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Multivariable Investigation of Current-Carrying Capacity and Thermal Reliability in Inner-Layer Conductors of Flexible Cable PCBs: Effects of Conductor Geometry, Temperature Rise, and Bending Conditions

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ABSTRACT

The electrical and thermal reliability of flexible printed circuit board (FPCB) conductors becomes increasingly important as compact aerospace, unmanned, wearable, and embedded electronic systems require higher power density within restricted mechanical envelopes. Conventional current-carrying-capacity calculations generally emphasize conductor cross-sectional area and allowable temperature rise, while the combined influence of conductor geometry, ambient temperature, duty cycle, and mechanical bending is less frequently incorporated into a unified design methodology. This study develops a multivariable framework for evaluating the current-carrying capacity and thermal reliability of inner-layer conductors in flexible cable PCBs. Unlike conventional assessments based primarily on conductor width and temperature rise, the proposed approach introduces conductor thickness, trace width, ambient temperature, electrical duty cycle, bending radius, and temperature-dependent copper resistivity as coupled design variables.

The investigation establishes analytical relationships between current, conductor resistance, Joule heating, temperature rise, and mechanical bending strain. Three redesigned conductor configurations with widths of 3.2, 4.6, and 6.0 mm and copper thicknesses of 18, 25, and 35 μm are considered. A temperature-dependent resistance model is incorporated to account for the increase in copper resistivity with temperature. In addition, a bending-reliability factor is introduced to evaluate the influence of mechanical deformation on conductor performance. The analytical framework is supplemented by a proposed experimental matrix covering continuous-current, transient-current, thermal-cycling, and repeated-bending conditions. The results indicate that conductor width and copper thickness strongly influence allowable current, while ambient temperature and bending radius significantly affect the available thermal and mechanical reliability margins. The analysis further demonstrates that a conductor that is electrically acceptable under straight, room-temperature conditions may possess substantially reduced reliability when operated at elevated ambient temperature or under repeated bending. The proposed framework therefore provides a more comprehensive design methodology for flexible PCB power conductors than a single-variable current-capacity calculation.

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1. Introduction

The rapid development of compact electronic systems has resulted in a continuous increase in functional density, power density, and mechanical integration. Flexible printed circuit boards (FPCBs) are particularly attractive in applications where conventional wire harnesses cannot satisfy requirements for weight, volume, routing freedom, and three-dimensional packaging. Flexible circuits are increasingly employed in aerospace electronics, unmanned systems, automotive electronics, medical devices, wearable electronics, robotic systems, and compact power modules.

The fundamental advantage of an FPCB is that electrical interconnection and mechanical routing can be integrated into a thin flexible structure. However, this advantage also introduces an important engineering trade-off. Reducing conductor width and copper thickness decreases mass and occupied volume but simultaneously increases electrical resistance and Joule heating. Conversely, increasing conductor dimensions improves current capacity but may compromise flexibility, packaging density, and mechanical integration.

Current-carrying capacity is therefore not an isolated electrical parameter. It is a coupled electrothermal-mechanical problem.

For a conductor carrying current **(I),** the generated Joule heat can be expressed as

$$P = I^2 R$$

where **(P)** is the electrical power converted into heat and **(R)** is conductor resistance. Because copper resistivity increases with temperature, resistance is itself temperature-dependent. Consequently, conductor heating produces an increase in resistance, which subsequently increases heat generation at constant current. This electrothermal feedback becomes increasingly important at high current density and elevated ambient temperature.

The IPC-2152 standard explicitly treats current-carrying capacity as a relationship among conductor size, current, and allowable conductor temperature rise, rather than as a single universal current value. (electronics.org) IPC-2221A also contains guidance concerning conductor current capacity and thermal management and includes provisions relevant to flexible printed wiring and bending endurance. (electronics.org)

For flexible circuits, however, thermal behavior cannot be separated completely from mechanical reliability. Repeated bending can produce tensile and compressive strains within the copper layer, potentially resulting in resistance growth, localized damage, fatigue cracking, or eventual electrical discontinuity. Experimental studies of flexible electronic systems have demonstrated that bending mode and repeated deformation can substantially influence electrical resistance and lifetime. (MDPI)

The present research therefore extends the traditional current-capacity problem by introducing three additional variables:

1. **Ambient temperature ((T_a))**;
2. **Mechanical bending radius ((R_b))**;
3. **Conductor thickness ((t_c))**.

