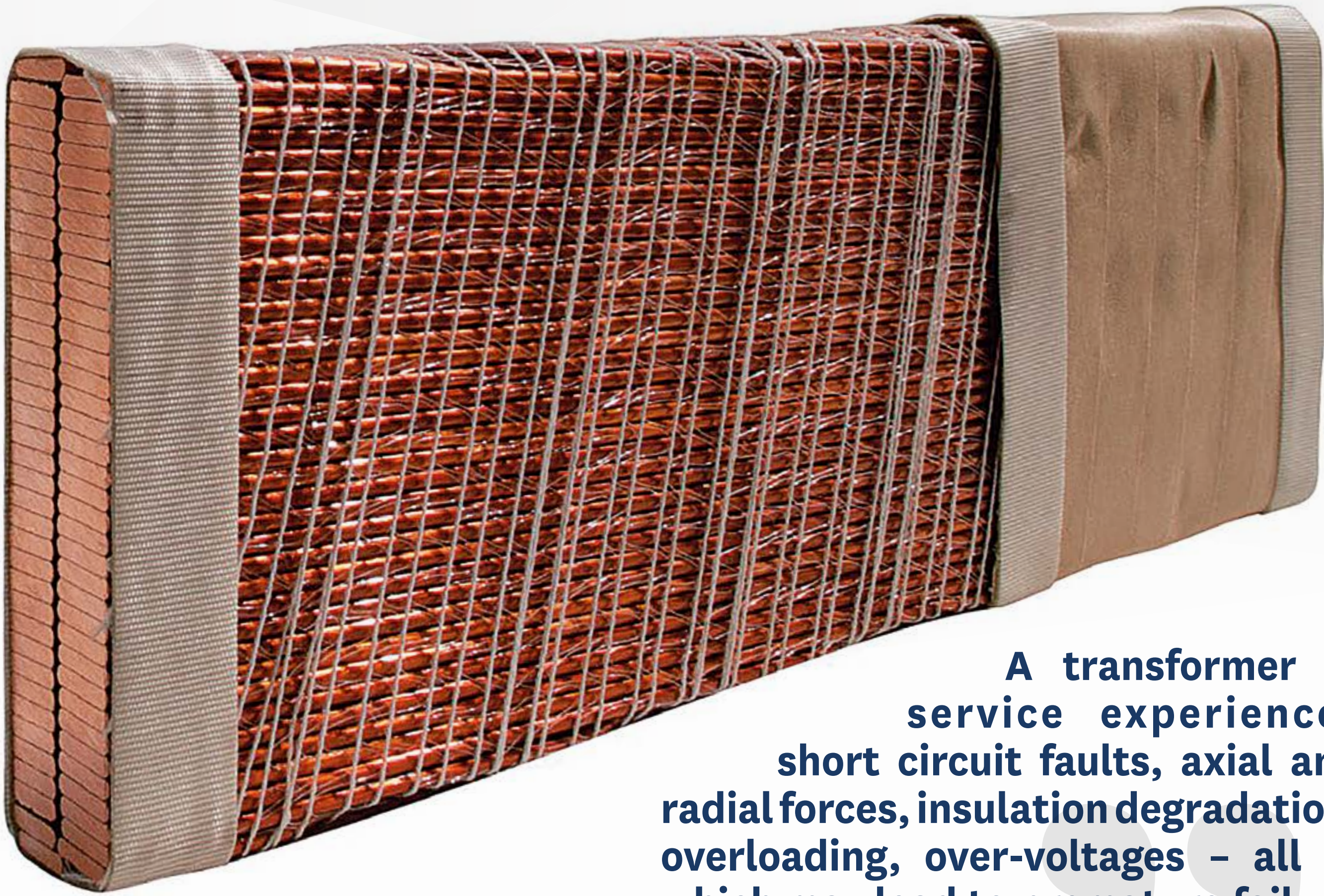

**A transformer in service experiences short circuit faults, axial and radial forces, insulation degradation, overloading, over-voltages – all of which may lead to premature failure**

# Role of copper in continuously transposed conductors


## ABSTRACT

This article explores the critical importance of the proper selection of copper, one of the key raw materials used in the making of continuously transposed conductors for extra high voltage power transformer windings. Windings are one of the most vulnerable components of a power transformer in terms of withstanding various types of electrical disturbances that lead to transformer failure. They have to satisfy complex transformer requirements, but also fit into the economics reasonably well in order to be competitive. Therefore, the expectations about the transformer health and longevity will largely depend on the right choice of its active components and the materials used in their production.



## KEYWORDS

continuously transposed conductors, CTC, copper, transformer windings


## 1. Introduction

It has always been a challenge for a power transformer designer to have a winding solution that not only satisfies complex transformer requirements, but also fits into the economics reasonably well in order to be competitive. With the growing market in the power sector, the demand for higher reliability index has also increased several folds. One such example is the imposition of additional five-year warranty for transformers by the Power Grid Corporation of India (PGCIL)[1] in case any defects, as specified in their contract, are observed within the

[1] PGCIL is the Central Transmission Utility of India with the 58:42 ratio of shareholding between the government and the public. It is one of the largest transmission utilities in the world with a total transformation capacity of 240,954 MVA. It has indigenously developed world's highest voltage 1,200 kV UHV AC technology and has recently commissioned world's longest multi-terminal ± 800 kV, 6,000 MW HVDC transmission line project in Agra.

warranty period of the transformer in service.

