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Degradation Analysis of Planar Magnetics

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***Abstract*— This paper presents the degradation testing results of a type of planar transformer under accelerated thermal conditions. The likely failure mechanisms are analyzed. Thermal-related degradation models and lifetime models are obtained based on certain end-of-life criteria and assumptions.**

***Keywords*—Planar transformer, magnetic core, winding, degradation, lifetime model, reliability.**

I. Introduction

Planar magnetics are widely used in high-frequency and high-density circuits for the features of low profile, excellent thermal dissipation capability, and simple manufacture workload [1, 2]. On the other side, there are severe stray capacitance, skin and proximity effects, and ununiformly-distributed core loss in the high-frequency range. They result in the current ringing and overheating in both component and system level. Also, the complexity in the winding structure increases the electrical stress in the insulation. The print circuit board (PCB) winding makes the structure vulnerable, especially under thermal stress. Moreover, the industrial-driven pressure on the volume and cost reduction leaves limited design margins. Planar magnetics are required to keep the high efficiency and limited parameter shifting range during the whole service life. Those challenges bring increasing reliability stress to them. To quantify their long-term effect requires to investigate the degradation mechanism and establish the benchmark from the perspective of the reliability. Therefore, the study of the degradation and lifetime of planar magnetics is essential for their application in high-power-density power electronic systems [3].

Until now, there is no systematic research on the reliability of planar magnetics. The research in the area of the line-frequency power transformers and the electrical machines is used as the reference. They mainly focus on the failure mechanism and lifetime model of the insulation system, including the Kraft paper and insulation oil for the power transformer [4, 5], and the main, phase, and turn insulation for the electrical machine [6, 7]. The Arrhenius model is used for their thermal aging modeling.

There are mainly two kinds of insulation in the planar transformers. The first is the solder mask and FR4 in the printed circuit board (PCB), which provides the board insulation and the copper trace turn-to-turn insulation. Different solder masks include epoxy liquid, dry-film photoimageable solder mask, and liquid photoimageable solder mask inks, etc. The board base material is with FR4 or other grades. The reliability of the PCB is investigated in [8, 9] and the applied stresses include thermal shock, vibration, humidity, etc. However, no lifetime model is reported. The thermo-mechanical failure such as cracks is reported in the thermal shock test. The failure mechanism is the mismatch of board material properties between the copper layer, solder mask, FR4, etc.

The second insulation is the insulation tape/insulator between the PCBs and provide the insulation between boards. It is usually made of Polyvinyl chloride (PVC), Vinyl, Polyimide, mica, etc. The research on the aging of the Polymide covers the electrical, thermal, and humidity stress. In [10, 11], their aging process is studied from the perspective of chemical reaction. The hydrolysis and thermo-oxidative is also investigated in [11]. The Arrhenius model and inverse power law are used for lifetime modeling under the thermal and electrical stresses, respectively [12].

The magnetic core is regarded as relatively stable. A few aging tests are reported for the iron-based amorphous core [13] and iron-powder core [14], respectively. For the iron-based amorphous material in air, below 150 °C, the core loss increases gradually during the first 16 months (11680 hours), and then becomes stable; at 200 °C, the loss increase gradually before 16 months and then increases rapidly. From the experimental analysis, the deterioration of the aging performance is attributed to the formatted oxide layer and the arisen stress rather than the crystallization. The thermal aging curve of the iron powder cores is significantly different from the iron-based amorphous core. The core loss increases slowly at the first, and then speed up with increased slope. The aging attributes to its organic binder. This material is with low resistivity above 125 to 150 °C. Once exceeded the temperature, its eddy current loss increases, which further increases the temperature and causes the irreversible core loss and thermal aging [15, 16]. The ferrite cores are widely used for planar magnetics with low eddy current loss in the high-frequency range. Its reliability is investigated in [17, 18] for the impact of the thermally-induced mechanical stress to the core. The mechanical reliability of the core glue is studied in [19].