The resulting research problem can be expressed as:

How does the allowable current of an inner-layer flexible PCB conductor change when electrical loading, conductor geometry, ambient temperature, and mechanical bending are simultaneously considered?

The principal objective is to establish a unified analytical and experimental framework for determining safe operating current rather than relying exclusively on a nominal current value.

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2. Research Objectives and Contributions

The objectives of this study are:

1. To establish a revised analytical model for inner-layer FPCB current-carrying capacity.
2. To investigate the effect of conductor width and copper thickness on electrical resistance.
3. To incorporate temperature-dependent copper resistivity into the thermal model.
4. To introduce ambient temperature as an independent design variable.
5. To investigate the influence of bending radius on conductor reliability.
6. To distinguish continuous-current capacity from transient-current capability.
7. To develop a multidimensional experimental test matrix.
8. To establish engineering safety margins for flexible PCB power conductors.
9. To provide a design methodology applicable to compact aerospace and embedded electronic systems.

The principal novelty is the integration of **electrical, thermal, and mechanical variables** into one design framework.

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3. Theoretical Framework

3.1 Electrical resistance of the inner-layer conductor

The resistance of a rectangular copper conductor can initially be expressed as

$$R = \rho \frac{L}{A}$$

where

- **(R)** = conductor resistance, *Ω;*
- ρ = copper electrical resistivity, *Ω·m;*

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- **(L)** = conductor length, m;
- **(A)** = conductor cross-sectional area, *m²*.

For a rectangular conductor,

$$A = Wt_c$$

where **(W)** is conductor width and **(t_c)** is copper thickness.

Therefore,

$$R = \rho \frac{L}{Wt_c} \tag{1}$$

Equation (1) demonstrates that increasing either conductor width or copper thickness reduces electrical resistance.

3.2 Temperature-dependent copper resistivity

Copper resistivity is temperature-dependent and can be approximated over the relevant engineering range by

$$\rho(T) = \rho_{20}[1 + \alpha(T - 20)] \tag{2}$$

where

- ρ_{20} is copper resistivity at 20 °C;
- $\boldsymbol{\alpha}$: is the temperature coefficient of resistivity;
- **(T)** :is conductor temperature in °C.

For copper, a representative value of (\alpha\approx3.9\times10^{-3},^\circ\mathrm{C}^{-1}) can be used for preliminary engineering calculations.

Substitution into Equation (1) yields

$$R(T) = \rho_{20} \frac{L}{Wt_c}[1 + \alpha(T - 20)] \tag{3}$$

Thus, the electrical resistance is directly coupled with conductor temperature.

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4. Joule Heating Model

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The heat generated by the conductor is

$$P(T,I) = I^2 R(T) \tag{4}$$

and therefore

$$P(T,I) = I^2 \rho_{20} \frac{L}{W t_c} [1 + \alpha(T - 20)]. \tag{5}$$

Equation (5) is particularly important for flexible PCB design because it shows that:

- increasing current increases heating approximately with (I^2);
- increasing width decreases heating;
- increasing copper thickness decreases heating;
- increasing temperature increases resistance and therefore increases heating.

The thermal problem is consequently nonlinear.

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5. Thermal Equilibrium Model

For steady-state operation, the generated heat must be approximately balanced by heat dissipated through conduction, convection, and radiation.

A simplified lumped model is

$$P = G_{\mathrm{th}}(T_c - T_a) \tag{6}$$

where

- G_{th} = effective thermal conductance;
- T_c = conductor temperature;
- T_a = ambient temperature.

The temperature rise becomes

$$\Delta T = T_c - T_a$$

and

$$\Delta T = \frac{I^2 R(T_c)}{G_{\text{th}}}.$$

This equation provides the basis for calculating the maximum permissible current for a specified temperature-rise limit.

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6. New Variable: Bending Radius

The major additional variable introduced in this study is the **bending radius**.

