High Conductivity Copper Rod and Wire

Figure 1. Copper Rod (left) and Copper Wire (right) Made at Essex Furukawa

Copper has been widely used for electrical and electronic applications in industries and in our daily life. Copper usually is the first metal for considerations in such applications because its unique combinations of performance and availability. Copper has highest electrical conductivity after silver among all other metals whereas it has a relatively low cost with abundant resources.

There are two types of high-conductivity, pure coppers commercially being made and available - electrolytic tough-pitch (ETP) copper and oxygen free copper. See the Table 1 below for different pure copper destinations. Table 2 lists the specification of chemical composition of ETP and oxygen free copper for electrical applications.

Table 1. Commercial Pure Copper

Trade name	Former CDA#	UNS#
Electrolytic tough-pitch (ETP) Copper	CDA 110	C11000
Electrolytic tough-pitch (ETP) Copper		C11040
Oxygen Free (OF) Copper	CDA 102	C10200
Oxygen Free Electronic (OFE) Copper	CDA 101	C10100

Table 2. Chemical Composition of Pure Copper for Electrical Applications –ASTM B 49

			C11000	C11040	C10200	C10100
			ETP	ETP	OF	OFE
Copper (Cu)	min.	%	99.90	99.90%	99.95%	99.99%
Oxygen (O)		ppm	-	100~650	10 max	5 max
Silver (Ag)	max.	ppm	-	25	-	25
Arsenic (As)	max	ppm	-	5	-	5
Bismuth (Bi)	max	ppm	-	1.0	-	1.0
Iron (Fe).	max	ppm	-	10	-	10
Nickel (NI)	max	ppm	-	10	-	10
Lead (Pb)	max	ppm	-	5	-	5
Sulfur (S)	max	ppm	-	15	-	15
Antimony (Sb)	max	ppm	-	4	-	4
Selenium (Se)	max	ppm	-	2	-	3
Tin (Sn)	max	ppm	-	5	-	2
Tellurium (Te)	max	ppm	-	2	-	2
Bi+Se+Te	max	ppm	-	3	-	-
Total impurity	max	ppm	-	65	-	-
Cadmium (Cd)	max	ppm	-	-	-	1
Phosphorus (P)	max	ppm	-	-	-	3
Zinc (Zn)	max	ppm	-	-	-	1
Manganese (Mn)	max	ppm	-	-	-	0.5

ETP Copper and Oxygen Free Copper

The major difference between ETP copper and oxygen free copper is oxygen content, that is ETP copper has 100~ 600 ppm (parts per million), higher than the oxygen level (1 ~ 10 ppm) in oxygen free copper. The oxygen in ETP copper is remained to a certain low level with the intension to combine the residual impurity to form the tiny impurity oxides so that the copper matrix is “clean” for easy electron travel which helps to ensure high electrical conductivity. The remained oxygen in ETP copper can also combine with copper to form fine copper oxides particles. ETP copper has a higher annealability with lower annealing temperature and better wire drawability with lower drawing force, but no meaningfully higher strength through dispersion hardening than oxygen free copper.

One of the concerns on ETP copper with its high oxygen content is its susceptibility to hydrogen embrittlement in hydrogen environment at an elevated temperature either in wire manufacturing process or during its service. Fusion welding using shielding gas containing hydrogen could lead to a brittle crack in ETP copper weldment. To remove free oxygen in copper matrix that could cause hydrogen embrittlement, a strong deoxidant, such as phosphorus, can be added into the ETP copper to combine with oxygen to form phosphorus oxides and thus to remove free oxygen available for hydrogen embrittlement. However, this will decrease the electrical conductivity of the copper. Therefore, phosphorus deoxidized copper is not preferred to use for high conductivity demand in electrical or electronic applications. Instead, oxygen free copper will be chosen. Because the residual oxygen level in oxygen free copper is so low that its availability to combine with free residual impurity in copper matrix is limited. Therefore, the maximum total amount of impurity has to be lowered to ensure that the high electrical conductivity is still kept in oxygen free copper. That is one of the reasons for the increased minimum limit of total copper for oxygen free copper (99.95% or 99.99%Cu) in the standard compared to that for ETP copper (99.90%Cu). Oxygen free copper also provides better mechanical performance (such as fatigue and fatigue-creep resistance) for long term service applications at an elevated temperature than ETP copper. Oxygen free copper can have more amount of work reduction in wire drawing before annealing than ETP copper. On other hand, it needs a higher temperature or longer time to anneal than ETP copper to obtain softness through recrystallization of the work hardened copper microstructure.

