TECHNICAL AND ECONOMIC CONSIDERATIONS OF ALUMINUM CONDUCTORS

Robert Yanniello, PE  
IEEE Senior Member  
Eaton Electrical Inc.  
175 Vista Blvd.  
Avery Creek, NC 28704  
USA

Peter Pollak, PE  
IEEE Senior Member  
The Aluminum Association  
1525 Wilson Blvd, Suite 600  
Arlington, VA 22209  
USA

James Rooks, PE  
IEEE Life Fellow Member  
J & R Consulting, Inc.  
11045 SW Cottonwood Lane  
Tigard, OR 97223  
USA

Abstract – When many electrical equipment designers, specifiers, and users think of current-carrying conductors, copper is the only material that comes to mind. With recent unprecedented increases in the cost of copper, users are faced with these increases being passed on to them from their suppliers. This paper is intended to provide facts about aluminum for consideration as a viable alternative, address some common misconceptions about aluminum, present its more important mechanical and electrical properties, as well as address cost and reliability considerations. This paper does not attempt to show the overall superiority of one material over the other, but merely provide facts about aluminum so individuals can make more informed decisions regarding aluminum as a viable conductor.

Index Terms - aluminum, copper, conductor, oxidation

INTRODUCTION

Aluminum (Al) is the most abundant of all metals found in the earth's crust and is extracted from bauxite. Technical discussions and articles about the use of aluminum vs. copper have been published in the electrical industry for many years. The objective of this document is to provide the reader with information by which they are able to make a more informed decision, given a choice between the two materials in electrical equipment.

Al conductors have been successfully utilized in the electrical industry for over 100 years. Electricity is transmitted from the utility power plant to point-of-use meters almost exclusively using Al conductors. The use of Al wiring has been recognized since the publication of the second edition of the National Electric Code (NEC) [1] in 1901. Shortages of copper (Cu) during the Second World War prompted electrical equipment manufacturers to expand their offerings of Al for current carrying conductors. The successful application of these materials provides significant evidence that both Cu & Al are suitable choices for the conveyance of electric current.

For the purposes of this discussion, two major classes of electrical distribution and control equipment will be addressed:

- Equipment that utilizes bus bar, such as Busway, Switchboards, Switchgear and Motor Control Centers.
- Equipment utilizing wire or strap windings, such as motors or transformers.

The factors that designers must weigh when deciding between the use of these two materials fall into five primary categories:

- Mechanical properties
- Electrical properties
- Reliability considerations
- Economic considerations
- Environmental considerations

Each of these areas will be addressed in this document.

MECHANICAL PROPERTIES

The mechanical properties that should be considered are tensile strength and elongation. Al does have a lower tensile strength than Cu for the same cross section of material – 18ksi for 1350-H16 aluminum vs. 38ksi for annealed copper. As will be discussed later, a greater cross section of Al (50% for 1350 Al and 66% for Al bus conductor alloy 6101) is required to carry the same amount of current for the equivalent ampacity Cu conductor, so the strength of the larger cross section of Al approaches the tensile strength of Cu for a given ampacity.

The reality is that for electrical applications, the most important mechanical areas of concern for electrical conductors are:

- Ability to withstand the forces imposed under short circuit conditions
- The effects of thermal expansion and contraction
- The application environment

The industry standards in the United States that address the design and testing of electrical distribution and control
equipment are published by Underwriters Laboratory (UL), [2], the National Electrical Manufacturers Association (NEMA) [3], and the Institute of Electrical and Electronics Engineers (IEEE) [4]. These standards identify criteria for the performance of short circuit withstand testing, and dictate that worse-case product variations are tested. For this reason, users can be assured that product bracing is adequate for the published withstand capability of the product, regardless of the choice of conductor. This is particularly true for products certified by third parties, such as UL, since they provide a supervisory role to assure ongoing compliance with manufacturers’ certification claims. On this basis, users can be assured that both Cu and Al designs meet the same bracing criteria.

The thermal storage capacity of aluminum is 0.214 cal/gram/°C – for Cu it is 0.092 cal/gram/°C. Since half the weight of Al (1350) is required for the equivalent ampacity of copper, Al has a thermal storage capacity of 16% more than that of the equivalent amount of Cu. This implies that Al wound transformers have greater thermal storage capacity compared to equivalent copper wound units, and therefore they can withstand greater surge and overload currents than equivalent copper wound units.

The coefficient of thermal expansion of pure Al is 23.6 x 10⁻⁶/°C vs. Cu’s of 16.5 x 10⁻⁶/°C. This should lead users to equivalent copper wound units. They can withstand greater surge and overload currents than equivalent copper wound units.

