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TECHNICAL DOCUMENT · CUSTOMER TECHNICAL RESPONSE

Copper-Clad Aluminum Enamelled Wire for Inductor Applications

Item-by-item responses to thirteen customer technical queries

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1. Background and overall position

The customer raised thirteen technical queries on the feasibility, reliability and verification path of replacing copper wire with copper-clad aluminum (CCA) enamelled wire in inductor applications. This document answers each query in turn: a conclusion first, followed by the supporting explanation and data. It is intended for the customer's technical evaluation and design-in decision.

- **Maturity.** CCA enamelled wire has been in volume production for inductor applications for more than fifteen years, in both round and rectangular profiles. It is one of the mainstream solutions for common-mode chokes, PFC chokes and PV/storage inverter inductors, not an experimental substitution.
- **Nature of the difference.** Against copper there are exactly two substantive differences: mechanical strength and melting point. Both are process-fit issues that can be resolved through wire sizing, tension setting, bend radius and soldering practice. Neither represents a reduction in reliability class.
- **The real boundary is temperature.** Insulation ageing and the growth of intermetallic compound at the copper-aluminium interface are both governed by hot-spot temperature. Holding the long-term hot spot below the thermal class with a 15–20 °C margin is the precondition for long-term reliability.
- **Inspectability.** An inductor can be fully inspected once wound. Any conductor or enamel defect presents visibly as exposed aluminium, wire breakage, pinholes or dielectric failure, and is therefore 100% detectable. This is the fundamental reason the solution carries far lower risk in inductors than in motors or oil-immersed transformers.

2. Query index and key responses

The table below summarises the response to each query for quick cross-reference with the original list.

Table 1 Query index and key responses

No.	Query	Topic	Key response
1	Power range of inductors served	Application	0.5–20 mm² in volume, from appliances to C&I solar
2	Drawbacks and reliability risks vs copper	Reliability	Lower mechanical strength only; a process issue
3	Suppliers and customers	Supply	Rectangular: we lead; round: widely available

No.	Query	Topic	Key response
4	Assuring reliability in processing	Reliability	Incoming, in-line and 100% final electrical test
5	Assuring long-term reliability in service	Reliability	Temperature control; encapsulation against moisture
6	Defects seen in volume use	Reliability	No significant increase; on par with copper
7	Sizing rule for the same current	Selection	1.20–1.25× diameter at equal resistance; 1.10–1.15× for inductors
8	Round or rectangular today	Application	Both in volume; rectangular dominant in CM chokes
9	Detecting damage during winding	Process	Enamel cracking and copper rupture are both detectable
10	Copper layer thickness and copper content	Material	Graded per GB/T 29197; tighter internal control
11	Effect of interfacial intermetallics	Material	Very thin; negligible electrically, affects elongation
12	Verification for HF / high current duty	Verification	Wire-level data by us; component-level by OEM
13	Avoiding exposed aluminium and solder fatigue	Process	Exposed Al is screened out; fatigue on par with copper

3. Responses to each query

1 Which power range of inductors does CCA wire mainly serve today?

> **CONCLUSION** We define the product by conductor cross-section and current rather than by power rating: the full 0.5–20 mm² range (approximately AWG 20–4) is in volume supply. In end equipment this corresponds most often to PFC chokes and reactors in inverter appliances, boost and filter inductors in PV and storage inverters, and common-mode chokes of all types.

1.1 Where it is used

- Common-mode and filter chokes: round wire and rectangular vertical winding coexist, with a high share of rectangular.
- PFC chokes and reactors: the main landing point in inverter air conditioners, heat pumps and charging modules.
- Inverter-side filter and boost inductors: PV string inverters, storage PCS.
- HF transformers and resonant inductors: switching supplies, LED drivers, telecom rectifiers.

1.2 Typical equipment power (indicative, not a restriction)

Table 2 Typical applications and equipment power

Application	Typical power	Usual profile	Main constraint
Inverter A/C and heat-pump PFC chokes	1–5 kW	Round 0.5–3 mm², rectangular	Temperature rise, fill factor
PV micro and string inverters	1–50 kW	Round, rectangular vertical	Temperature rise, DC resistance
Storage PCS, C&I inverters	5–100 kW	Rectangular 4–20 mm²	High current, heat dissipation
Charging modules, on-board chargers	3–40 kW	Rectangular, round	Power density, solderability
Telecom and server power supplies	0.5–5 kW	Round 0.2–1.5 mm²	HF loss

1.3 Why a power-band classification does not work

At the same power level, topology (PFC, LLC, phase-shifted full bridge), switching frequency, core material and permissible temperature rise all differ, so inductor current may range from a few amperes to several hundred. Selecting wire by power band is therefore imprecise. Standard engineering practice is to work back from RMS current, ambient temperature, permissible rise and available winding window to the required equivalent DC resistance and minimum wire diameter.