ETP 11000 copper defines only the required minimum amount of total copper including silver to 99.90% with the specified oxygen content range, while C11040 ETP coper has additional specified control maximum limit of each of selected residual impurity elements. Therefore, C11040 ETP copper automatically meets the specification of C11000 ETP copper and thus has more restrict residual impurity controls. ETP copper made and shipped from Essex Furukawa always meets the C11040 ETP copper specification for its magnet wire applications. Moreover, Essex Furukawa uses only Grade 1 high purity copper cathode to make its copper rod, with only a very small percentage of internal high quality copper magnet wire scraps. This guarantees the copper rod and wire made at Essex Furukawa is highly pure copper compared to other copper made with different resources. In addition, the internal specification on the copper rod at Essex Furukawa has more constrain limits in five critical elements than those in ASTM B 49 standard.

Oxygen free copper has two grades as in the Table 2. Oxygen copper electronic grade copper C10100 not only has the lower oxygen residual than oxygen free copper C10200 but also provides more control limits in individual residual elements with higher minimum total copper content requirement. Essex Furukawa normally uses oxygen free electronic copper C10100 for its magnet wire applications when oxygen free copper is requested.

It should be noticed that both ETP copper or oxygen copper can be added by a small quantity of silver during melting process before rod casting to get corresponded silver-bearing tough pitch (STP) copper and oxygen-free silver (OFS) copper, respectively. Depending on the amount of silver added, there are different grades. For STP copper, there are C11300 (0.027~0.034% Ag), C11400 (0.034~0.054% Ag) and C11500 (0.054~0.085% Ag). On the other hand, most common OFS coppers are C10400 (0.027~0.034% Ag), C10500 (0.034~0.054% Ag) and C10700 (0.085% Ag min). Additional silver content provides higher creep resistance and strain relaxation resistance at elevated temperatures, while keeping high electrical conductivity at 100%IACS or a little higher.

Manufacturing of Copper Rod

To make copper wire for electrical and electronic applications, copper rod needs to be made first. Both ETP copper rod and Oxygen copper rod can be made by continuous casting but normally in very different ways. Nowadays, ETP copper rod is made by wheel-and-belt continuous casting (concast in short), followed by hot rolling. This is totally away from ingot casting followed by separated descaling and rolling processes developed in early industrial revolution. In wheel-and-belt caster, molten copper from a melting furnace is transferred through a holding furnace and tundish and then poured into the rotating wheel rim cavity retained by a continuous moving steel belt. Following rotating wheel, the molten copper between the wheel rim cavity and the steel belt is solidified by cooling water in the cooling section, and a continuous copper bar is then formed and fed into a tandem hot rolling mill. The red hot concast copper bar is rolled through series rolling mill stands, and the copper cross section is becoming smaller and smaller and finally to the required final copper rod size with a near round or oval shape. A surface oxide removal section is normally integrated after hot rolling in a continuous casting line, either by alcohol reducing or acidic pickling. A wheel-and-belting continuous casting line can make ETP copper rod at a high casting speed with high efficiency and productivity. ETP copper rod made such way in hot rolled condition has great workability for further processing.

The Essex Furukawa concast line is unique among other wheel-and-belt concast systems. One of its features is that a special siphoned stainless steel tube is used to introduce the molten copper into the wheel rim cavity, different from pouring of molten copper directly from the tundish. This practice helps keep clean molten copper into the wheel cavity easier before solidification for high quality copper rod with much less chance to get casting inclusions.

On the other hand, oxygen free copper rod is made by vertical upward casting process (upcast in short). In this process a graphite die (or mold) with a cylindrical hollow is immersed in the molten copper, and its upper section is fastened with the cooling water copper jackets. The molten copper rod can be then solidified inside of the die at the cooling section. As the solidified copper rod is slowly moved upward, the molten copper fills into the inside of the die from its bottom, keeping floating molten copper surface to touch the solidified rod for more solidification of copper rod again. The copper rod is withdrawn upward continually at a proper short pull and stop pulse, a continuous oxygen free copper is thus made into a coil. It should be noticed that the upcast speed is very slow at the order of single digit foot rod per minute. To increase thermal efficiency and productivity, an upper caster normally has 4 to 20 parallel multiple upcast die-strand units. Consequently, the upcaster does not incorporate other process work in tandem with casting. In practice, either cold rolling or cold drawing operations are performed separately after upcasting, followed by annealing process. The oxygen free copper rod made by upcast is supplied usually in annealed condition in the market. The productivity of upcast for oxygen free copper rod therefore is much lower than that of the wheel-and-belt concast for ETP copper rod in an order of magnitude.