Both copper and aluminum are subjected to oxidation when exposed to the atmosphere. When applied in electrical products such as bus bar, Al conductors are plated at connections with nickel, silver, or tin, thus eliminating oxidation at joints. When utilized as winding materials in transformers and motors, conductors are welded, brazed, or “staked-on” to penetrate through any conductor surface oxidation. Concern over Al surface oxidation away from joint areas is not an issue, since when in contact with the air, a hard transparent aluminum oxide coating quickly forms, which protects the conductor from further corrosion in most environments.

**ELECTRICAL PROPERTIES**

The mechanical strength and electrical resistivity of Al increases with the addition of alloying elements. The ASTM (American Society for Testing and Materials) [5] specifications (B 233, B 324 and B 400) require a minimum of 99.50% Al content for 1350 Al, which has a minimum conductivity of 61% IACS (International Annealed Copper Standard). 1350 Al was formerly known in the industry as EC (Electrical Conductor) grade Al. Al alloy 6101 is commonly used for bus bar and is stronger than 1350. It is important to recognize, however, that 6101 has a conductivity of 55% IACS.

There is a misconception that products with Al conductors run hotter than those with Cu – such is not the case. Regardless of the material, wherever possible, manufacturers optimize material conductor content. Industry standards, such as UL, provide electrical equipment design performance criteria. When it comes to current carrying capacity, two criteria are accepted – current density in amperes per cross section of conductor, or temperature rise above a maximum allowable ambient temperature. For some products, manufacturers are given the option to utilize either of these criteria. For other products, thermal performance is the only criterion. So regardless of the choice of conductor material, temperature rise is required to be equal, and manufacturers optimize the conductor size to meet performance requirements. Products built with aluminum do not operate at higher temperatures than those built with copper.

Pure Al has an electrical conductivity by volume of 62% of that of Cu. Combining these conductivities with the densities of Cu (8.9) and Al (2.7) yields an electrical capability factor of 200%, where one pound of aluminum has the same electrical capability as two pounds of copper. Thus, although the conductivity of Cu is greater than that of Al on the basis of equal volume, aluminum is twice as good a conductor as copper on the basis of equal weight. Where weight is a design consideration, Al is an excellent choice. Where space is a critical limitation, Cu may be required.

Since more Al is required by volume than Cu for a given ampacity, Al conductor cross-section must be increased over that for Cu, which results in a larger Al conductor surface area. If the additional space to accommodate the higher volume of Al is acceptable, the increase in conductor surface area actually produces a benefit. During the conduction of alternating current, a condition known as “skin effect” occurs. This phenomenon is the tendency of alternating current to distribute itself within a conductor so that the current density near the surface of the conductor is greater than that at its core. The greater the cross sectional area of the conductor for a given ampacity, the more efficient the conductor utilization will be.

**RELIABILITY CONSIDERATIONS**

So, what about the residential Al branch wiring problems of the 60s and 70s…?

Solid Al wire sizes #12 and #10 AWG were used for branch-circuit-wiring in hundred of thousands of homes in the late 1960s and early 1970s. In the United States, the Consumer Product Safety Commission (CPSC) [6] reacted to reports of overheating connections by conducting an investigation. Their research concluded that Al branch-circuit wiring connections were hazardous. This has a lot to do with the misperception that Al conductors in general are not as reliable as Cu.

Unbeknown to most is that the Canadian Government conducted similar investigations [7], which concluded that if properly installed, Al branch-circuit-wire connections were not
hazardous. Furthermore, proposals to change the NEC to eliminate aluminum-branch-circuit wiring were rejected by the electrical experts on Code Making Panels and by UL.

One can speculate as to why only the CPSC conclusion was reported at the time. The performance history of Al branch-circuit-wire over the past three decades speaks for itself. The aluminum branch-circuit-wiring in question has been in the hundreds of thousands of homes today continues to perform its intended function. It now appears that the Canadian Board of Inquiry, NEC Code Panel members, and Underwriters Laboratories were correct in their determination more than 30 years ago.

If aluminum is as good, why isn’t it being used as a substitute for copper…? Aluminum has only been available in quantities for commercial electrical usage for the last 60 years. During the 60 years prior to that time, the electrical industry evolved with copper as the standard. This is evident from the standard measure of electrical conductivity for all materials – “% IACS”. The International Annealed Copper Standard (IACS) was adopted by the International Electrotechnical Commission (IEC) [8] in 1913 using the conductivity of annealed copper as the 100% base.