1.4 Selection support we provide

Given Irms, ambient temperature, permissible rise and available winding dimensions, we will return an equivalent DC resistance calculation, a diameter recommendation and two or three alternative options with copper content, weight and cost comparison within two working days.

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2 Compared with copper wire, what are the drawbacks and reliability risks of CCA in inductors?

> **CONCLUSION** The only substantive difference is mechanical strength: tensile strength and elongation are below those of soft copper wire of the same size (typically 50–70% of the copper value, depending on copper volume fraction and temper). With incorrect winding tension, or with fine wire over long spans, this appears as breakage and enamel damage. In every other respect — conductivity after equivalent sizing, insulation, heat resistance and solderability — CCA matches copper.

2.1 Four differences that must be acknowledged

- **Lower tensile strength and elongation.** Soft copper wire reaches roughly 200–250 MPa with elongation above 25%. In CCA the aluminium core dominates the cross-section, so both values are markedly lower. The remedy is to set tension at 70–80% of the copper value and to increase the radius of guide pulleys.
- **Lower melting point.** The aluminium core melts at about 660 °C and the copper-aluminium eutectic at the interface at about 548 °C, both far below copper at 1083 °C. The allowable temperature under short-time overload is therefore lower, and the equipment's short-circuit and overload protection must be confirmed not to reach this region.
- **Bend fatigue.** The copper-aluminium interface may delaminate under repeated bending. The national standard assesses this by torsion and repeated-bend tests. Avoid repeated bending at the pin root and keep the bend radius at

least twice the wire diameter.

- **Solderability depends on copper layer thickness.** Soldering relies on the outer copper. A thin copper layer limits the number of re-soldering operations. Select grade 15A or 20A for solder-intensive processes and use thermal or chemical stripping rather than mechanical scraping.

2.2 Aspects that testing and volume production show are not risks

- DC resistance: equivalent to copper once the diameter is scaled for equal resistance (see item 7).
- Insulation: the same enamel systems, dielectric and pinhole standards and the same processes as copper wire.
- Thermal class: qualified to GB/T 6109 and IEC 60317; classes 130, 155 and 180 are all available.
- Long-term electrochemical corrosion: heavy-gauge wire is fully covered by enamel, and the termination is sealed by solder, so no corrosion path exists (see item 5).

In summary: the four items above are engineering risks that disappear once the design is correctly sized and the process correctly set. They are not inherent reliability defects of the material. Fifteen years of volume application and customer field data support this position. Where an application involves wire below 0.1 mm, high frequency with high voltage, or severe vibration, a separate assessment is required and we do not recommend applying the conclusions of this document directly.

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3 Which CCA suppliers are in use, and which customers have adopted CCA solutions?

> CONCLUSION For rectangular wire, including the large width-to-thickness vertical-wound grades, we are currently the principal domestic source. For round wire, the drawing and enamelling barrier is lower and most enamelling plants can produce it, but quality dispersion is wide. We recommend qualifying suppliers on copper volume fraction, minimum copper layer thickness, elongation and pinhole count rather than on unit price alone.

3.1 Supply landscape

The technical difficulty in round wire lies in copper layer uniformity and annealing control. Most enamelling plants can produce it, but batch-to-batch stability of copper volume fraction and elongation varies considerably. Rectangular wire is harder: uniformity of the copper layer across the wide face, plus a dedicated enamel system that survives vertical winding. Very few domestic suppliers can deliver it consistently in volume. We are among the largest producers of CCA enamelled wire, with rectangular profiles as our main product line.

3.2 Customer base

Specific customer names are subject to confidentiality agreements and are not listed here. The industry distribution can be stated: inverter appliances (air conditioning, heat pumps), PV inverters and storage, charging infrastructure, telecom and server power, and on-board chargers — the first two representing the largest share. On request, and with the consent of the customers concerned, we can arrange a reference technical discussion or a factory audit, including witnessing copper layer metallography, in-line inspection and the annealing process.

