Developments in Alloy Conductors

by
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Alloy conductors have long been used in wire and cable. But the cadmium alloyed with copper to make these conductors is hazardous to the environment. Developments in copper alloys can now satisfy both engineering and environmental aspects.

Copper's main attribute is its high electrical conductivity. The electrical conductivity of pure copper, which is in excess of 101% *IACS* (*International Annealed Copper Standard*), sets the standard and makes it the material of choice as a conductor. However, copper has low strength and softens readily at relatively low temperatures, whereas many applications require higher strength, greater softening resistance while still maintaining a high electrical conductivity. Adding various elements to copper will modify its properties and increase its strength. The trade-off is that additions to copper, whether an impurity or an intentional alloying element, reduce copper's electrical conductivity.

Among the various elements commonly alloyed with copper, silver, cadmium and zinc have the least effect in reducing conductivity, while phosphorus, silicon and iron are among the most potent. **Figure 1** illustrates the effect of various elements on the electrical conductivity of copper.

Commercially pure copper is the most widely used conductor material. It has excellent conductivity, attains limited strength, is easily processed and is a commodity item. But pure copper falls short in other properties and fails in many demanding high-performance applications.

The basic requirements for a high performance conductor alloy are as follows:

- **Electrical Conductivity**—Primary conductor requirement.
- **Strength**—For reliability in service.
- **Softening Resistance**—To maintain strength when exposed to elevated temperatures.
- **Flex Life**—To withstand vibration or repeated bending.
- **Solderability**—Surface easily activated with standard flux.
- **Fabrication**—Reliable, efficient, economical processing.
- **Plating—**Readily plated with surface coatings of nickel, silver or tin.
- **Economy**—Provides a price to performance value.

Copper alloys are not new to the wire and cable industry. The specifications *ASTM B 105* and *ASTM B 624* deal with alloy conductors. As with all metals, each alloy system currently used for conductors has its own attributes and deficiencies as compared to pure copper:

- **Cadmium Copper (C16200 or C162)—**Good conductivity, good strength, good softening resistance and reliable processing, but contains cadmium.
- **Cadmium Chromium Copper (PD135)**—Good conductivity, excellent strength, excellent softening resistance, difficult processing and contains cadmium.
- **Tin Copper (CT37™)—**Moderate conductivity, strength, and softening resistance as well as reliable processing.
- **Zirconium Copper (C15000 or C150)**—Excellent conductivity, moderate strength, very good softening resistance, but difficult processing.
- **Beryllium Copper (CS95®)** - Low conductivity, excellent strength, excellent softening resistance, difficult processing and contains beryllium.

Cadmium copper (C16200) and cadmium chromium copper (PD135) are the two most commercially established alloy systems employed by the wire and cable industry. These are established alloy systems and are well tested in wire and cable applications. However, both of these copper alloy systems contain cadmium—which is an element of increasing environmental concern and product liability.

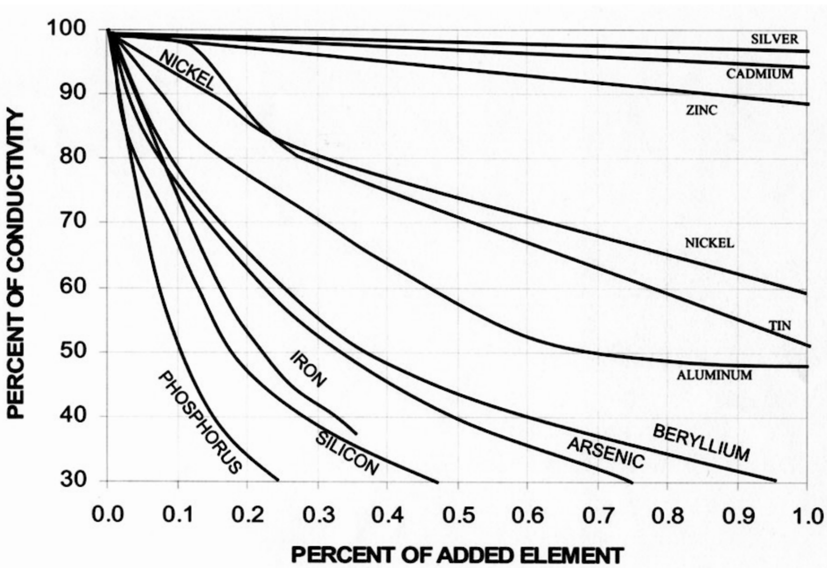

Fig. 1 — Effect of various elements on the electrical conductivity of copper.

