Application Paper **AP083003EN**

Aluminum—the other conductor

Abstract

Aluminum 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 using aluminum wiring almost exclusively. The use of aluminum wiring has been recognized since the publication of the second edition of the National Electrical Code® in 1901. Shortages of copper (copper) during the Second World War prompted electrical equipment manufacturers to expand their offerings for aluminum (Al) for current-carrying conductors. The successful application of these materials provides significant evidence that both copper and aluminum are suitable choices for the conveyance of electric current.

Aluminum is the most abundant of all metals 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.

For the purposes of this discussion, two major classes of electrical distribution and control equipment will be addressed—first, equipment utilizing bus bar, such as busway, switchboards, switchgear, and motor control centers; and second, equipment utilizing wire or strap windings, such as motors or transformers. The factors that designers must weigh when deciding between these two materials fall into four primary categories:

- Mechanical properties
- Electrical properties
- Reliability considerations
- Cost considerations

Misconceptions—What are the facts?

The following misconceptions have led to the perspective that aluminum is an inferior conductor to copper:

Misconception #1—Many electrical equipment manufacturers have completely eliminated aluminum conductor options from some of their product offerings, which is evidence that aluminum is an inappropriate conductor for some electrical equipment.

Misconception #2—It is common knowledge that aluminum is a poorer conductor of electric current because it has a higher resistance than copper.

Misconception #3—The public is aware of the problems that resulted during the late 60s and early 70s when the industry introduced aluminum residential wiring, thus aluminum must be inferior because it was replaced by copper.

Misconception #4—The public knows that aluminum is less expensive than copper, thus copper must be better.

Based upon these misconceptions, the common conclusion is that the clear choice between the two materials would seem to be copper.

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Mechanical properties

Technically, the mechanical properties of aluminum are shear and tensile strength, hardness, and modulus of elasticity.

Aluminum does have a lower tensile strength (37%) than copper for the same cross-section of material; however, a 66% greater cross-section of aluminum is required to carry the same amount of current as would be required for a copper conductor, so the larger cross-section of aluminum approaches the tensile strength of copper for a given ampacity.

The reality is that for electrical applications, the 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 classes of industry standards in the U.S. that address the design and testing of electrical distribution and control equipment are Underwriters Laboratories (UL®), the National Electrical Manufacturers Association (NEMA®), and the Institute of Electrical and Electronics Engineers (IEEE®). 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, because they provide a legal oversight role to ensure ongoing compliance with manufacturers' certification claims. On this basis, users can be ensured that both copper and aluminum product designs meet equivalent bracing criteria.

The thermal storage capacity of aluminum is 0.214 cal/gram/°C—for copper it is 0.092 cal/gram/°C. Thus, aluminum has a thermal storage capacity of over 2.3 times that of copper. aluminum-wound transformers have a superior thermal storage capacity compared to copper-wound units, and they can withstand more surge and overload currents than copper-wound units.

Pure aluminum has a coefficient of thermal expansion of 23.6 x 10^{-6}/°C vs. copper's 16.5 x 10^{-6}/°C. This would lead users to believe that joints for aluminum conductors are prone to more fatigue from thermal cycling than copper—which is correct, however, manufacturers have connection methods to address this issue. The utilization of spring-type conical washers in bolted joints provides for the proper contact pressures and more than accommodates the thermal expansion difference. Because the melting temperature of aluminum is well over 600 °C, the maximum application temperature of electrical equipment does not come close to these limits, so material flow contributing to the weakening of electrical joint pressure is not a concern.

Both copper and aluminum are subjected to oxidation when exposed to the atmosphere. When applied in electrical products such as bus bars, aluminum conductors are plated with nickel, silver, or tin, thus eliminating the high-resistance characteristics of surface oxidation at joints. When utilized as winding materials, as in transformers and motors, conductors are welded, braised, or "staked-on" to penetrate through and conductor surface oxidation. Concern over aluminum surface oxidation away from joint areas is not an issue; as 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 electrical resistivity of aluminum increases with impurities. ASTM specifications permit a minimum of 99.45% aluminum content to be classified as Electrical Conductor (EC) grade aluminum. Currently, the aluminum producers offer EC grade with a minimum of 99.6% aluminum. Aluminum 1350 is a common EC grade with a content of 99.5% aluminum.

There is a misconception that products with aluminum conductors run hotter than those with copper, but that is not the case. Regardless of the material, wherever possible, manufacturers optimize material conductor content. The industry standards, such as UL cited earlier, 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 criteria. For some products, the manufacturers are given the option to use either of these criteria, in other cases, thermal performance is the only criteria. So, regardless of the choice of conductor material, temperature rise tends to be equal and manufacturers optimize the conductor content to meet performance requirements. Products built with aluminum do not operate at higher temperatures than those built with copper.