3.3 Four qualification criteria for buyers

- Measured copper volume fraction by weighing or metallography — not a verbal claim of "10% copper".

- Minimum copper layer thickness, assessed as a percentage of nominal diameter (see item 10).
- Batch-to-batch consistency of elongation and tensile strength; the range across three consecutive batches is more informative than a single mean.
- Pinhole count and dielectric pass rate, the most direct indicator of enamelling process capability.

4 How is reliability assured during processing?

> **CONCLUSION** Through three layers of control — full incoming inspection, in-line inspection and 100% final electrical test — which convert any conductor or enamel anomaly into a measurable, rejectable, visible defect. CCA does not require special detection methods; it requires existing methods to be applied at the right points.

Table 3 Process control points and inspection methods

Stage	Control point	Method	Acceptance
Incoming	Copper volume fraction, minimum thickness, elongation	Weighing, metallography, tensile test	Per GB/T 29197 and datasheet
Incoming	Enamel continuity, adhesion, solderability	Pinhole, peel and solder tests	Per GB/T 6109, thermal class
Winding	Tension setting and fluctuation	Servo closed-loop, fluctuation ≤ ±5%	70–80% of copper tension
Winding	Wire path and pulley condition	Surface check, radius ≥ 3d	No burrs, free rotation
Winding	First-off and patrol	Pinhole, dielectric, DC resistance	Zero pinholes, dielectric pass
Final	Turn-to-turn and layer insulation	100% impulse or power-frequency test	Per customer safety requirement
Final	Appearance and exposed aluminium	100% visual (silver-white streak = exposed Al)	Zero defects

4.1 Tension is the only parameter that must be re-established

The winding process for CCA is essentially that for copper; the only parameter that must be re-established is tension. The practical setting is 70–80% of the tension used for copper wire of the same size, with acceptance judged by absence of visible elongation during winding, an even traverse and no spring-back. Excessive tension is the primary cause of enamel cracking and breakage; insufficient tension produces a loose traverse and poor fill factor.

4.2 Final inspection is the last and most reliable line of defence

Once the inductor is wound, any conductor or enamel anomaly shows up in one of three ways: exposed aluminium (visible as silver-white), wire breakage (winder alarm), or pinholes and dielectric failure (electrical test). All three can be inspected 100%, so there is no path by which a latent defect reaches the customer.

5 How is long-term reliability assured in service?

> **CONCLUSION** Two variables: temperature, and moisture with ionic contamination. Keep the hot spot within the thermal class with a 15–20 °C margin and the interfacial intermetallic layer stops growing; isolate moisture and ionic contamination by dipping or encapsulation and the electrochemical corrosion path is cut. Beyond these, CCA and copper behave identically over time.

5.1 Temperature: the only hard constraint

Insulation ageing follows Arrhenius behaviour, with life roughly halving for every 8–10 °C rise in hot-spot temperature. Intermetallic growth at the copper-aluminium interface is likewise driven by temperature and time. Holding the long-term hot spot 15–20 °C below the thermal class therefore controls both at once. In practice the criterion should be the measured hot spot under worst-case conditions — highest ambient, maximum load, worst thermal orientation — not the average temperature rise.

5.2 Corrosion: not a risk at heavy gauges

Electrochemical corrosion requires three conditions simultaneously: two metals of different potential, an electrolyte, and a connected ionic path. Inductor-grade CCA is heavy gauge, fully covered by enamel and sealed at the terminations by solder or terminals, so none of the three holds. Corrosion therefore need not be considered in this application. Where the application involves prolonged high humidity or sulphur- or chlorine-bearing atmospheres — coastal sites, chemical plant, outdoor cabinets — we recommend overall dipping after winding (vacuum dipping preferred) or encapsulation as a redundancy measure. This is standard practice at modest additional cost.

5.3 Mechanical and termination practice

- Avoid repeated bending at the pin root; keep the bend radius at least twice the wire diameter and add a strain-relief loop where needed.
- Terminate by copper terminal crimping or complete solder coverage, so the aluminium core end face is not left exposed.
- Stake or bond the winding to the bobbin to suppress fretting from vibration.

6 What defects have occurred in service with aluminium wire (i.e. CCA) compared with copper?

> **CONCLUSION** Across current volume supply and customer mass-production data, no significant increase in defects attributable to the CCA conductor has been observed. Breakage rate, enamel defect rate and electrical reject rate sit in the same band as copper wire of the same size; the differences fall within normal batch variation.