During its life cycle, a transformer undergoes short circuit faults, comprehensive axial and radial forces, a loss of insulation life due to degradation of oil/paper, overloading, lightning and switching transients – all of which may lead to premature failure of a transformer in service.

A sharp increase in premature failures of extra high voltage (EHV) power transformers and reactors has forced the energy supplying authorities to run a deeper analysis of the risks involved in such failures and a loss of huge revenue due to the resulting outage. Figure 1 presents an analysis of the main causes of power transformer failures recorded between 1997 and 2001 [1], while a similar analysis for a 20-year period between 1991 and 2010 is plotted in Figure 2 [2].

Insulation failure was the leading cause in the former study. Combined with the design/material/workmanship and unknown causes, these three categories accounted for 65 % of total failures and 85 % of the total amount paid out for the related claims.

Rearrangement in the categorization of causes in the latter study, both of which were done by the same group, paints a more compact picture.

Electrical disturbances included phenomena such as the switching surges, voltage spikes, line faults/flashovers, and other utility abnormalities, but excluded lightning. Windings (the main current carrying components) are considered to be the most vulnerable components of a power transformer when it comes to withstanding any of these electrical disturbances. All of the listed failures, directly or indirectly, cause huge stress in the transformer windings. While designing the transformer windings, a designer takes enough precautions to take care of such stresses and expects windings to remain healthy for the entire service life of the transformer – which could be at least 35-40 years. The expectation, however, largely depends on the right choice of active components. Out of many reasons of failures, one that is often given less attention is an improper selection of raw materials.

Copper is one of the key raw materials required in the making of continuously transposed conductors for EHV power transformers and this article is primarily dedicated to emphasizing the criticality of the proper selection of copper. The article will also briefly touch upon some important processing and quality check features, without which, despite using good raw materials, reliability of the finished product remains uncertain. It would be useful to have articles discussing other key raw materials, such as enamel, epoxy and insulation paper.

**Increase in transformer failures has forced the industry to run a deeper analysis of the risks involved in such failures, and huge revenue losses ensuing from the resulting outages**

## 2. Copper in continuously transposed conductors

In large power transformers, the current carrying conductors in the windings are made of copper strips. The size and number of these strips are decided by the transformer designer based on the capacity rating of the transformer. Efficiency and performance of transformers are greatly influenced by their losses (no-load and ohmic losses or $I^2R$). Energy losses can have a significant impact on the total life cycle cost of transformers since they have a very long lifetime.

Continuous improvements by the manufacturers of copper conductors in terms of reducing energy losses in transformers have resulted in many innovative designs – continuously transposed conductor

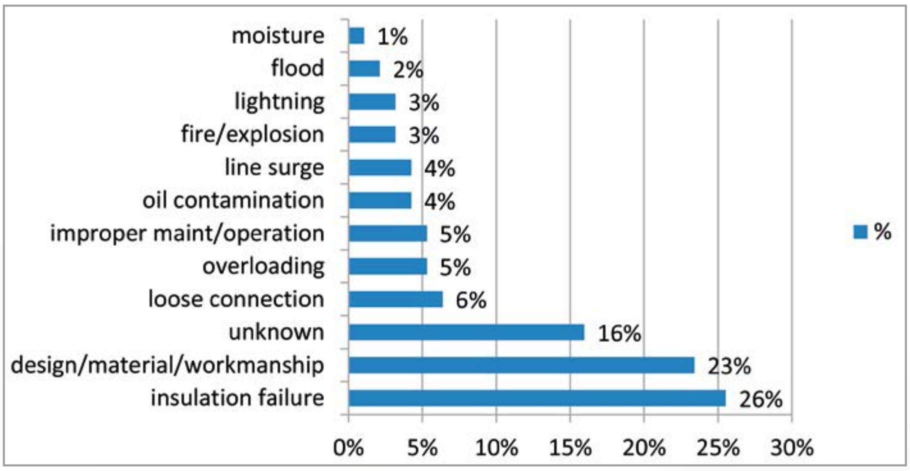


Figure 1. Causes of power transformer failures (1997-2001)

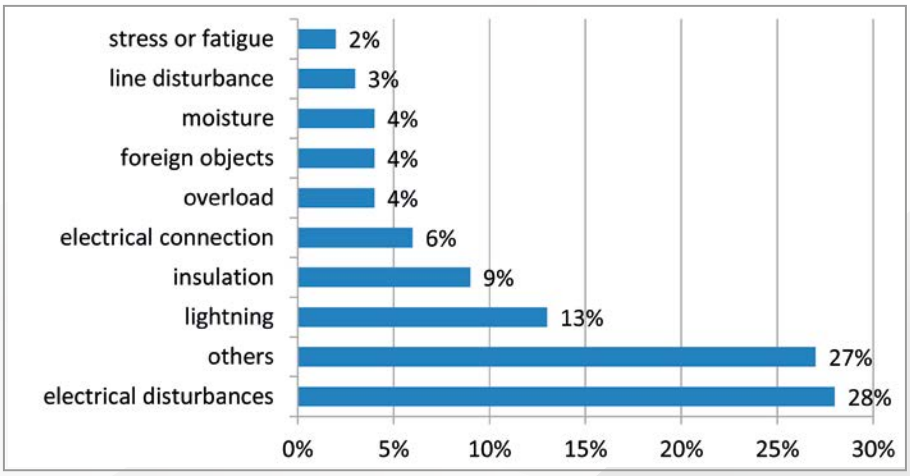


Figure 2. Causes of power transformer failures (1991-2010)