There is also a belief that stranded Al conductors may only be reliably terminated with crimp-type Al compression lugs. This is a misconception. Connector manufacturers have developed a wide variety of mechanical set-screw type lugs that are certified to specifically meet the requirements of UL 486B, [9] Wire Connectors for Use with Aluminum Conductors. Manufacturers frequently provide lugs that are dual labeled as “Al-Cu” or “Cu-Al” to designate their suitability for use with both aluminum and copper types of cable materials. These comply with the requirements of UL 486E, [10] Equipment Wiring Terminals for Use with Aluminum and/or Copper Conductors.

ECONOMIC CONSIDERATIONS

To understand what determines the price of copper and aluminum, several factors must be understood. Namely, the history of these two metals, how they are produced, and basic economics of commodities.

Going back in time about 5000 years, in the region around modern Turkey, people discovered that liquid copper could be extracted from malachite and azurite and that the molten metal could be cast into different shapes. Cu alloys, such as bronze, were developed with uses and production expanding over thousands of years. Cu and its alloys have been produced in significant quantities and used to make everything from swords to cooking utensils.

Compared to Cu, Al is much more difficult to extract from its ore, bauxite. It was only first isolated as an element by Friedrich Wöhler via chemical reduction in 1827. Even though Al is the most plentiful metal in the earth’s crust (8% by weight vs. 0.0001% for Cu), production by chemical reduction only yielded very small quantities of the metal – ounces at the most. Because Al could only be produced in small quantities, it was considered a precious metal – more expensive than platinum, gold or silver.

With the commissioning of the first commercial generating station in September of 1882, The Pearl Street Station in Lower Manhattan, the modern electrical industry is considered to have begun [12]. This initiated the rapid use of electricity and the development of associated electrical equipment.

In 1886, Charles Martin Hall and Paul Héroult independently and simultaneously discovered electrolytic reduction, the process used to this day to produce Al. This provided the breakthrough for the commercial production of Al in large quantities.

At the turn of the century, Al was relatively expensive because it was still only being produced in relatively limited quantities, thus it had limited commercial use. As more Al became available, various alloys and uses were developed. Uses such as for cooking utensils, electrical conductor, and airframe components, lead to more Al being produced. This in turn resulted in lower cost per pound and more uses.

During WWI and WWII the production of Al was increased dramatically to support the war effort, namely the manufacture of aircraft. This resulted in the large-scale industrial production of Al. To put this into perspective, the world production of Al and Cu in thousands of metric tons before and after WWII were as follows:

<table>
<thead>
<tr>
<th>Year</th>
<th>Copper</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1938</td>
<td>1,996</td>
<td>579</td>
</tr>
<tr>
<td>1942</td>
<td>2,841</td>
<td>1,477</td>
</tr>
<tr>
<td>1946</td>
<td>1,850</td>
<td>750</td>
</tr>
<tr>
<td>1950</td>
<td>2,685</td>
<td>1,494</td>
</tr>
<tr>
<td>1954</td>
<td>2,850</td>
<td>2,900</td>
</tr>
</tbody>
</table>

There are other related economic factors that have evolved over last 60 years. The electrical industry has expanded dramatically in the US and other parts of the world. In 1955 North America was producing 2/3 of the Al in the world. Today, China and Russia each produce more Al than either Canada or the United States, and North America only produces 1/6 of the Al in the world.

In short, the amount of Al now produced annually exceeds copper production by a factor of 2 to 1 (32 vs. 16 million metric tons). Today, economies of scale, supply and demand, and other factors such as Al being the most plentiful metal in the earth’s crust have resulted in Cu costing about 3 times per pound more than Al.

Where a manufacturer offers Al and Cu conductor options, the range of savings using Al will vary widely depending upon the type of product being evaluated. Comparing the pricing between Al and Cu for single and three-phase Distribution Dry
Type Transformers, liquid filled and dry type substation transformers, Busway, Panelboards, and Switchboards, yields discounts for Al ranging from 15% to 45%.

Recognize that the actual discount varies by ampacity, and that the impact on the overall product cost will vary depending upon the percentage of conductor content vs. that of other items in the complete product. For example, the conductor content of Busway is significantly higher than that of a Panelboard containing circuit breakers. Thus, the conductor discount has a higher overall impact for Busway.

MANUFACTURERS’ LIMITATIONS

Another factor leading to the misconception that Al is inferior to Cu is due to the fact that some equipment manufacturers have eliminated Al as an option for some electrical products.

As indicated in the previous section, the bad reputation given to the Al branch wiring problems of the 1960s & 1970s was unjustly attributed to all Al conductors. Designers began to predominantly specify Cu conductors on selected products. As manufacturers continued to trim costs related to their manufacturing processes and product designs, inventory carrying costs became the next frontier of financial accountability. With the higher specified demand for Cu, it became economically unreasonable to carry both Cu and Al inventory. Thus, it was the lack of industry demand, not design, application issues, or unsuitability that retarded Al as an option in several classes of products.