For a flexible circuit of effective neutral-axis distance (y) from the copper layer, the approximate bending strain is

$$\varepsilon_b = \frac{y}{R_b} \tag{9}$$

where (R_b) is the bending radius.

This means that smaller bending radii produce larger mechanical strains.

The mechanical reliability of flexible conductors is strongly related to repeated bending and deformation. Studies of flexible electronics have shown that resistance can increase during cyclic bending, while bending configuration and metal material significantly affect fatigue behavior. (MDPI)

A simplified bending-reliability factor can therefore be defined as

$$K_b = 1 - \beta \left(\frac{R_{\text{ref}}}{R_b} \right)^m \tag{10}$$

where β and **(m)** are experimentally determined coefficients.

The effective allowable current can then be represented as

$$I_{\text{allow,b}} = K_b I_{\text{allow}} \tag{11}$$

This relationship should be calibrated experimentally rather than treated as a universal material law.

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7. Research Variables

The redesigned investigation uses the variables shown in Table 1.

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Table 1. Variables incorporated into the proposed investigation

Category	Variable	Symbol	Proposed levels
Electrical	Current	(I)	1–12 A
Geometry	Conductor width	(W)	3.2, 4.6, 6.0 mm
Geometry	Copper thickness	(t_c)	18, 25, 35 µm
Thermal	Ambient temperature	(T_a)	25, 40, 55 °C
Thermal	Maximum temperature rise	$\Delta Tmax$	15, 25, 35 °C
Mechanical	Bending radius	(R_b)	4, 8, 12 mm
Mechanical	Bending cycles	(N_b)	0–50,000
Electrical	Load duration	(t)	10 s–600 s
Reliability	Resistance variation	($\Delta R/R0$)	measured
Reliability	Temperature	(T_c)	measured

This multidimensional structure is substantially different from an investigation based only on current and conductor width.

8. Redesigned FPCB Specimen

To avoid reproducing the original specimen dimensions, a new geometric configuration is proposed.

Table 2. Redesigned specimen configurations

Specimen	Copper width	Copper thickness	Length	Cross-sectional area
F1	3.2 mm	18 µm	120 mm	0.0576 mm²
F2	4.6 mm	18 µm	120 mm	0.0828 mm²
F3	6.0 mm	18 µm	120 mm	0.1080 mm²
F4	3.2 mm	25 µm	120 mm	0.0800 mm²
F5	4.6 mm	25 µm	120 mm	0.1150 mm²
F6	6.0 mm	25 µm	120 mm	0.1500 mm²
F7	3.2 mm	35 µm	120 mm	0.1120 mm²
F8	4.6 mm	35 µm	120 mm	0.1610 mm²
F9	6.0 mm	35 µm	120 mm	0.2100 mm²

The nine configurations permit the effects of width and thickness to be separated.

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9. Analytical Resistance Comparison

For comparison, assuming (L=120) mm and copper resistivity at 20 °C of approximately (1.72\times10^{-8},\Omega\mathrm{m}), the theoretical room-temperature resistance is calculated using Equation (1).

Table 3. Calculated conductor resistance at 20 °C

Specimen	Area (mm²)	Approx. resistance (mΩ)
F1	0.0576	35.8
F2	0.0828	24.9
F3	0.1080	19.1
F4	0.0800	25.8
F5	0.1150	18.0
F6	0.1500	13.8
F7	0.1120	18.4
F8	0.1610	12.8
F9	0.2100	9.8

These calculated values demonstrate the importance of cross-sectional area. Increasing copper thickness from 18 to 35 µm substantially decreases resistance without requiring an equivalent increase in conductor width.

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10. Current-Density Analysis

Current density is defined as

$$J = \frac{I}{W t_c} \tag{12}$$

where (J) is expressed in A/mm² when (I) is in amperes and cross-sectional area is in mm².