**Windings are considered the most vulnerable components of a power transformer when it comes to withstanding electrical disturbances**

Figure 3. An 8-mm-diameter copper wire rod

Figure 4. Drawn copper wire after the wire drawing stage

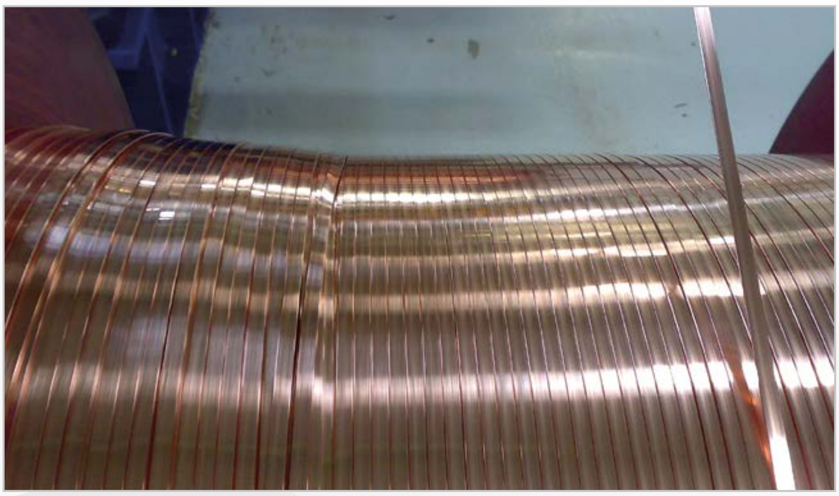

Figure 5. Flat bare strip after the flat rolling stage

(CTC) is one of them. Copper strips, individually insulated with enamel, are transposed together with a pre-designed pitch to form a well-knit bundle which is then helically wrapped with a defined number of layers of insulation paper to make a complete CTC.

A classic CTC is made in just four steps: round wire drawing, flat rolling, enamel/epoxy coating, and transposing.

An 8-mm-diameter copper wire rod, in coil form, is the most common size for making CTC and is sourced from copper wire rod manufacturers. Depending on the size of the copper strip required by the transformer designer, the 8-mm-diameter wire rod is first drawn into smaller diameter wires during the round wire drawing process, and then cold-rolled to the desired size of the flat strip during the flat rolling phase. The cold-rolled bare strips are hard and need to be annealed (to let the molecular structure recrystallize and allow the strip to become soft) before applying an enamel coating. The desired coating is achieved in steps through the fine incremental thickness of a few microns (in order to get perfect curing and flawless surface). It is done in highly precise temperature controlled vertical ovens. The strip may be further coated with epoxy, when high bonding properties are required in the CTC by the designer. Annealing, enamelling and epoxy coating are, in fact, completed in tandem during the same process, when the proof-stress ($Rp_{0.2}$)[2] requirement is less than 200 N/mm$^2$ as in-line proof-stress rollers are good enough to achieve such requirements. However, for higher proof-stress ($Rp_{0.2}$) requirements (≥200 N/mm$^2$), these in-line proof-stress rollers are not adequate and therefore off-line annealing is required. The desired high proof-stress of the strip is then achieved through the controlled re-rolling process, by running the annealed strip, once again, through the flat-rolling machine. In this case, while enamelling, the in-line annealing oven and proof-stress rollers are by-passed. In the final stage of CTC, called transposing, these coated strips are transposed together and covered with insulation paper or sometimes, for LV windings, with netting tape.

[2] $Rp_{0.2}$ is the yield strength as commonly applied to copper and copper alloys. It is the stress which will produce an extension of 0.20 % under load.

The CTC making process is illustrated in Figures 3-8.

It is important to note that copper wire rods, as received by the CTC manufacturer, must be inspected/tested for quality in accordance with a comprehensive quality plan that should include, apart from routine physical/dimensional/electrical/mechanical tests, a detailed metallographic and microscopic inspection of the copper wire rod specimens for detecting some of the serious defects like sub-surface oxides, inclusions, porosity, overlaps, grain structure, etc., Figs. 9-17.

While routine tests may be conducted in the CTC manufacturer's lab for each lot, the test for chemical composition of the copper wire rod (also indicating oxygen ppm) may be conducted on a monthly basis by an approved lab. Torsion test must be conducted on the samples from the incoming wire rod, the drawn round wire after round wire drawing and the bare copper strip after cold rolling to detect any splintering defects, Figs. 9 and 10. Acceptable samples are shown in Figures 18, 19 and 20. The frequency of this test may be decided based on the consistency of the supplied lots.

The eddy current losses (largest contributor to no-load losses) are reduced significantly by transposing the conductors. The overall compact shape of the CTC provides a better winding space factor (enhanced cooling of the windings), high short circuit stability of the windings and considerable decrease in capitalization cost.

Copper accounts for 94-98 % of the CTC depending on its size. Power transformer windings are largely made of electrolytic tough pitch copper (type ETP/ETP1), also identified by its chemical composition as UNS C11000 or C11040 [3]. A few more important grades of copper are listed in Table 1.