Copper Alloy Metallurgy

Cadmium copper and tin copper are examples of solid-solution alloys where the alloying addition is completely dissolved in the copper forming a single phase. These alloys have higher strength than pure copper, but they also have lower conductivity. Solid-solution alloys can be further strengthened by cold work such as rolling or drawing. However, increasing amounts of cold work result in further reductions in conductivity.

Precipitation strengthened alloys such as PD135 contain elements with limited solubility at lower temperatures and increasing solubility at higher temperatures. This solubility temperature relationship forms the basis for precipitation hardening. These alloys are initially heated to a high temperature, where most or all of the alloying elements are dissolved in the copper, then rapidly cooled (quenched). Quenching essentially freezes the high-temperature structure to form a supersaturated solid solution. In this “solutionized” condition, the alloy is soft and has the lowest electrical conductivity for the specific composition. The alloy is then heated (aged) at an appropriate temperature to allow controlled precipitation of the second phase particles out of the copper matrix. Precipitation of the second phase simultaneously increases the strength and electrical conductivity of the alloy. Similar to solid-solution alloys, precipitation hardened alloys can also be additionally strengthened by cold work.

Dispersion strengthening is another method of increasing copper alloy strength. Here, stable particles that do not easily dissolve in the copper matrix are introduced by various techniques. The particles increase strength by a mechanism that is similar to the second phase particles in precipitation hardening. As the dispersion particles don’t dissolve into the copper matrix, there is minimal effect on the electrical conductivity and the alloy may not require solutionizing or aging heat treatments.

As is the case with most metals, the mechanical properties of the dispersion hardened alloys can be controlled through cold work and heat treatment processes.

The metallurgy of an alloy determines its properties, however, casting limitations may restrict the alloy’s utilization to specific product categories such as tube or strip. Copper alloys may be cast into special shapes, billets and bars or it can be continuously cast. Recent technologies have developed alloys utilizing powder or spray metallurgy techniques. An alloy can possess the desired engineering attributes that are required for a good alloy conductor, however, the alloy is only commercially cast in a form that cannot be processed into a rod or wire.

Further, commonly deployed metal casting technologies that are used for producing copper alloy rod often have difficulties maintaining the melt chemistry when the alloy contains volatile elements that are often used in high performance alloys. Keeping the alloy homogenous during cooling and clean of impurities that impede wire drawing and, which affect final properties, can also prove to be problematic when using these technologies.

A technique developed by Fisk Alloy Wire, Inc., to convert copper alloy bars into rod has enabled many new high-performance alloys to be produced in wire form. In addition, this method bypasses a major problem where alloy chemistry renders it incapable to cast into rod form. This technique has proven to be a very effective method in increasing the availability of many of the new high-performance copper alloys for applications in wire.

Copper Alloy Development

The increasing demand placed on integrated circuits, connectors and terminations in the operation of electronic components has caused the development of a number of high-performance copper alloys. These alloys have been designed to meet specific performance requirements. Part miniaturization and higher contact forces require alloys with higher strength. The need to carry more current and dissipate a larger amount of heat demand alloys with a higher conductivity. These alloys must also be highly ductile so as to be formed into parts. The alloys must operate at higher temperatures requiring improved stress relaxation resistance. Lastly and of great importance, all these new alloys must employ environmentally responsible chemistries and processes.