For example, for specimen F5:

$$A = 4.6 \times 0.025 = 0.115\ \mathrm{mm}^2$$

and therefore

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$$J = \frac{I}{0.115}.$$

Table 4. Current density of selected conductor configurations

Configuration	Area (mm²)	3 A	5 A	7 A	9 A
F1	0.0576	52.1	86.8	121.5	156.3
F3	0.1080	27.8	46.3	64.8	83.3
F5	0.1150	26.1	43.5	60.9	78.3
F7	0.1120	26.8	44.6	62.5	80.4
F9	0.2100	14.3	23.8	33.3	42.9

The table illustrates why identical current values cannot be assigned to conductors having substantially different cross-sectional areas.

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11. Influence of Ambient Temperature

A major modification introduced by this study is the explicit consideration of ambient temperature.

Three thermal environments are considered:

- 25 °C: nominal laboratory condition;
- 40 °C: elevated operating environment;
- 55 °C: severe thermal environment.

The maximum conductor temperature is defined as

$$T_{\max} = T_a + \Delta T_{\max}. \qquad (13)$$

Therefore, for an allowable conductor temperature of 90 °C, the available thermal margin becomes:

Table 5. Available thermal margin

Ambient temperature	Maximum conductor temperature	Available temperature rise
25 °C	90 °C	65 °C
40 °C	90 °C	50 °C
55 °C	90 °C	35 °C

This demonstrates an important design principle: **the same conductor cannot be assigned the same current limit under all ambient conditions**.

12. Proposed Steady-State Test Method

The proposed experimental procedure differs from the original methodology by combining electrical, thermal, and mechanical loading.

Each specimen is mounted inside a temperature-controlled chamber.

The current is increased in predefined increments while the following parameters are continuously recorded:

1. input current;
2. conductor voltage;
3. conductor resistance;
4. surface temperature;
5. ambient temperature;
6. thermal stabilization time;
7. bending radius;
8. resistance variation.

The steady-state test sequence is proposed as shown in Table 6.

Table 6. Proposed steady-current test sequence

Stage	Current range	Duration	Ambient temperature
S1	1–3 A	10 min/level	25 °C
S2	3–6 A	10 min/level	25 °C
S3	6–9 A	8 min/level	25 °C
S4	1–5 A	10 min/level	40 °C
S5	1–5 A	8 min/level	55 °C
S6	selected limit	30 min	55 °C

The current limit is defined as the highest current for which all predefined electrical and thermal criteria remain satisfied.

13. Transient-Current Investigation

Steady-state capacity alone is insufficient for applications in which the FPCB experiences short-duration high-current pulses.

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The transient test is therefore formulated as

$$I(t) = I_0 + \Delta I \, e^{-t/\tau} \tag{14}$$

for an exponentially decaying pulse, or as a rectangular pulse when the application requires a simplified representation.

The proposed pulse matrix is shown in Table 7.

Table 7. Proposed transient-current test matrix

Test	Peak current	Pulse duration	Number of pulses
P1	6 A	20 ms	10
P2	8 A	50 ms	10
P3	10 A	100 ms	5
P4	12 A	200 ms	3
P5	14 A	50 ms	3

The objective is not merely to determine whether the conductor survives a pulse, but also to determine:

$$\Delta T_{\text{pulse}}$$

and

$$\frac{\Delta R}{R_0}.$$

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14. New Experimental Variable: Bending Radius

Three bending radii are introduced:

$$R_b = 4,\ 8,\ 12 \text{ mm.}$$

The specimens are divided into:

- straight specimens;
- 12-mm-radius specimens;
- 8-mm-radius specimens;
- 4-mm-radius specimens.

Table 8. Mechanical test matrix

Group	Radius	Electrical condition	Bending cycles
B0	Straight	no current	0
B1	12 mm	rated current	10,000
B2	8 mm	rated current	10,000
B3	4 mm	rated current	10,000
B4	8 mm	rated current	25,000
B5	4 mm	rated current	25,000
B6	4 mm	rated current	50,000

Repeated-bending reliability is particularly relevant because flexible electronics must retain electrical functionality while undergoing mechanical deformation. (MDPI)

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15. Resistance-Based Reliability Criterion

The electrical condition after bending is quantified using

$$\Delta R_{\%} = \frac{R_N - R_0}{R_0} \times 100 \tag{15}$$

where

- (R_0) = initial resistance;
- (R_N) = resistance after **(N)** bending cycles.

A specimen can be classified according to Table 9.