While properties of copper, as specified by most of the national and international standards (ASTM B-49 [3], EN 1977 [4], ISO 197-1 [5], ISO 197-2 [6], ISO 197-3 [7], etc.), cover wide ranging applications, one needs to add more specifics to its requirements when it comes to ordering copper for making CTC. Requirements of proof stress, grain size and torsion tests are some of such additions. All these special

**Continuous improvements introduced by the manufacturers of copper conductors in terms of reducing energy losses in transformers have resulted in many innovative designs – CTC is one of them**

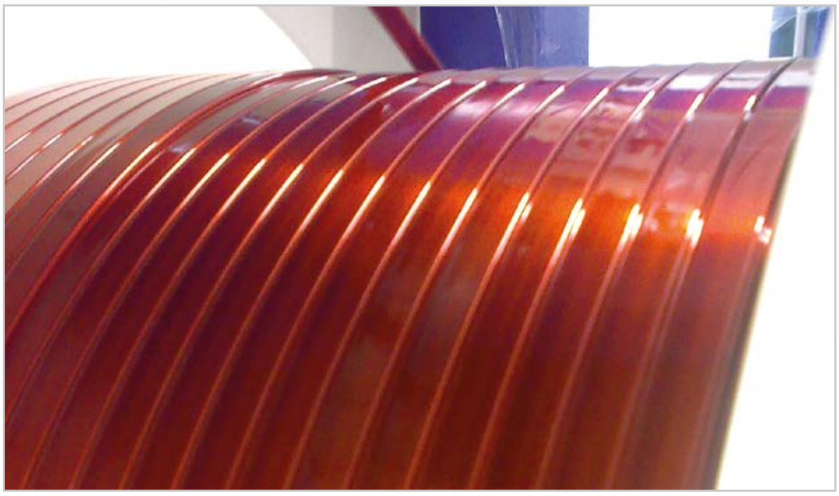

Figure 6. Enamel/epoxy-coated copper strip

Figure 7. Paper-covered CTC after transposing

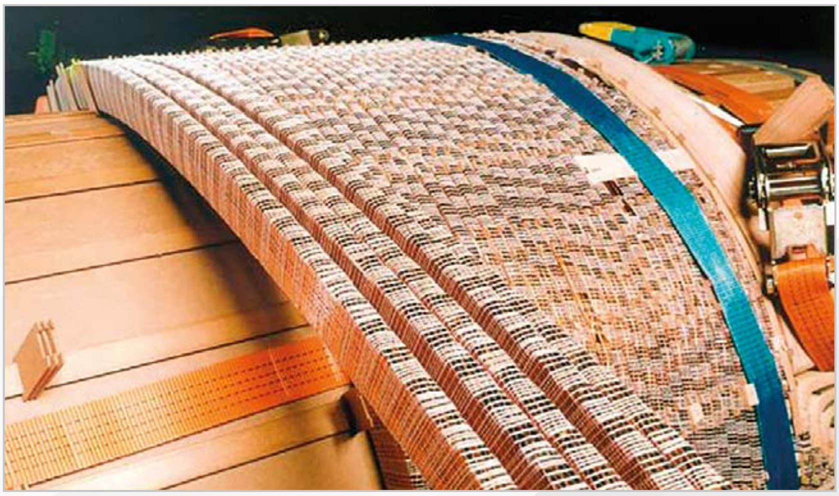

Figure 8. Netting-taped CTC after transposing

Table 1. Classification of copper according to ASTM B224

| Copper type as per ASTM B224 (Classification of copper): |
|---|
| ETP (UNS C11040) - Electrolytic tough pitch – *99.90 % purity excluding silver* |
| ETP (UNS C11000) - Electrolytic tough pitch – *99.90 % purity excluding silver* |
| OF (UNS C10200) - Oxygen-free – *99.95 % purity excluding silver* |
| OFE (UNS C10100) – Oxygen-free electronic – *99.99 % purity excluding silver* |
| STP (UNS C11300) – Silver-bearing electrolytic tough pitch |
| OFS (UNS C10400) – Oxygen-free, silver-bearing |

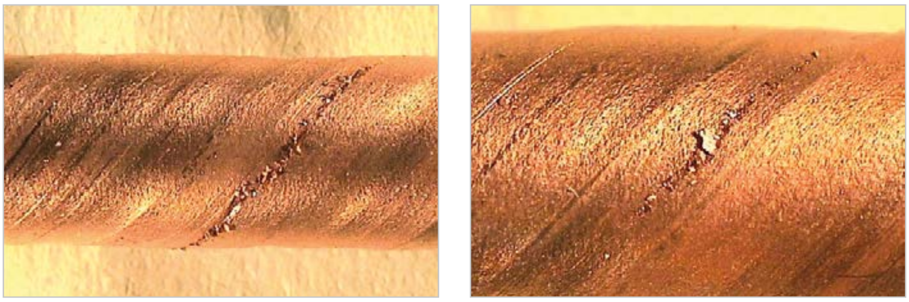

Figure 9. Torsion test failures at the point of receiving a copper rod: images show heavy splintering in an 8-mm-diameter copper rod

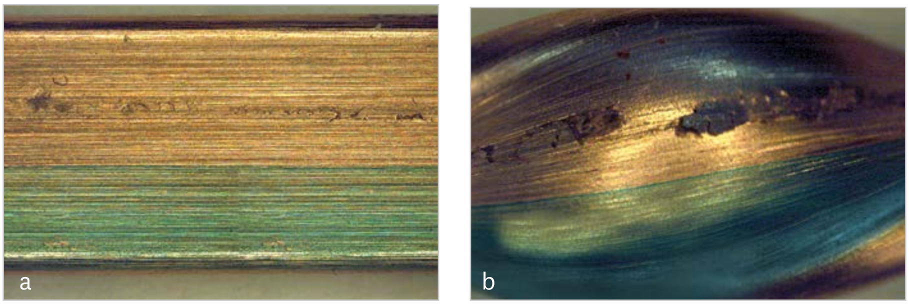


Figure 10. An effect of copper rod torsion test failures on cold-rolled copper strip: (a) before and (b) after the torsion test conducted at the strip stage – a vital processing stage for making CTC