Regardless of the metallurgy used to develop these alloys, the conductivity versus strength tradeoff is the principal challenge facing the alloy designer. Plotting the combination of conductivity and strength of different conductor alloys gives a comparison of this performance tradeoff. **Figure 2** illustrates the electrical conductivity versus tensile strength for conductor alloys in their commercially employed soft temper. **Figure 3** illustrates the electrical conductivity versus tensile strength for hard temper conductor alloys. These graphs also present the developments in alloy conductors. The progression of conductor alloys offering higher strength with the same or minimum sacrifice to conductivity is evidenced by the continued shifting of the performance curves to the right.

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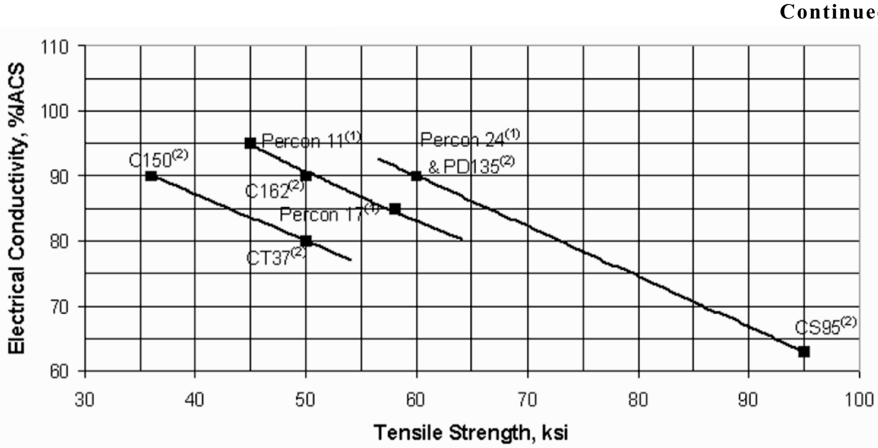

Fig. 2 — Tensile strength for various “soft” conductor alloys vs. annealed electrical conductivity. Reference: FAC[1], PDHPC[2].

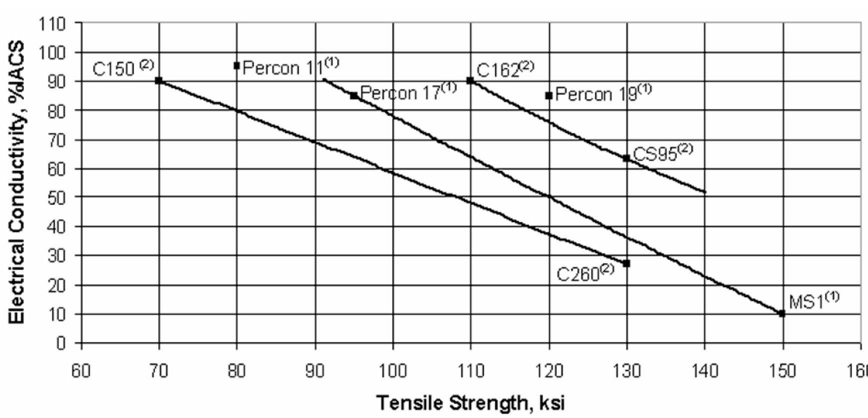

Fig. 3 — Tensile strength for various “hard” conductor alloys vs. annealed electrical conductivity. Reference: FAC[1], PDHPC[2].

The Percon® alloys are new and offer similar or superior properties without the use of cadmium, beryllium or other environmentally hazardous substances.

Environmental Issues

A legal reality facing many existing and new products is the ever-increasing regulation of hazardous materials being released to the environment. The list of regulated materials covers heavy metals, solvents and other compounds that affect the quality of human life when excessive levels are introduced to the environment or food chain. Many materials, once considered environmentally safe and acceptable, are now being regulated or are listed for future regulation.

Cadmium appears on the **Environmental Protection Agency's (EPA's)** list of persistent, bio-accumulative and toxic (PBT) chemicals that was compiled to identify chemicals and chemical categories that may be found in hazardous wastes regulated under the Resource Conservation and Recovery Act (RCRA). The list was created to help implement the EPA's national RCRA waste minimization policy to reduce the generation of PBT chemicals.