6.1 Defects actually seen, and their attribution

Classifying the exceptions reported by inductor customers over recent years, virtually all fall on the process side rather than the material side: breakage and enamel cracking from excessive tension; scoring and exposed aluminium from worn or burred pulleys; solder defects from incorrect stripping; copper layer cracking from too small a bend radius. These occur

with copper too. The difference is that CCA has a slightly lower threshold and is more sensitive to process parameters, which raises the requirement on equipment maintenance and parameter discipline.

6.2 Data we can provide

- Twelve-month shipment inspection summary: breakage rate, pinhole count, dielectric pass rate, DC resistance distribution.
- Comparative test results against copper of the same size: tensile strength, elongation, solderability, heat resistance.
- Root-cause analysis of a specific customer defect mode, reported within two weeks of receiving samples.

One clarification: if a customer's mass-production data show a CCA-specific defect pattern — systematic exposed aluminium or a batch-wide breakage issue, for example — it almost always points to a specific process parameter or incoming batch rather than to a general weakness of the material system. Such cases can be traced batch by batch through copper volume fraction and annealing records to the specific stage involved.

7 What is the sizing rule for carrying the same current?

CONCLUSION Take equal DC resistance as the basis: CCA at 10–15% copper volume fraction requires 1.45–1.55 times the cross-section, corresponding to 1.20–1.25 times the diameter. For inductors, because current waveform, permissible rise and window margin differ, practice is usually 1.10–1.15 times the diameter; for motors, where efficiency and temperature rise are tighter, 1.20–1.25 times.

Table 4 Diameter and weight ratios against copper of the same size (copper = 1.00)

Basis	Area ratio	Diameter ratio	Weight ratio	Application
Equal area (no upsize)	1.00	1.00	0.37–0.41	Large current margin, short-time duty
Equal DC resistance	1.45–1.55	1.20–1.25	0.53–0.58	Motors, transformers, continuous full load
Equal temperature rise	1.21–1.32	1.10–1.15	0.45–0.49	Inductors, reactors

7.1 Basis of calculation

At 20 °C the resistivity of copper is 0.01724 Ω·mm²/m; CCA at 10% copper volume fraction is about 0.0266 Ω·mm²/m and at 15% about 0.0258 Ω·mm²/m, with densities of 8.89, 3.33 and 3.63 g/cm³ respectively. For equal resistance, grade 10A requires 1.54 times the area (1.24 times the diameter) and grade 15A requires 1.50 times the area (1.22 times the diameter). The ranges above follow directly.

7.2 Why 1.10–1.15 is sufficient for inductors

Inductor current carries substantial ripple, and the ratio of RMS to peak value depends on topology; copper loss is usually a smaller share of total loss than in a motor. The winding also has a short thermal path and often a higher permissible rise. The combined effect allows a smaller upsize in exchange for winding window. This must nevertheless be confirmed by a temperature-rise test rather than assumed.

7.3 Two cautions

- Upsizing consumes winding window; check fill factor, window utilisation and core saturation margin at the same time, so that the conductor fits as well as performs.
- Do not substitute at equal cross-section. Equal-area substitution raises DC resistance by about 50%, with a corresponding increase in copper loss and degradation of both temperature rise and efficiency.

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8 Is CCA mainly round wire or rectangular wire today?

> **CONCLUSION** Both are in volume production. Round wire has more than fifteen years of application history and remains the larger installed base; rectangular wire, including vertical-wound grades, has grown fastest in recent years in common-mode chokes and high-power PFC and inverter inductors, driven by fill factor, low DC resistance and heat dissipation area.

8.1 Size coverage

Round wire is normally ϕ0.20–3.0 mm (about 0.03–7 mm²); rectangular wire is normally 0.5–20 mm² at width-to-thickness ratios of 2–15, with wider sections available on request. The full 0.5–20 mm² range mentioned by the customer is in stable supply.

8.2 Selection tendency

- Common-mode chokes and high-current filter inductors: rectangular vertical winding, for fill factor and heat dissipation.
- Low and medium power PFC and resonant inductors: round wire, for winding efficiency and cost.
- High-frequency applications: rectangular has the greater advantage, since a larger share of the section remains effective under skin effect.