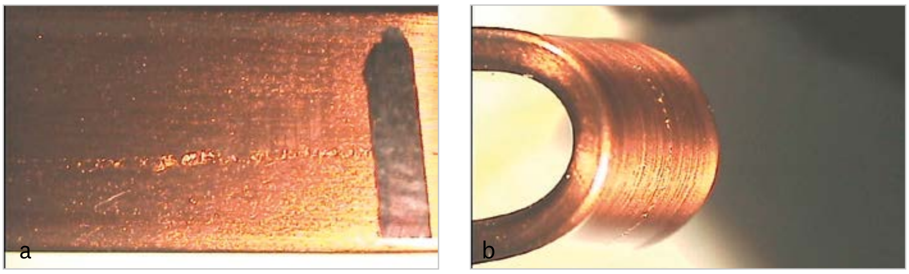


Figure 11. Heavy splintering on an enamelled strip (a) before and (b) after bending – a potential source of electrical failure in transformers

Figure 12. A 26 μm hole in the inner surface

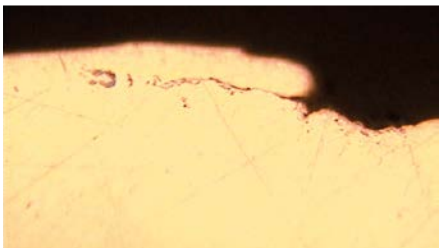

Figure 13. An overlap – a source of serious surface defect on the strip and electrical failure

requirements are vital for processing copper rods into fine quality strips suitable for making CTC.

Proof stress of copper coils between 90-120 N/mm$^2$ assures controlled spread during cold rolling of the flat strip. It is crucial for obtaining perfect corner radius and stable dimensions in terms of width and thickness. Over- or undersized round inlet wire results in an uncontrolled spread that may lead to dimension variation in width and uneven corner radius. The moderate hardness at coil stage also helps in shaping the rod before it is drawn into round wire of smaller diameter.

Like any other engineering material, the microstructure of copper is related to its composition, properties, processing history and performance. Therefore, studying microstructure of copper provides information linking its composition and processing to its properties and performance. Microstructural features such as grain size, inclusions, impurities, second phases, porosity, segregation and surface effects are a function of the starting material and subsequent processing treatments. These microstructural features affect the properties of a material. While impurities adversely affect the conductivity and recrystallization temperature, Figs. 21 and 22, inclusions could lead to partial discharge. Poor microstructures exhibit poor electrical, thermal and mechanical properties contributing to risk of higher losses. Grain size of copper plays an important role in the selection of right quality of copper for CTC. Figures 23 and 24 show cross-sections of acceptable grain sizes between 10-15 micron for the copper rod and the copper strip, respectively, for better mechanical and electrical properties, which also improves processing ability.

**Copper strips, insulated with enamel, are transposed together to form a well-knit bundle, which is then helically wrapped with insulation paper to make a complete CTC**