When cadmium enters the food chain and is ingested, it accumulates in the liver and kidney causing damage. High concentrations of cadmium in kidneys can lead to proteinuria (protein in the urine) and excretion of calcium from bones. Cadmium affects the body at levels lower than that specified for lead. The EPA considers cadmium a "probable human carcinogen" and has classified it as a Group B1 carcinogen, and therefore falls under the Waste Minimization National Plan.

Elemental cadmium and cadmium compounds have had a wide variety of uses in the wire and cable industry as pigments for insulation, stabilizers for PVC, plating of electrical connector shells and in alloy conductors. Cadmium occurs naturally in different ores. But large industrial releases have been attributed to manufacturing operations involving cadmium and zinc. Release of cadmium can occur during the many stages of a product's life. For cadmium-containing alloys, the manufacture of raw materials, casting, waste products during manufacture, disposal in landfills and remelting or improper recycling are all potential release sources to the environment.

Cadmium restrictions differ in various parts of the world and more severe restrictions are passed each year. As previously mentioned, in the USA, cadmium appears on the EPA hazardous materials list. Cadmium's use is not prohibited in the USA, but minimization of its use and control of its release to the environment have been a priority. For example, USA automobile manufacturers have effectively banned the use of cadmium-containing materials in all their products. A January 1, 2007, deadline has been proposed by the European Commission to reduce Waste from Electrical and Electronic Equipment (WEEE) as part of the Restriction of Hazardous Substances (RoHS) directive. Hazardous materials such as cadmium, lead and mercury, among others, will be restricted from a wide variety of equipment.

Environmental regulations are now addressing the entire life cycle of a product. Proposed legislation is pending to require electrical and electronic equipment manufacturers to be responsible for their products throughout their life including their disposal. This "Take-Back" policy will require manufacturers to bear the costs of proper recycling and disposal if their products contain listed hazardous materials.

As previously mentioned, the two predominant copper alloy systems used in wire and cable are cadmium copper (C16200) and cadmium chromium copper (PD135). Because of the environmental issues, it is to be noted that the number of cadmium copper alloy producers in the world has been decreasing through the years. There has been no indication that additional capacity will be added in the near future.

Until recently, there has been little research and development to provide alternatives to these cadmium-containing alloys for wire and cable. Other industries have responded to the increasing cadmium restrictions with new environmentally safer products. The pigment industry has responded with new colorants based on organic materials and other elements to replace cadmium-based colors. PVC stabilizers based on zinc and calcium have been effective against the effects of light and heat. Alternatives to cadmium plating, such as with Ion Vapor Deposition (IVD) and nickel-boron plating, unplated connector systems and sophisticated plastics are being implemented. The copper alloy strip industry has also developed cadmium-free alloys, but as previously mentioned, not in a rod form for wire. Before introduction of the Percon alloys, material development in the high-performance conductor industry has not followed the lead of other industries.

Cadmium-Free Alloy Conductors

The environmental regulations on cadmium, already affecting the electronics and connector industries, will affect the wire and cable industry. Percon 11, Percon 17 and Micro-Shield are examples of cadmium-free alloys originally developed for and widely accepted in electronics. These alloys have excellent mechanical and electrical properties, but were either not readily available in rod form, nor easily drawable to the fine sizes for use as stranded conductors. Percon 19 and Percon 24 are also cadmium-free alloys. They were developed specifically for applications in alloy conductors.

Percon 11 is similar to copper alloy C150—the traditional zirconium copper alloy. It contains less zirconium, about 0.1% by weight. The lower zirconium concentration, combined with the special casting techniques employed for this alloy, controls the size and distribution of zirconium particles. This results in higher elongation and drawability than the standard C150 alloy. This alloy is typically used in hard drawn temper in conductor applications. But it may also be heat treated to increase elongation. The alloy has a hard drawn tensile strength in excess of 80,000 psi (552 MPa) with an electrical conductivity of 90% *IACS* minimum. Additionally, Percon 11 does not contain any hazardous elements and is also graded as Class I scrap, mixing in directly with copper scrap.