Although upcast is a major process to make oxygen free copper rod commercially, there are other different methods. One of them is dip-forming, originally developed by GE R&D. In this process, a clean, cold oxygen free copper wire or rod, as a casting solidification "seed", passes through a batch of molten copper where molten copper "frees" onto the moving cold copper core wire or rod. Dip-formed oxygen free copper rod is then cooled by water spray in a protective atmosphere camber to prevent oxidation. The processing sequences may be repeated for a desirable size of the rod.

Manufacturing of Copper Wire

A copper rod can be further processed readily through metal work to achieve a smaller size wire. It is usually a cold metal work processes, as copper is one of most ductile and workable metals and cold work ensures good surface quality. The conversion of copper rod to wire can be accomplished by cold rolling, cold drawing and continuous extrusion forming (conform). To ensure the consistent wire dimension and high surface quality, wire drawing is normally applied to the final size wire. This is a very case for the magnet wire to get its final dimension bare copper wire with high quality surface before enameling or coating process.

In many situations, an intermediate annealing is needed between cold metal work processes to soften the work hardened copper wire for further wire processing. Although conforming may be considered as cold metal work, its dramatic metal deformation during extrusion generates a significate amount of heat which makes the conformed copper wire self-annealed. Therefore, no additional annealing process is needed for conformed copper wire.

Properties and Testing

The most profound characteristic of copper is its chemical composition. The ASTM B49 standard specifies the chemical composition of copper rod made for electrical applications as Table 1. To realize a quick analysis in real time during copper manufacturing, usually, a special analyzer such as the LECO oxygen analyzer is used for oxygen content analysis, and an arc spark optical emission spectrometer or atomic absorption spectrometer is used to analyze the rest of residual elements.

ASTM B 49 standard also defines the requirements of mechanical and physical properties for copper rod stock for electrical applications as in Table 3. Table 3 also lists a typical range of the relevant properties.

It should be noticed that ASTM E8 shall be followed for tensile testing except the test gauge length shall be 10 inches as defined by ASTM B49. Electrolytic reduction test method, initially developed by Dr. H. Paps at Essex Furukawa in late 1970's, is used to determine the surface oxide thickness of copper rod per ASTM B49.

Although a twist test is not required by ASTM B 49 standard and neither adopted by many copper rod manufacturers because it is subjective to make visual grading, Essex Furukawa still uses it as a reference along with a real-time, inline Eddy current defect detecting system for internal quality controls on surface and sub-surface defects during copper rod production.

Hydrogen embrittlement bend test is only for oxygen free copper. The testing sample shall be a drawn wire that has been annealed at 1550+/-45 F for 30 min in the atmosphere containing at least 10% hydrogen before the reversal bending test at 90 degree.

Electrical conductivity %IACS (International Annealed Copper Standard) is converted from electrical resistance measurement by the method per ASTM B193. To ensure accurate measurements, a consistent diameter at 0.080" or equilibrant size annealed wire drawn from a rod should be used.

Table 3. ASTM B-49 Standard Specification and Typical Range

		Ultimate Tensile Strength	0.2% Yield Strength	Tensile Elongation	Surface Oxide Thickness	Hydrogen Embrittlement Bend Test ^	Electrical Conductivity ^
		Ksi	ksi	% in 10"	A	bending # w/o break	%IASC
C11000 ETP	B49	---	---	>30%	<750	N/A	>100%
C11040 ETP	B49	---	---	>30%	<750	N/A	>100%
C11040 ETP	Range-Hot Rolled	32~35	11~17	32~44%	200~375* <600**	N/A	100.0~102.0%
C10200 OF	B49	---	---	>30%	<750	>8	>100%
C10100 OFE	B49	--	---	>30%	<750	>10	>101%
C10100 OFE	Range-Annealed	33~36	9~15	35~45%	85~100	13~18	101.0~101.5%

^ For annealed wire. * For wire drawing. ** For shaving or conforming. N/A: Not applicable.