Figure 14. A big oxide lump

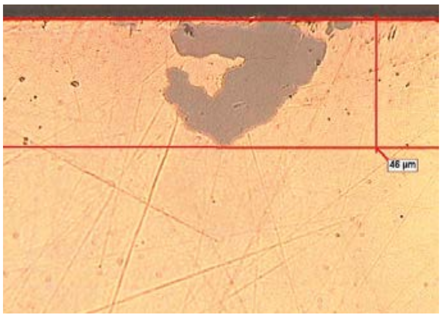


Figure 15. A big oxide inclusion at 46 µm deep

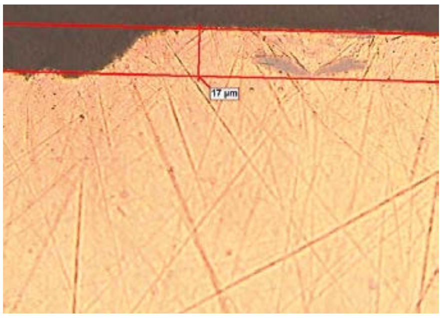


Figure 16. An oxide at 17µm with a groove

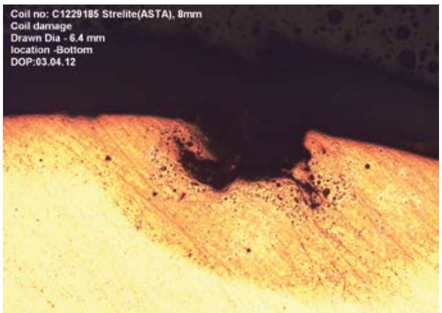


Figure 17. A deep cut on the copper rod

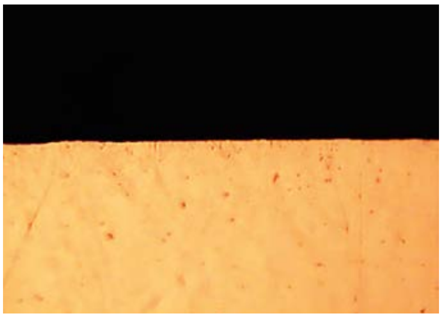

Figure 18. An acceptable Cu-rod after the met test

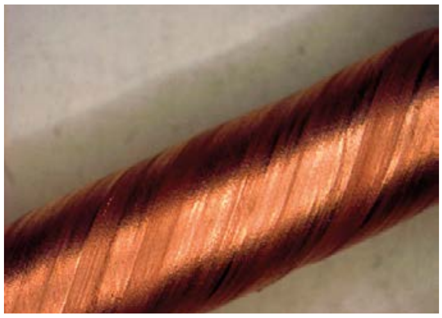

Figure 19. An acceptable Cu-rod after the torsion test


Figure 20. A flawless Cu-strip after the torsion test

Torsion test of copper rods is probably the most revealing test about the supplier's ability to produce quality copper rods for CTC. Any kind of surface defects, whether superficial (dents, grooves, seams, cracks, etc.) or sub-surface (oxide inclusions, impurities, holes, etc.), get exposed in this test. These surface/sub-surface defects are the worst kind of quality hazard that, if go undetected, could be disastrous at any later stage of processing, Fig. 10. Conductors with such defects are susceptible to failure due to electrical stress and may develop hotspot and eventual failure of solid insulation when the transformer encounters turbulent conditions, even for a short time.

**A classic CTC is made in just four steps: round wire drawing, flat rolling, enamel/epoxy coating, and transposing**

Illustrations of such defects and their impact down the line are shown in Figures 9-11.

Sub-surface defects in the copper rod can be detected through metallographic inspection of the transverse section specimen of the copper rod. Some of the metallographic images capturing such defects are shown in Figures 12-17. All these defects have deleterious effect on the long term health of power transformers and may shorten their life. They all, in one way or another, may contribute to hotspot, initiation of corona discharge leading to failure of insulation paper and generation of fault gases in transformer oil and eventual failure of transformer.

Proper selection of the copper rod is, therefore, crucial for making fine quality copper strips for CTC. An acceptable copper rod after the metallographic test and after the torsion test is illustrated in Figures 18 and 19, respectively. A cold-rolled copper strip, after the torsion test, made of such copper rod – which is free from any defects shown in Figures 9-17 – is presented in Figure 20.

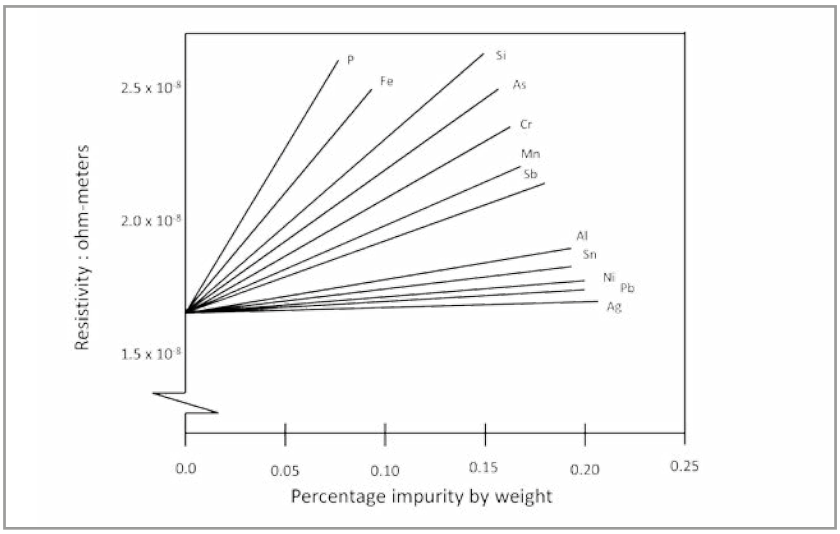


Figure 21. Effect of impurity elements on the resistivity of copper at room temperature

**The quality of copper rods for CTC must be tested, including a detailed metallographic and microscopic inspection to detect defects such as sub-surface oxides, porosity, overlaps, etc.**

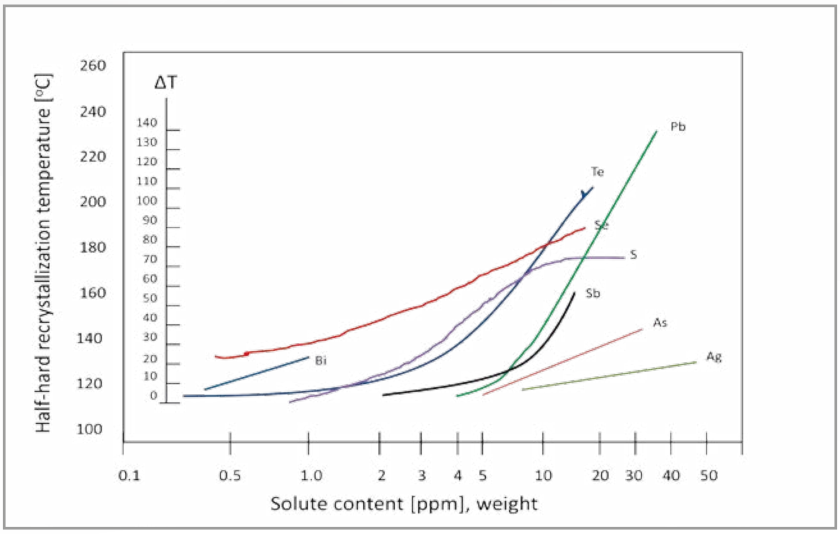


Figure 22. Effect of single-element additions to ETP copper on the half-hard crystallization temperature

Figure 25 shows the copper strip after it has been coated with enamel. Enamelling process is at the heart of the CTC making process and is responsible for all crucial physical, mechanical, electrical and thermal properties of the final CTC product. Some of its varieties are shown in Figures 7 and 8. All tests mentioned in this article with respect to copper are conducted at the CTC manufacturer's lab. All images shown in Figures 9-20 and Figures 23-24 have been collected from ASTA's Quality Labs and its facilities in Austria and India[3].