Table 9. Proposed electrical reliability classification

Resistance increase	Classification
<2%	Excellent
2–5%	Acceptable
5–10%	Marginal
10–20%	Degraded
>20%	Failure-risk condition

These limits are proposed research criteria and should be adjusted according to the qualification requirements of the intended application.

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16. Electrothermal Coupling

The central analytical improvement of the present research is the coupling between current and temperature.

Combining Equations (3) and (4):

$$P = I^2 \rho_{20} \frac{L}{W t_c} [1 + \alpha(T_c - 20)]. \tag{16}$$

At thermal equilibrium,

$$G_{\text{th}}(T_c - T_a) = I^2 \rho_{20} \frac{L}{W t_c} [1 + \alpha(T_c - 20)]. \tag{17}$$

Equation (17) can be solved numerically for (T_c).

This formulation provides a substantially more realistic representation than assuming constant copper resistance.

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17. Thermal Simulation Method

A three-dimensional finite-volume or finite-element thermal model can be developed using the following components:

- polyimide substrate;
- copper conductor;
- coverlay;
- adhesive layer;
- surrounding air;
- mounting fixture.

The heat source is assigned to the copper conductor according to

$$q''' = \frac{I^2 R}{V_c} \tag{18}$$

where (V_c) is the conductor volume.

The thermal model should include:

1. temperature-dependent copper resistivity;

2. natural convection;
3. conduction through the substrate;
4. conduction through mounting interfaces;
5. radiation where required;
6. bending geometry where mechanical deformation changes thermal configuration.

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18. Proposed Simulation Cases

Table 10. Numerical thermal-simulation matrix

Case	Width	Thickness	Current	Ambient
T1	3.2 mm	18 µm	3 A	25 °C
T2	3.2 mm	18 µm	5 A	25 °C
T3	4.6 mm	25 µm	5 A	25 °C
T4	4.6 mm	25 µm	7 A	40 °C
T5	6.0 mm	25 µm	8 A	40 °C
T6	6.0 mm	35 µm	9 A	55 °C
T7	4.6 mm	18 µm	6 A	55 °C
T8	6.0 mm	35 µm	10 A	25 °C

These are **proposed numerical test cases**, not claimed measurements from an already conducted experiment.

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19. Design-of-Experiments Framework

To reduce the number of physical tests while retaining statistical information, a factorial or Taguchi-type design can be employed.

The principal factors are:

$$W, \quad t_c, \quad T_a, \quad I, \quad R_b.$$

Table 11. Factor-level structure

Factor	Level 1	Level 2	Level 3
Width	3.2 mm	4.6 mm	6.0 mm

Thickness	18 µm	25 µm	35 µm
Ambient temperature	25 °C	40 °C	55 °C
Bending radius	4 mm	8 mm	12 mm
Current	3 A	6 A	9 A

The response variables are:

- maximum temperature;
- temperature rise;
- resistance;
- resistance growth;
- transient peak temperature;
- number of bending cycles to failure.

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20. Statistical Analysis

Analysis of variance (ANOVA) can be used to determine the relative contribution of each factor.

The total variance can be expressed as

$$SS_T = SS_W + SS_t + SS_{T_a} + SS_{R_b} + SS_I + SS_E \quad (19)$$

where the terms represent the contribution of width, thickness, ambient temperature, bending radius, current, and experimental error.

The percentage contribution of a factor is

$$P_i = \frac{SS_i}{SS_T} \times 100\%. \quad (20)$$

This permits the research to identify whether electrical capacity is dominated primarily by geometry, temperature, or mechanical deformation.

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21. Proposed Reliability Index

To combine electrical, thermal, and mechanical effects, a normalized reliability index is proposed:

$$RI = w_1 M_I + w_2 M_T + w_3 M_R + w_4 M_B \quad (21)$$

where

- (M_I) = current-capacity margin;
- (M_T) = thermal margin;
- (M_R) = resistance margin;
- (M_B) = bending-reliability margin;
- (w_i) = weighting factors.

The weighting coefficients should be selected according to application requirements.

For aerospace applications, for example, thermal and electrical reliability may be assigned greater weighting than packaging flexibility.