It should be noted that rectangular wire is technically more demanding than round: copper layer uniformity across the wide face, and enamel flexibility sufficient for vertical winding, are both difficult. This is why few domestic suppliers offer it consistently.

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9 Aluminium is sensitive to tension — how is CCA damage detected during winding?

> **CONCLUSION** Damage takes only two forms: enamel cracking or rupture, and copper layer rupture (appearing as exposed aluminium or breakage). Both are detectable on line — enamel by pinhole and dielectric tests, copper by visual inspection (exposed aluminium appears as a silver-white streak) and DC resistance. There is therefore no hidden damage requiring special instrumentation.

Table 5 Failure modes, causes and detection

Failure mode	Mechanism	Detection	Detectability
Enamel cracking or rupture	Excess tension, burred pulleys, tight bend radius	Pinhole test, dielectric test, mandrel plus elongation	On line or sampling, 100% detectable
Copper layer rupture, exposed Al	Tension beyond copper layer limit, bend fatigue	Visual (silver-white streak), resistance rise, breakage alarm	100% on line
Interfacial delamination	Repeated bending, severe overload or overheating	Metallography, repeated-bend test	Off-line analysis

9.1 Tension control in practice

- Set tension at 70–80% of the value used for copper of the same size, with fluctuation within ±5%.
- Use servo tension control with a dancer or buffer to absorb transient shocks from the pay-off.
- Keep pulley radius at least three times the wire diameter; polish faces, ensure free rotation and inspect for wear and grooving.
- For fine wire below 0.2 mm, reduce line speed by 10–20% to lower transient tension peaks.

9.2 On defect rates

Production data show the winding defect rate for CCA to be essentially equivalent to copper, with no evident increase. Where breakage is concentrated at specific positions, the spool and fracture photographs allow us to determine whether the cause lies at the pay-off, a pulley or the traverse; a conclusion is normally provided within two working days.

10 How are copper layer thickness, minimum copper layer thickness and copper content determined?

> **CONCLUSION** For round wire, the grade is selected per GB/T 29197-2012 (10A/10H, 15A/15H, 20A/20H), with minimum copper layer thickness assessed as not less than 1.75%, 2.5% and 3.5% of nominal diameter respectively. Our internal control adds a requirement that the minimum point be not less than 50% of the mean thickness, which is achieved on 100% of production. For rectangular wire we currently control the minimum point at not less than one third of the mean thickness, with copper volume fraction referenced to grade 15A.

Table 6 Copper layer and copper content requirements

Grade	Cu volume fraction (GB)	Min. thickness (GB)	Our tighter control	Cu mass share (approx.)
10A / 10H	8%–12%	≥ 1.75% × d	Min. ≥ 50% of mean	27%
15A / 15H	13%–17%	≥ 2.5% × d	Min. ≥ 50% of mean	37%
20A / 20H	18%–22%	≥ 3.5% × d	Min. ≥ 50% of mean	45%
Rectangular (provisional)	Referenced to 15A	—	Min. ≥ 1/3 of mean	As measured

10.1 Do not confuse volume fraction with mass share

The standard defines grades by copper volume fraction, whereas settlement and quotation are usually based on copper mass. The conversion is approximately 10% by volume to 27% by mass, 15% to 37% and 20% to 45%. Technical discussions must state which basis is being used, otherwise copper content becomes a source of disagreement.

10.2 What thickness variation actually affects

Variation in copper layer thickness has little effect on DC resistance, which is governed principally by volume fraction. What it does affect is solderability, the number of re-soldering operations, and the risk of exposed aluminium. Customers with solder-intensive processes should therefore select grade 15A or 20A rather than demand tighter thickness uniformity.

10.3 Measurement

Minimum thickness is measured by metallographic sectioning with six points distributed around the circumference, taking the lowest value; volume fraction by weighing (section mass against theoretical density) or by metallographic area analysis; in-line eddy-current or X-ray gauging is used for trend monitoring. We can supply section photographs and measured data per batch.

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11 What is the effect of the copper-aluminium compounds formed at the interface?

> **CONCLUSION** The interfacial layer consists of copper-aluminium intermetallics, principally $CuAl_2$ and Cu_9Al_4, formed by solid-state diffusion during cladding, drawing and annealing, typically 10–30 µm thick. Its conductivity is lower than either parent metal, but because the layer is so thin its contribution to overall DC resistance lies within measurement error. The real effect is mechanical: an excessively thick layer reduces elongation and bend performance, most noticeably in fine wire.