[3] ASTA Group (known as ASTA Energy Transmission Components), having its three manufacturing facilities – one each in Austria, China and India, manufactures and supplies winding wires to almost all major manufacturers of power transformers and generators globally. It is owned by Montana Tech Components AG, Austria.

Table 2. Comparison of the typical properties of Cu-ETP and Cu-OF [9]

| Typical properties of three types of a 8-mm-diameter copper redraw wire rod | | | |
|---|---|---|---|
| **8 mm rod type** Test/Units | **Contirod® Cu-ETP-1** | **SCR® Cu-ETP-1** | **Conticast® Cu-OF-1** |
| Yield STR,Rp$_{0.2}$ [N/mm$^2$] | 110 | 120 | 110 |
| UTS Rm [N/mm$^2$] | 226 | 234 | 175 |
| Fracture elongation A$_5$ [%] | 59 | 56 | 57 |
| Conductivity [%] IACS | 101.5 | 101 | 101 |
| Oxygen content [ppm] | 210 | 325 | 2 |

*Note: The above products were all manufactured from Cu-CATH-1 specification raw material.*

## 3. Copper for high proof stress requirement

For higher proof stress requirements (Rp$_{0.2}$ > 240 N/mm$^2$), it is recommended to go for silver-bearing electrolytic tough pitch copper [8] (Cu-Ag 0.10, STP UNS C11300, see Table 1). Presence of silver in copper acts as an anti-softening agent. It increases the recrystallization temperature of copper to counteract annealing and subsequent reduction of tensile strength of conductors at higher operating temperatures. It prevents buckling/collapsing of windings under short circuit conditions where extreme electro-mechanical forces are encountered.

## 4. Oxygen-free copper vs. electrolytic tough pitch copper

Electrolytic tough pitch (ETP) copper is the most common copper, universal for electrical applications. ETP has a minimum conductivity rating of 100 % IACS[4] and is required to be 99.9 % pure. Typically, it has 0.02 % to 0.04 % oxygen content. Most ETP sold today will meet or exceed the 101 % IACS specification.

ETP copper is the standard electrical conductor with the best electrical conductivity available in copper conductors and is by far the lowest cost material because of the method used to produce ETP copper. It has closely controlled addition of oxygen (150-400 ppm) added to the alloy during melting for the purpose of oxidizing impurities and maximizing the electrical conductivity.

With oxygen-free (OF) copper, according to the standard ASTM B49-10 [3] silver (Ag) content is counted as copper (Cu) in its chemical composition for purity purpose. Any impurity adversely affects the electrical properties, Fig. 21. Typically,

[4] The International Annealed Copper Standard (IACS) is a standard established in 1994 by the United States Department of Commerce [10]. The standard was established in 1913 by the International Electrotechnical Commission (IEC) for the conductivity of commercially pure annealed copper. The Commission established that, at 20 °C, commercially pure, annealed copper has a resistivity of 1.7241x10-8 ohm-meter or 5.8001x107 Siemens/meter when expressed in terms of conductivity. For convenience, conductivity is frequently expressed in terms of percent IACS. A conductivity of 5.8001x107S/m may be expressed as 100 % IACS at 20 °C. All other conductivity values are related back to this standard value of conductivity for annealed copper.

oxygen-free coppers are not entirely free of oxygen; however, oxygen-free copper will have less than 10 ppm oxygen. The primary purpose of low oxygen content in these grades is to prevent hydrogen embrittlement when the copper conductor may be in contact with hydrogen bearing gas at high temperatures (above 400 °C).

ETP copper is not recommended for use in hydrogen environments because of its susceptibility to hydrogen embrittlement when exposed to these temperatures. Many applications specifying oxygen-free copper are over specified and may use ETP copper for conducting electrical currents.

OF copper is valued more for its chemical purity than its electrical conductivity. It is used in the manufacture of semiconductors and super-conductor components. It is critical to use OF copper in applications where the release of oxygen (and other impurities) can cause undesirable chemical reactions with other materials in the local environment, Figs. 26 and 27. For the comparison of ETP and OF copper properties, see Table 2.

Power transformers, if subjected to operate in hydrogen environments, are not recommended to use ETP copper for their windings. OF copper, instead, is used in this case.

## 5. Influence of impurity elements in copper

Establishment of high electrical conductivity is influenced by the presence of impurity elements in the copper [11]. The most harmful of these elements can significantly decrease electrical conductivity, increase the mechanical strength of the annealed wire, retard recrystallization, and will sometimes induce hot shortness (cracking) during the hot rolling process in the production of rod. Many investigations have shown that very small addition of these impurities can increase the resistivity of copper in a linear manner, Fig. 21, while many impurities increase the half-hard recrystallization temperature in a non-linear manner, Fig. 22.

Oxygen acts as a scavenger in reacting with most of the impurities which have their most serious effect on the properties and annealing response when they are dissolved in copper matrix. In contrast, harmful effects may be nullified when impurities are tied up as an insoluble oxide. The maximum conductivity of copper occurs at approximately 200 ppm of oxygen. Consequently, oxygen content for ETP coper is in the range of 175-450 ppm. While lower oxygen values have a hot cracking tendency resulting from uncombined impurities, oxygen values in excess of this range have an adverse effect on formability. Actual oxygen content is a compromise between attaining better annealing behaviour and avoiding possible drawability problems.