Percon 17 has been engineered specifically to replace cadmium copper C162 in applications where alloy conductivity is of first order importance. The alloy is a dispersion strengthened alloy with iron and magnesium phosphides in the copper matrix. Percon 17 can be used in the hard drawn condition or it can be heat treated to soft temper at finish for higher elongation. In hard temper the tensile strength of Percon 17 can exceed 95,000 psi (655 MPa) with electrical conductivity of 80% IACS minimum; in soft temper 58,000 psi (400 MPa) and 85% IACS.

Percon 19 has also been designed to replace cadmium copper C162. Percon 19 is an alloy of copper, magnesium, phosphorous and tin. The alloy and its processing have been engineered for applications where the design criteria are for conductor strength and high flex life. In these applications, its flex life exceeds the performance of C162. These applications require that the alloy be used in the hard drawn condition where its tensile strength is commonly 120,000 psi (827 MPa) and electrical conductivity is 73% IACS.

Percon 24 is an alloy designed to exceed the specifications of *ASTM B624*. It is a precipitation hardened alloy system of copper, chromium and zirconium. This alloy is cast to obtain a highly clean melt with an oxygen content of less than 10 ppm. The casting method also insures uniform distribution of the alloy constituents which assures drawing to ultra fine wire diameters. Percon 24 is offered in the heat treated condition. Typical tensile strengths are greater than the *ASTM B624* minimum of 60,000 psi (414 MPa). Minimum electrical conductivity is 90% *IACS*, also exceeding the spec requirement. Conductor flex life and softening resistance are excellent.

MicroShield is a solid-solution alloy of copper, nickel and tin and has been long used in telecommunication electronics for its solderability and corrosion resistance. A beneficiary of the improvements in casting and processing, the alloy can now be reliably drawn to very high strengths and to ultra-fine gauge sizes. Tensile strengths of over 150,000 psi (1034 MPa) and 10% electrical conductivity make the alloy an ideal candidate for high-strength coaxial shielding applications or to replace stainless steel shielding in other applications where the low conductivity of stainless steel is of concern. In addition to its strength and unlike stainless steel, MicroShield is highly solderable when bare or can be plated with nickel, silver or tin.

Performance Testing

Military, aerospace, automotive and medical applications are the primary users of alloy conductors. With few exceptions, military wire and cable specifications require qualification of the manufacturer. Many commercial specifications are based on comparable military specs and users often accept a manufacturer's military qualification. Before approval as a qualified supplier, the manufacturer must show that its product consistently meets specification. Regardless of whether pure copper or copper alloy is used as the conductor, the qualification tests have historically focused on the properties of the insulation. There are many requirements for the insulation material, tested before and after long-term environmental exposure, but few requirements for the conductor. The conductor must meet physical, mechanical and electrical requirements. However most of these parameters are measured as received and not after long-term environmental exposure.

There are no standard qualification tests for conductor materials in military and commercial wire specifications as they generally specify only three basic attributes: minimum tensile strength, maximum electrical resistance and minimum elongation in the finished wire. As a result, in addition to developing new conductor alloys it was necessary to develop a program to validate long-term reliability of these alloys when used in wire and cable. The objective was to not only test Percon 24 for military and commercial application, but to also establish a test program for future alloy development and qualification.

Testing was designed and conducted to compare the long-term performance of Percon 24 with PD135 and copper wire. Electrical and mechanical tests were performed on terminated and un-terminated specimens of *MIL-W-22759* (*M22759*) insulated wire in the as-received condition, after thermal aging, after thermal shock and after exposure to controlled vibration environments. Additional tests were performed on wire specimens terminated after thermal aging to simulate a repair operation on wire already in service. Thermal aging and thermal shock conditioning were performed at the maximum rated operating temperatures of the specific conductor/insulation as specified in the mil-spec and standard mil-spec termination contacts (*M39029/56-348* and */58-360*) were used.

