strength requirement while the 4 mm² cables had 36% lower tensile 
strength than the minimum requirement. The setup of the test is shown in figure 51 and 52.

![Figure 51. Tensile strength test of aluminium cable with CSA of 2.5 mm²](image1)

![Figure 52. Tensile Strength test of Aluminium cable with CSA of 4 mm².](image2)
6 Discussion

Creep is an irreversible deformation which effect the conductor termination by raising the potentials for overheating. As indicated in Table 6, aluminium’s tendency for creep is higher than copper at normal operating temperature and room temperature. Additionally aluminium’s tendency to cold flow under pressure is high, this leads to loosening of the terminals [14]. Creep coupled with cold flow is a factor challenging termination of aluminium conductors. Due to this aluminium should have its own regulations and standards for torque settings for terminals, connection and terminating methods [17].

Aluminium has larger thermal expansion coefficient than copper [17], this may result into incompatible expansion between the terminal and conductor. Coupling dissimilar metals with increase the thermal expansion leading to loosening of the connection over time and increased contact resistance which in turn leads to arcing and overheating of the surface which challenge the safety and reliability of the connection [17]. Additionally galvanic corrosion which occurs when two dissimilar metals are in contact with each other and in presence of an electrolyte is another issue that affect the contact behaviour, weaken the conductor and lead to contact failure. Using different metals at the termination join hampers handling high temperature, high vibration conditions and thermal shock due to aluminium’s thermal expansion coefficient which along with those conditions deteriorate the connection with a failure as result.

With respect to corrosion issues indicated in Table 6, aluminium conductors have higher tendency for corrosion owing its low zero potential. Connecting aluminium with metals having higher zero potential results into galvanic corrosion. Formation of insulating Al₂O₃ is one of the most damaging factors since it inhibit current flow, cause formation of hot spots in the contact spots.

A force is applied during termination and crimping, this applied force reduces the contact pressure which results into non-gastight contact interface where corrosion and oxidation can occur even if the termination joint is sealed. This result into loosening of the connection and increased contact resistance which generate heat and further creep and cold flow of the conductor. Additionally increased resistance result into fatigue behaviour and high voltage drop [32].

Aluminium is a ductile metal with low melting point which enables customary processing with excellent workability but since it has one third of mechanical strength of copper one have to take that into account dimensioning the conductor in order to achieve the desired mechanical strength for both wire and enough pull out strength of the connection. Additionally, aluminium forms an oxide layer which have an insulating function and protect the material from corrosion but for a good electrical connection the oxide layer have get destroyed during termination [78]. The formed oxide layer can be destroyed methods such as serration [78] during crimping, an additional oxide breaker with tapered protrusions which breaks through the oxide layer [79] or an electrical connection including tubular shaped shank that is filled with contact grease which enable breakage of the oxide film formed at the surface [82].

Coating of the connection material is done for avoiding formation of insulating surface layer, mechanical wear and corrosion decrease the hardness and promote conductivity [3].

Conventional crimping that is used for copper is not suitable for aluminium conductors. Aluminium, according to study done by Otsuka [6], for stabilization the contact resistance, aluminium require a
higher crimping compression than copper in order to improve the wire retention force that enable electrical connection.

The conductive area is essential for a reliable electrical contact which in turn is affected by both internal and external factors, shown in Figure 17 but according to [43] one of the most simple and efficient way of achieving large contact points are by lubrication and mechanical abrasion which together with application of a contact aid (grease) prevent oxidation of the metal.
7 Conclusion

The conventional crimping that is used for copper is not suitable for aluminium conductors. Other solutions such as

- Welding
- Soldering
- Modified conventional crimp

Have to be adapted for enabling a safe and reliable usage of aluminium conductors in vehicles.

Welding and soldering is the preferable solution since they offer a reliable contact that last during a long period of time with less damage and degradation. The most common for aluminium conductors are:

- Friction welding
- Ultrasonic welding
- Resistance welding
- Plasma soldering

Even though welding and soldering is the most preferable solution, modification and enhancement of the conventional crimp by for example applying sealing, shrinkage tube or sleeve for protection of conductor from being exposed to external environment.

Breaking the oxide layer by crimping can also be done by featuring the F-crimp barrel with serration or adding extra elements such as “oxide breaker and sealing ring into the terminal. However, there are many different patented solutions when it comes to enhancing the conventional crimp and make it more suitable for aluminium’s properties where the most preferable depend on application it is going to be used for.

Additionally, coating with copper, tin and nickel as treatment before crimping is used as corrosion protection of termination joint.
7.1 Challenges of electrical connections for aluminium conductors

If Scania wants to replace copper cables by aluminium cables, an awareness of potential problems such as corrosion, creep and relaxation that leads to increased contact resistance and failure is essential. As shown in figure 53, the implementation of aluminium conductors faces 6 main challenges which Scania have to be aware of.

![Figure 53. Six main challenges of implementation of Aluminium conductors in trucks and busses.](image)

It means that that there is no best solution and it is not easy to determine whether welding or crimping is the best solution since aluminium is a demanding material. Depending on the size of the cable, the required and suitable technology varies. When it comes to choosing the “right” supplier for the selected component one have to consider if the supplier is aware of the difficulties with aluminium contacts and how do they solve these challenges to ensure a liable connection that last and meet the Scania standards.
8 Future work

In order to be able to determine the most suitable electrical connection method for different aluminium conductors, Scania will need:

- A closer collaboration with supplier that Scania is working with at the first stage in order to see what kind of solutions they offer.
- Order samples that can be tested at Scania in order to see if they fulfil the requirements of Scania vehicles.
- Cost assessment of each approach.
- Evaluation of the most suitable connection method for each application and if it is usable, even in aftermarket and service.
9 References


[51] M. Braunovic and M. Marjanov, “Thermoelastic Ratcheting Effect in Bolted Aluminum-to-


[80] “Copper tubular terminal for Aluminium wire,” in Confidential information, for internal usage inside PKC only.