**Enamelling process is at the heart of the CTC making process and is responsible for all crucial physical, mechanical, electrical and thermal properties of the final CTC product**

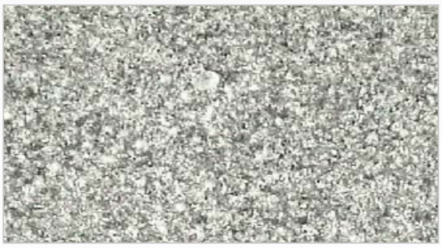

Figure 23. Grain size of a Cu-rod: 10-15 μm (cross-section of copper rod)

Figure 24. Grain size of a Cu-strip: 10-15 μm (cross-section with corner radius)

It is desirable to limit the amount of cold work prior to the final anneal in order to have good conformability (the ability of wire to hold its shape during forming or winding with minimal spring back).

## 6. Surface defects

At ambient temperature, copper wire always contains a residual oxide film that originates from the rod making stage. The oxide films can be quite deleterious – leading to generation of defects during drawing, excessive wear of drawing dies, inadequate solderability and poor adhesion between enamel coating and bare conductor. Surface defects in copper rod include slag and copper oxide inclusions, hot cracks, slivers, foldovers, insufficient removal of scales, or coining of oxide particles into the rod surface. Most of the intermetallic inclusions are brittle and lead to crack initiation and propagation in the as-drawn wire. With respect to defects, CTC strips are the most critical product to produce.

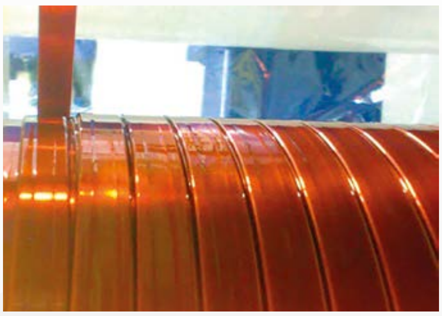

Figure 25. A fine quality enamelled strip

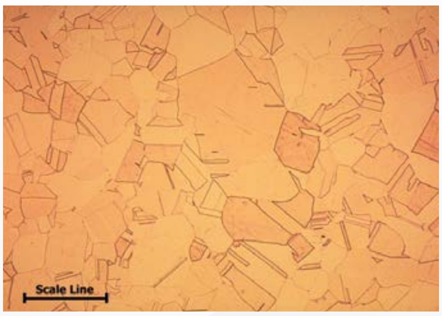


Figure 26. Nom composition – 99.99 %: rod, Cu-OFHC (C10100), where chemical purity is more important

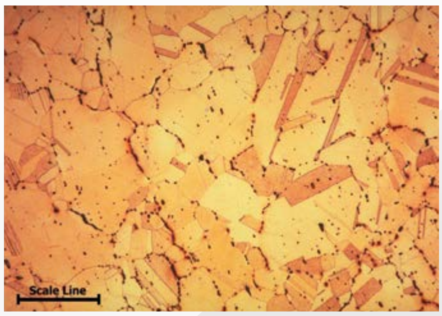


Figure 27. Nom composition – 99.99 %: embrittled, Cu-ETP (C11000) in hydrogen environments

**Conductors with defects are susceptible to failure due to electrical stress, and may develop hotspot and eventual failure of solid insulation when the transformer encounters turbulent conditions**

Surface defects may also originate from wire drawing in the form of die marks, mechanical damage, gouges or slivers. Slivers form during drawing when the wire tends to be free from entrapped oxides. Surface damage is often caused by misalignment of the moving wire within the drawing machine or by the compaction of copper fines inside the throat of the wire drawing die.

## Conclusions

Power transformers are highly capital intensive investments which are designed to last for an average life of 40 years. Any premature failure is a huge loss. An estimated cost of raw materials accounts for 57-67 % of the total cost of a power transformer, out of which 18-27 % is for copper itself and 22-24 % is for the electrical steel [12]. There have been a number of innovations over the last decades, both in the design and quality of active materials, in order to improve the life of transformers and capitalization cost of investment.

This article has tried to focus on the quality aspect of the electrical windings, which largely relies on the quality of incoming copper itself received by the manufacturers of winding wires from copper suppliers in the form of coiled rods. The defects in the copper coiled-rod may be transmitted to the final product despite best inspection and control. Therefore, it is extremely important to let the copper rod suppliers understand thoroughly the kind of defects in their supply and the consequences to the end users. Constant dialogue and exchange of quality/processing information between the CTC manufacturers and the copper rod suppliers needs to be improved in order to improve the quality of the supplied copper.

It has been a major concern for the CTC manufacturers to have defect-free copper rod with superior drawability. To help reduce the problem of high quantity of surface defects in wire, emphasis is being placed on improvements in the rod surface quality, drawing lubricants, filtration of solid particulates, and production of synthetic single crystal diamond drawing dies.

An impending challenge for the copper rod suppliers is to develop more sensitive sensors for the non-destructive detection of defects on rods using non-contact test methods. Many harmful surface defects are too small to be detected by the eddy-current inspection equipment which is currently in use. In addition, on-line inspection equipment needs to be developed to easily detect the presence of macro-porosity and other internal defects.

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[3] ASTM B49-10, Standard Specification for Copper Rod Drawing Stocks for Electrical Purpose

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