The actual range of properties of ETP and OFE copper are listed in Table 3 along with the ASTM B 49 standard limits. Table 4 lists a typical range of tensile properties of ETP and OFE copper wires after drawing and continuous strand annealing. Different metal work processes and heat treatments could result in different wire tensile properties even at the same wire size. That is a wire process history can affect strength and ductility of the wire. It should be noticed that magnet wire could have a little higher yield strength than a full annealed wire. This makes it more viable to avoid the stretch-out of magnet wire under tension during its winding in a downstream process.

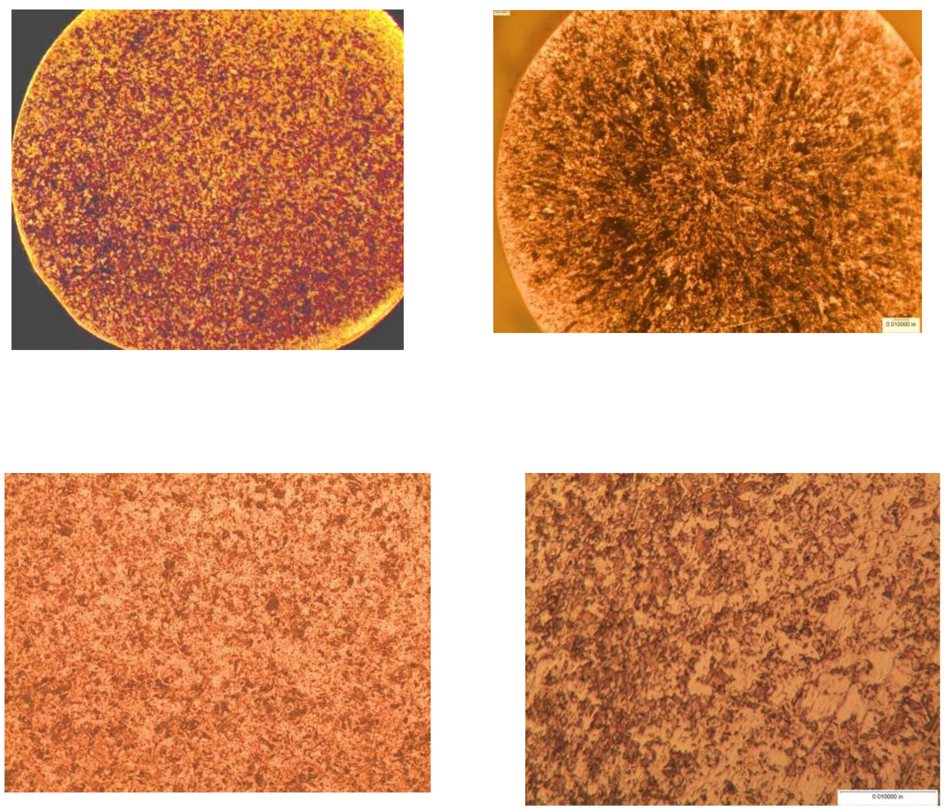
Table 4 Typical Tensile Properties of ETP and OFE Cupper Wires

	Ultimate Tensile Strength	0.2% Yield Strength	Elongation
	ksi	Ksi	% in 10"
ETP Cu-Annealed Wire	26-35	8~12	32~44
ETP Cu- Magnet Wire	33~39	16~22	32~42
OFE Cu –Annealed Wire	30~33	9~12	34~45
OFE Cu- Magnet Wire	32~34	12~14.5	32~43

Figure 2 shows the microstructures of ETP copper and OFE copper in both rod and annealed wire form. It can be seen that copper oxide particles exist in ETP copper while OFE copper does not.

Rod

Wire



ETP Cu OFE Cu

Figure 1. Microstructure of ETP Copper and OFE Copper

Final Words

Both ETP copper and OFE copper have been used in magnet wire products made at Essex Furukawa as well as in the various electrical and electronic application worldwide. Each of them has its own advantages. Whereas OFE copper magnet wire is preferred in choice for automotive under-hood applications by many automotive manufacturers, where welding is performed under protective atmosphere with hydrogen, ETP copper magnet wire is more cost effective.

Essex Furukawa has been in magnet wire world since its infant stage. Essex Furukawa not only knows what copper should be for its magnet wire, but also understands copper rod and wire making and applications with know-how expertise and innovative technologies. Essex Furukawa can provide the information and services as its customers' needs when there is a sticking issue to be solved or there is a rising opportunity for new business or technology.