Samples of 24 AWG (19 x36 AWG or 0.127 mm Unilay) silver-plated Percon 24 and PD 135 and 22 AWG (19 x 34 AWG or 0.16 mm Unilay) silver-plated copper conductors were insulated with a 6 mil (0.1524 mm) extruded wall of cross-linked ethylene-tetraflouroethylene copolymer (XL-ETFE) per *M22759/33* (for alloys) and *M22759/44* (for copper). Also, stranded nickel-plated Percon 24, PD135 and copper samples were insulated with 6 mil (0.1524 mm) thick composite tape-wrap insulation according to *M22759/82* and *M22759/92*. Wires containing both alloy conductors were simultaneously exposed to environmental conditions. Comparative testing would then quantitatively determine the relative performance of each alloy. Copper wire samples were included as control specimens throughout the test program. As stated earlier, test samples were prepared in four different conditions:

- Unconditioned—As-received wire from the insulating firm.
- Thermal Aged—Wire exposed to 1000 hours at maximum operating temperature, in an air-circulating oven. (200°C or 392°F for wire with silver plated conductor and 260°C or 500°F for wire with nickel plated conductor).
- Thermal Shock—Wire exposed to eight shock cycles. Each cycle equals one hour at wire's max operating temperature followed by immediate cooling to -55°C (-67°F) for an hour.
- Vibration—Test conditions conformed to *MIL-C-39029 para. 3.5.10 and 4.7.11* and *MIL-STD-1344, Method 2005, test condition VI, letter J*. Vibration duration of eight hours in longitudinal and eight hours in perpendicular directions.

Conditioned wire samples were subjected to these tests: conductor dimensions and properties, insulted wire dimensions and properties, solderability, voltage drop, crimp tensile strength, center of wire tensile strength, flex life of crimp terminations, center of wire flex life and *SAE AS4373* flex test.

Test Performance Summary

The battery of tests performed showed that the alloy properties and long-term performance of Percon 24 is comparable to PD135 in all respects. The test results were forwarded to **Naval Air Systems Command (NAVAIR)** for review. NAVAIR will accept wire containing Percon 24 conductor for qualification to military high-strength wire and cable specifications.

Conclusions

Percon alloys are made using modern casting technologies. These new technologies produce alloys that are processed with more control, greater uniformity and offer users the selection of new conductor alloys for wire and cable.

Waste stream and environmental responsibilities are driving development of new materials and processes in many industries. The wire/cable industry must be proactive in removing hazardous materials from products and processes.

The testing program developed to qualify Percon 24 for military and aerospace applications is thorough and rigorous. It is an excellent model for the testing and qualification of new conductor alloys.

Percon alloy conductors are engineered and performance tested to provide drop-in replacement capability for existing wire and cable specs. Percon alloys are engineered "green" and allow for the elimination of cadmium from wire and cable without sacrificing conductor performance.

To learn more, contact the author or **Circle 204.** WCTI

Author Profile...
Eric S. Fisk *is President of* ***Fisk Alloy Wire, Inc.****,* ***Fisk Alloy Conductors, Inc.*** *and* ***Electroplated Wire Corporation****. He holds a BA and BS from the* ***University of Washington*** *and an MS from* ***Columbia University****.*

Company Profile...
Fisk Alloy Wire, Inc. *(ISO-9000 & AS-9100 certified), manufactures copper alloy wire to meet specific alloy, shape and quality requirements. Wire is produced in flat, round, square and special shapes to customer specifications. A part of Fisk Alloy Wire,* ***Fisk Alloy Conductors, Inc.****, employs technologies for fine wire drawing, stranding and heat treating copper alloys and bimetallic composites to produce specialty stranded conductors and bobbins. Also a part of Fisk Alloy Wire,* ***Electroplated Wire Corporation*** *is organized and equipped specifically to electroplate wire. The company plates to exacting thickness across a variety of alloys, sizes, shapes and plating systems.*

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- *Fisk Alloy Conductors (FAC) www.fiskalloy.com.*
- *Phelps Dodge High Performance Conductors (PDHPC), www.pdwireandcable.com, www.phelpsdodge.com.*
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