Pure aluminum has an electrical conductivity by volume of 62% of that of copper. Pure aluminum has an electrical conductivity by mass of 214% of copper. Combining these conductivity measures with the densities of copper (8.96) and aluminum (2.7) yields a 0.48 to 1 ratio. The result is that 1 pound of aluminum has the same conductive capability as 2.08 pounds of copper. Thus, although the conductivity of copper is better than that of aluminum, on a per pound basis, aluminum is twice as good a conductor as copper. Where weight is a design consideration, aluminum is an excellent choice. Where space is a critical limitation, copper may be required.

Because more aluminum is required by volume than copper for a given ampacity and environment, aluminum conductor volume must be increased vs. that for copper, which results in a larger aluminum conductor surface area. If the additional space to accommodate the higher volume of aluminum is acceptable, the increase in conductor surface area actually produces two benefits. 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 surface area of the conductor for a given ampacity, the more efficient the conductor utilization will be. Additionally, larger aluminum cross-section area generally results in wider conductors or more conductors per phase. This increased conductor size results in more joint contact surface area, which provides for lower current transfer density.

Reliability considerations

As indicated above, both copper and aluminum oxidize over time. Aluminum conductors oxidize until all exposed aluminum surfaces are covered with a thin oxide layer. At that point, oxidation stops unless the aluminum oxide barrier is broken and the aluminum conductor is re-exposed to the air. If this occurs in a relatively clean and dry environment, such as when conductors are sheared and punched in an equipment manufacturing facility, surface oxidation occurs again, and the exposed conductor surfaces are once again protected. Copper, on the other hand, oxidizes completely over time. These factors combine to give aluminum conductors a long life.

Regarding the residential aluminum branch wiring problems of the 60s and 70s, upon close examination it was found that the root causes of those problems were related to the use of wiring devices with steel terminals. The physical properties of the aluminum/steel interface tended to loosen the connection more over time. aluminum and steel have significantly different rates of expansion. Because the two materials expand and contract at different rates under varying load and temperature conditions, aluminum and steel connections would loosen and gradually develop progressively smaller contact areas. Because the contact area was reduced, the resistance increased, which caused the termination temperature to increase, resulting in the fires that brought scrutiny to the proper use of aluminum terminations. A similar problem occurred when the aluminum conductors were incorrectly terminated in push-in type connections intended only for use with copper conductors. If aluminum wire is used with wiring devices solely designed for use with copper wire, the connection heats up. Most transformer manufacturers address this problem by making a transition between the aluminum windings, either to a copper lead wire (or bus bar) or by terminating to an aluminum-copper certified connector.

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

Cost considerations

According to the Copper Development Association, since 1974 there has been a declining usage of aluminum building wire in the construction market. Its peak occurred in 1974 when 31% of the building wire market was aluminum. By 1991, aluminum had declined to an 8% share of the market. In 1992, the Copper Development Association conducted a survey of aluminum vs. copper in Electrical Contractor magazine and 675 responses were received. The basic question was: “Which do you prefer, copper or aluminum and why?” The results of the 675 returns—copper was preferred over aluminum by a 20:1 ratio. 243 of the respondents said they prefer copper because of its “quality image,” without being specific.

When buying habits are driven by misconceptions and emotion, it is often difficult for facts to dissuade one’s choices. The one factor that may be successful in accomplishing this is financial motivation.

Where a manufacturer offers aluminum and copper conductor options, the range of savings using aluminum will vary widely depending upon the type of product being estimated. Comparing the list pricing between aluminum and copper for single- and three-phase distribution dry-type transformers, liquid-filled and dry-type substation transformers, low-voltage busway, panelboards, and switchboards yields discounts for aluminum ranging from 15% to 45%. The actual discount varies by ampacity and 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, which also includes circuit breakers, therefore, conductor discount has a higher overall impact for busway.

Why is aluminum offered at a lower relative cost compared to copper? First of all, as indicated early in this document, aluminum is the most commonly found metal on earth. Its abundance is one of the factors that, despite its virtues, has historically caused its costs to be much less volatile than that of copper.

Manufacturers’ limitations

One of the misconceptions identified earlier in this document, is the perception that aluminum is inferior to copper, thus manufacturers have all but eliminated aluminum as an option for some electrical products.

As indicated in the previous section, the “bad rap” given to the aluminum branch wiring problems of the 60s/70s was unjustly painted across the electrical industry. Specifiers began to predominantly demand copper conductors on selected products. As manufacturers continued to lean-out and refine their manufacturing and design costs, inventory carrying costs became the next frontier of financial accountability. With the higher specifying demand for copper, it became economically unreasonable to carry aluminum inventory for the low demand, thus, it was demand, not design or unsuitability, that drove the elimination of the aluminum option in several classes of products.

Conclusion

In summary, aluminum, as proven by third-party standards such as UL, is a suitable conductor in many electrical products and has been given a bad rap due to problems associated with residential wire terminations. aluminum provides a lower weight to current-carrying ratio compared to copper. aluminum has a lower tensile strength than copper, but approaches that of copper for the equivalent ampacity. When terminated with appropriate plating, hardware and processes as stipulated by the governing standards, aluminum bussing, wiring, and terminations prove to be as reliable as copper. Finally, the choice of aluminum conductors can provide a significant cost savings.

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