11.1 Electrical effect: negligible

On a thin-layer series model the interfacial layer contributes less than 1% of total resistance, the same order as measurement deviation. This is why the national standard specifies resistivity rather than intermetallic thickness as the acceptance criterion.

11.2 Mechanical effect: it sets the annealing process

Layer thickness grows with annealing temperature and time, and the growth is non-linear. When the layer is too thick the two metals can no longer deform compatibly in tension or bending, elongation falls sharply and the wire becomes brittle. The essential control at the production end is therefore: anneal once, at finished size, and never re-anneal; hold furnace temperature in the 550–600 °C band with strict control of line speed so the conductor does not dwell too long in the tube. This is also why CCA demands far better furnace temperature uniformity than copper — a 20–30 °C spread between tubes is enough to put elongation out of specification.

11.3 Long-term effect: governed by temperature

The layer continues to thicken slowly in service at a rate set by hot-spot temperature. This is why item 5 concentrates on temperature control: hold the temperature and the layer thickness stabilises, so no degradation from interfacial growth occurs over a fifteen-year service life.

11.4 A commonly misunderstood point

Thinner is not better. A certain layer thickness is precisely the source of bond strength between copper and aluminium core; the national standard's torsion and repeated-bend requirements that the interface shall not delaminate are in essence a test of that bond. Pursuing an excessively thin layer sacrifices bond strength.

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12 What verification is carried out for direct substitution in high-frequency, high-current or high-overload applications?

> **CONCLUSION** Verification has two levels. The wire level is ours: resistivity, dielectric strength, pinholes, adhesion, solderability, heat resistance and elongation, reported per batch. The component level belongs to the equipment maker: temperature rise, saturation current, AC loss, short circuit and overload, thermal cycling — all of which depend on core, winding method and thermal design, and which an enamelled wire producer cannot report on the customer's behalf.

Table 7 Wire-level verification available from us

Test	Standard	Frequency	Remarks
Resistivity	GB/T 29197, GB/T 3048	Per batch	With temperature coefficient
Enamel continuity (pinholes)	GB/T 4074.5	Per batch	Salt bath or foil method
Dielectric strength	GB/T 4074.6	Per batch	Set by diameter and class
Adhesion and mandrel	GB/T 4074.3	Per batch	Including elongation mandrel
Solderability	GB/T 4074.4	Per batch	Solder temperature and time to order
Heat shock, softening breakdown	GB/T 4074.6, IEC 60317	Type test	Classes 130/155/180
Tensile strength and elongation	GB/T 29197	Per batch	With delamination check
Refrigerant and hydrolysis resistance	Relevant IEC 60317 sheet	On request	A/C and oil-immersed duty

12.1 Component-level tests the customer must perform

- Worst-case temperature rise: highest ambient, maximum load and worst thermal orientation combined.
- Saturation current and overload capability, including inductance decay and visual inspection after short-time overload.
- AC loss: skin and proximity effects must be included at high frequency, where rectangular wire has a clear advantage.
- Thermal cycling and vibration: verifying the mechanical integrity of solder joints and pin roots.
- Long-term ageing: dielectric and inductance drift after 1000 h at 85 °C/85% RH or high-temperature storage.

12.2 The temperature boundary must be stated plainly

The aluminium core melts at about 660 °C and the copper-aluminium eutectic at the interface at about 548 °C. These are the absolute temperature boundaries for the system. Normal inductor service temperatures of 100–150 °C, and short-time overloads possibly reaching 200–250 °C, remain within the capability of the insulation system and leave ample margin to these limits; the extreme temperature is not reached in practice. Nevertheless, the equipment's short-circuit

and overload protection should be confirmed such that conductor temperature cannot approach 500 °C under any fault condition. This is a design input condition, not a material defect.

12.3 One key point for high frequency

At 100 kHz the skin depth in copper is about 0.21 mm, the same order as the copper layer thickness. High-frequency current therefore flows mainly in the copper layer, and high-frequency resistance is determined by copper layer quality. High-frequency designs should specify a sound copper layer at 15% volume fraction or above, and use rectangular profile to reduce proximity loss.

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13 How are exposed aluminium and solder joint fatigue avoided?

> **CONCLUSION** Exposed aluminium is a visible defect that can be detected 100% by eye in inductor manufacturing; anything reaching the next operation can be screened out, so it presents no service risk. Solder joint fatigue is on par with copper: it is a mechanical and thermal-cycling stress issue resolved by lead fixation and strain relief, not a property of the conductor material.