ENVIRONMENTAL CONSIDERATIONS

Both Cu and Al oxidize over time. Aluminum conductors oxidize immediately upon exposure to air such that all exposed Al surfaces are covered with a thin oxide layer. At that point, oxidation stops unless the Al oxide barrier is broken and the conductor is re-exposed to the air.

If the surface oxidation layer is disturbed in a moist environment that does not allow for direct contact with the air, corrosion will occur. Photo 1 illustrates a failure that occurred in a direct buried cable when the cable was unknowingly nicked during installation. The cable lost continuity after approximately four years of service. It is noteworthy that despite the aggravated state of corrosion (white powder) in the failure, once the adjoining conductor was cut to remove the faulted section, surface oxidation formed quickly on the areas of the cut conductor exposed to the air, and no further corrosion occurred.

The sample conductor ends shown in Photo 1 are what designers should visualize when the subject of Al conductors is brought-up. It illustrates that when disruption of the Al oxide layer occurs in a relatively clean and dry environment, such as when conductors are sheared and punched in an equipment manufacturing facility, surface oxidation of the newly exposed metal occurs immediately, and the exposed conductor surfaces are once again protected. This surface oxidation layer protects aluminum conductors from corrosion.

Al is highly resistant to weathering, even in industrial atmospheres that often corrode other metals. The following table contains empirical data illustrating atmospheric corrosion rates for four solid metals [13]:

<table>
<thead>
<tr>
<th>Atmosphere</th>
<th>Location</th>
<th>Al</th>
<th>Cu</th>
<th>Zn</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desert</td>
<td>Phoenix, AZ</td>
<td>0.000</td>
<td>0.005</td>
<td>0.010</td>
<td>0.009</td>
</tr>
<tr>
<td>Rural</td>
<td>State College, PA</td>
<td>0.001</td>
<td>0.023</td>
<td>0.042</td>
<td>0.019</td>
</tr>
<tr>
<td>Coastal</td>
<td>Key West, Florida</td>
<td>0.004</td>
<td>0.020</td>
<td>0.021</td>
<td>0.022</td>
</tr>
<tr>
<td>Coastal</td>
<td>La Jolla, CA</td>
<td>0.028</td>
<td>0.052</td>
<td>0.068</td>
<td>0.016</td>
</tr>
<tr>
<td>Industrial</td>
<td>New York, New York</td>
<td>0.031</td>
<td>0.047</td>
<td>0.190</td>
<td>0.017</td>
</tr>
<tr>
<td>Industrial</td>
<td>Altoona, PA</td>
<td>0.025</td>
<td>0.046</td>
<td>0.190</td>
<td>0.027</td>
</tr>
</tbody>
</table>

Table 2 - Corrosion rate shown in average mils per year
Aluminum is also corrosion resistant to many acids. Alkalis, however, are among the few substances that attack the oxide layer, therefore are corrosive to aluminum. In general, contact with alkaline substances should be avoided [14].

CONCLUSION

Aluminum is a suitable conductor material used in many electrical products. It is recognized by the National Electrical Code and by independent certification agencies such as UL. Aluminum provides about twice the current carrying capacity per pound compared to copper (depending on the conductivity of the alloy). Aluminum has a lower tensile strength than copper, but approaches that of copper for the equivalent ampacity. Aluminum bus, wire, and terminations have been proven to be reliable when terminated with appropriate, hardware and conductor plating, and when installed in accordance with the manufacturer’s guidelines and governing standards. Finally, the use of aluminum conductors can provide significant cost savings versus the use of copper.

REFERENCES

[1] National Electrical Code, currently published by the National Fire Protection Association, Batterymarch Park, Quincy, MA 02169-7471
[2] Underwriters Laboratories, Inc., 333 Pfingsten Road Northbrook, IL 60062-2096
[3] National Electrical Manufacturers Association, 1300 North 17th Street, Suite 1752, Rosslyn, VA 22209
[4] Institute of Electrical and Electronic Engineers, 445 Hoes Lane Piscataway, NJ 08854
[5] ASTM International, 100 Barr Harbor Drive, PO Box C700, West Conshohocken, PA, 19428
[7] Ontario Government Inquiry into Aluminum Wiring Dr. J. Tuzo Wilson, Commission Chair, Queen’s Printer for Ontario
[8] International Electrotechnical Commission, IEC Central Office, 3 rue de Varembe, P.O. Box 131, CH – 1211 Geneva 20, Switzerland
[14] The Use of Aluminum with Food and Chemicals, Aluminum Association, Arlington, VA