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22. Comparison of Conventional and Proposed Approaches

Table 12. Comparison of methodologies

Parameter	Conventional approach	Proposed approach
Current	✓	✓
Width	✓	✓
Copper thickness	✓	✓
Temperature rise	✓	✓
Ambient temperature	Limited	✓
Temperature-dependent resistance	Limited	✓
Transient current	Limited	✓
Bending radius	—	✓
Bending cycles	—	✓
Resistance degradation	Limited	✓
Statistical analysis	Limited	✓
Electrothermal coupling	Limited	✓
Multivariable reliability index	—	✓

This constitutes the main conceptual difference between the present research and a conventional current-capacity calculation.

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23. Engineering Interpretation

The proposed framework produces several important engineering conclusions.

First, conductor width alone cannot adequately describe current capacity. Two conductors having the same width but different copper thicknesses can have substantially different resistance and heat generation.

Second, the allowable current decreases as ambient temperature increases because the available temperature-rise margin becomes smaller.

Third, transient-current capability should be treated independently from steady-state current capacity. A conductor can tolerate a short high-current pulse without being suitable for continuous operation at the same current.

Fourth, bending must be considered in flexible circuits. A conductor that satisfies the electrical requirement in a straight configuration may exhibit resistance growth or fatigue degradation after repeated bending. Research on flexible electronics confirms that mechanical deformation and bending configuration are important reliability factors. (MDPI)

Fifth, copper resistivity should not necessarily be treated as constant in high-temperature calculations. Incorporating temperature-dependent resistance provides a stronger electrothermal model.

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24. Proposed Failure Mechanisms

The principal failure mechanisms considered in this study are summarized in Table 13.

Table 13. Potential FPCB conductor failure mechanisms

Failure mechanism	Primary driving factor	Observable parameter
Excessive Joule heating	High current	Temperature
Copper oxidation/degradation	High temperature	Surface appearance
Copper fatigue cracking	Repeated bending	Resistance
Localized hot spot	Current-density concentration	Infrared image
Delamination	Thermal/mechanical stress	Visual inspection
Conductor necking	Manufacturing variation	Resistance
Thermal runaway tendency	(I^2R) feedback	Rapid temperature rise
Electrical open circuit	Mechanical fatigue	Infinite/very high resistance

Flexible-circuit reliability literature emphasizes that cyclic deformation can produce electrical degradation and mechanical fatigue in conductive layers. (MDPI)

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25. Recommended Experimental Procedure

The complete experimental sequence is proposed as follows.

Step 1 — Initial characterization

Measure:

- conductor dimensions;
- copper thickness;
- initial resistance;
- substrate thickness;
- room temperature.

Step 2 — Steady-current testing

Apply current gradually while recording temperature and voltage.

Step 3 — Transient-current testing

Apply short-duration pulses and measure peak temperature and resistance.

Step 4 — Thermal-environment testing

Repeat selected current levels at 25, 40, and 55 °C.

Step 5 — Bending testing

Subject the samples to controlled bending radii.

Step 6 — Combined electro-mechanical testing

Apply rated current while maintaining the prescribed bending radius.

Step 7 — Post-test characterization

Measure:

- resistance;
- visual condition;
- dimensional changes;
- thermal damage;
- mechanical cracks.

Step 8 — Statistical analysis

Use ANOVA and regression analysis to determine factor significance.

26. Proposed Figures

For the final journal manuscript, the following figures should be prepared.

Figure 1. Multivariable framework for FPCB current-carrying-capacity evaluation.

Figure 2. Three-dimensional structure of the proposed inner-layer flexible PCB conductor.

Figure 3. Cross-sectional geometry showing conductor width, copper thickness, substrate and coverlay.

Figure 4. Experimental arrangement for steady-state current testing.

Figure 5. Experimental arrangement for transient-current testing.

Figure 6. Bending-radius test configuration.

Figure 7. Temperature-versus-time response under different current levels.

Figure 8. Current versus temperature-rise relationship.

Figure 9. Influence of copper thickness on allowable current.

Figure 10. Influence of ambient temperature on current-carrying capacity.

Figure 11. Influence of bending radius on resistance variation.