13.1 Sources of exposed aluminium and countermeasures

- Drawing scratches: an incoming material issue, intercepted by pinhole and visual inspection.
- Burred or worn pulleys: inspect faces at fixed intervals and replace at the first sign of grooving.
- Over-stripping: use thermal or chemical stripping in preference to mechanical scraping, which can damage the copper layer.
- Bend cracking: keep the bend radius at least twice the wire diameter and avoid repeated bending at one position.

With these four applied at the process level, exposed aluminium essentially does not occur in inductor winding and assembly; and where it does, silver-white aluminium against a copper-coloured winding is immediately visible and screened out by 100% visual inspection. This is the basis for our position that exposed aluminium is not a risk in inductor production.

13.2 Solder joint fatigue: mechanism and countermeasures

Fatigue originates in alternating stress at the joint caused by mechanical vibration and thermal cycling, and has little to do with whether the conductor is copper or CCA. The coefficient of thermal expansion of CCA is about 19.5×10^{-6}/°C against 16.5×10^{-6}/°C for copper — a small difference, so the incremental interfacial stress under thermal cycling is limited. Fatigue in practice concentrates where pins are rigidly constrained and wire weight or vibration acts directly on the joint. The countermeasures are structural: a strain-relief loop in the lead, staking or bonding of the winding, and ensuring the joint carries neither the weight of the wire nor vibration load.

13.3 Failure analysis support

Where the customer has failed samples, we can perform metallographic sectioning with SEM/EDS to determine whether the cause is interfacial delamination, copper layer fracture or a soldering metallurgy problem such as a copper layer too thin for a sound joint, and recommend process improvements. Such reports are normally issued within one week.

4. Conclusions and recommendations

Taking the thirteen queries together, our position is that CCA enamelled wire is a mature solution capable of replacing copper in volume for inductor applications. It does not possess every physical property of copper, but in this particular application its shortcomings — mechanical strength and melting point — can be absorbed by design and process, while its advantages in weight, cost and fill factor are definite.

We recommend a three-stage verification path, six to eight weeks in total:

1. **Stage 1 — trial winding (1–2 weeks).** Convert the diameter on an equal-resistance basis, build 20–30 samples and verify the tension window, fill factor, stripping and soldering. The objective at this stage is not electrical performance but confirmation that the line can wind the wire consistently.
2. **Stage 2 — pilot run (4–6 weeks).** Take 30–50 units through worst-case temperature rise, saturation and overload, and thermal cycling; take a further group through 1000 h high-temperature ageing, watching inductance drift and dielectric behaviour. The objective is confirmation of long-term reliability.
3. **Stage 3 — production release.** Freeze diameter, tension, stripping method and soldering parameters into the work standard, and write copper volume fraction, minimum layer thickness, elongation and pinhole count into the incoming inspection baseline.

Support available from us: two or three diameter options calculated for the customer's duty, with copper content, weight and cost comparison; trial samples with full test reports; an engineer on site for first-article set-up; response to customer defects within 24 hours and root-cause analysis within two weeks.

Appendix A Documents and data available

- Product datasheet (copper volume fraction, minimum layer thickness, elongation, dielectric class, thermal class)
- Batch certificate of analysis (COA)
- Third-party test reports (RoHS, REACH, thermal class; UL certification by size)
- Twelve-month quality data summary (breakage rate, pinhole count, dielectric pass rate, resistance distribution)
- Resistance–temperature curves and solderability records for standard sizes
- Copper layer metallographic sections with measured minimum thickness
- Packaging, storage and handling instructions

Appendix B Standards referenced

- GB/T 29197-2012 Copper-clad aluminium wire
- GB/T 6109 (all parts) Enamelled round winding wires
- GB/T 4074 (all parts) Test methods for winding wires
- IEC 60317 series Specifications for particular types of winding wires
- Internal control standard (available on request; includes rectangular wire copper layer limits)

Disclaimer

This document is issued for technical exchange. Except where standard clauses are quoted, values given are typical or indicative ranges; the product datasheet agreed between the parties and the batch inspection report take precedence. Customer duty — topology, switching frequency, environmental conditions and safety requirements — varies widely, and final selection should be confirmed by sample and equipment-level verification. Information concerning third-party customers is subject to confidentiality agreements and has been omitted.