Figure 12. Infrared thermal distribution of the conductor.

Figure 13. Comparison between analytical and numerical thermal results.

Figure 14. Response-surface plot of current capacity as a function of width and thickness.

Figure 15. Multivariable reliability map combining current, temperature and bending radius.

These figures would make the manuscript substantially more research-oriented than a simple reproduction of the original current-capacity experiment.

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27. Discussion

The results of the analytical framework demonstrate that the current-carrying capacity of flexible PCB conductors should be interpreted as a multidimensional engineering quantity rather than a fixed value.

The conventional approach generally starts from the conductor cross-sectional area and allowable temperature rise. This remains an important foundation, and IPC-2152 explicitly addresses the relationship among conductor size, current, and temperature rise. (electronics.org) However, the practical operating environment of flexible circuits introduces additional variables that can substantially modify the available reliability margin.

The first is ambient temperature. An FPCB operating at 55 °C has a considerably smaller thermal margin than an identical FPCB operating at 25 °C. Consequently, current limits derived under laboratory conditions cannot automatically be transferred to high-temperature environments.

The second is mechanical bending. Flexible circuits are specifically designed to accommodate deformation, but flexibility does not mean immunity from fatigue. Repeated bending can produce cumulative mechanical damage in metallic conductors. (MDPI)

The third is electrothermal feedback. As copper temperature increases, resistivity increases. At constant current, this causes additional Joule heating, making a constant-resistance approximation increasingly inaccurate at elevated temperatures.

The fourth is transient operation. A short current pulse generates a thermal response that differs fundamentally from continuous operation. Therefore, a separate transient-current criterion is required.

The proposed framework consequently moves from a **single-variable design philosophy** toward a **multivariable reliability philosophy**.

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28. Design Recommendations

Based on the developed analytical framework, the following design recommendations are proposed:

1. Current capacity should always be calculated from the finished conductor cross-sectional area.
2. Copper thickness should be explicitly included rather than assuming a nominal foil thickness.
3. Ambient temperature should be included in the thermal design.
4. Temperature-dependent copper resistance should be considered for high-current applications.
5. Continuous and transient currents should have separate design limits.
6. Bending radius should be treated as a reliability variable in flexible applications.
7. Repeated bending should be accompanied by resistance monitoring.
8. Thermal imaging should be used to identify localized hot spots.
9. Analytical calculations should be verified using numerical thermal simulation.
10. At least one physical test campaign should be conducted before qualification of a critical design.

IPC guidance similarly emphasizes determining conductor dimensions in relation to required current and permissible temperature rise rather than assigning a universal current rating. (electronics.org)

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29. Conclusions

This study developed a new multivariable framework for investigating the current-carrying capacity and thermal reliability of inner-layer conductors in flexible cable PCBs.

The principal difference from conventional current-capacity studies is the simultaneous consideration of conductor width, copper thickness, current, ambient temperature, transient loading, and bending radius.

The theoretical model demonstrates that conductor resistance is inversely proportional to cross-sectional area and increases with temperature. Consequently, Joule heating cannot always be accurately represented using a constant-resistance assumption.

The redesigned conductor matrix incorporates widths of 3.2–6.0 mm and copper thicknesses of 18–35 µm, providing a broader design space than the original configuration. The proposed methodology also introduces three ambient-temperature levels and three bending radii, enabling electrothermal and mechanical reliability to be investigated simultaneously.

The introduction of bending radius represents an important extension because flexible PCB reliability is determined not only by the ability of a conductor to carry electrical current but also by its ability to maintain electrical integrity under repeated mechanical deformation. Existing flexible-electronics studies demonstrate the significance of bending mode, bending strain, and resistance degradation in determining long-term reliability. (MDPI)

The proposed research framework therefore provides a basis for moving from conventional current-capacity calculations toward integrated **electrothermal-mechanical reliability design**.

For future experimental work, the most important research direction is to obtain measured temperature and resistance data for the proposed nine conductor configurations and use these data to calibrate the bending-reliability coefficient and thermal-conductance parameters. Once calibrated, the resulting model can be used to generate application-specific current-rating maps for flexible aerospace and compact electronic systems.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

None.

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