For the whole planar magnetics, there are degradation tests

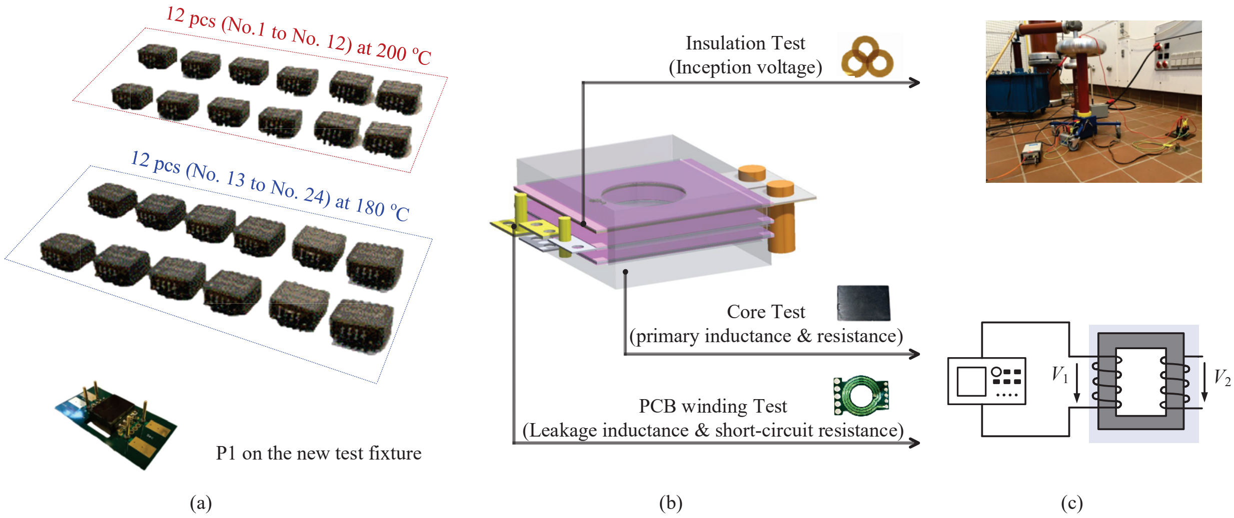

Fig. 1: Thermal degradation test of Planar transformers. (a) The planar transformers P1 and the new test fixture. 12 pieces applied with 200°C stress are numbered from 1 to 12; 12 pieces applied with 180°C stress are numbered from 13 to 24, respectively. (b) Basic structure of a planar transformer. (c) Magnetic parameters test setup. The upper figure is the insulation test and the inception voltage is measured in a partial discharge (PD) experiment. The lower figure is the impedance analyzer test while the primary inductance and resistance are measured in a core test, and the leakage inductance and short-circuit resistance is measured in the PCB winding test.

in [20], as summarized in Fig. 1. The parasitic parameter shifting during the degradation is also reported.

This paper is a further research of [20] and investigates the failure mechanism and lifetime assessment of planar magnetics. It is with three major contributions:

- Report the up-to-date test results, including the parameter shifting and appearance change.
- Give a detailed analysis of the degradation and failure mechanism of each planar magnetics components.
- Propose lifetime calculation procedure of planar magnetics with the assumed end-of-life criteria.

II. Degradation and Failure Mechanism Analysis

The planar transformer test setup and the specimen are detailed introduced in [20]. In that work, the core and impedance measurement is with non-negligible errors. Therefore, planar transformers P1 are tested again in this work with a new batch of samples and new test fixture for a better data acquisition. At this time, P1 at 200 °C are numbered 1 to 12; while at 180 °C are 13 to 24, respectively, as in Fig. 1. As the test results, Fig. 3 is the partial discharge results; and Fig.4 are the transformer parasitic test results, respectively.

A. Insulation Degradation

The change of the appearance of the insulation in our test is in Fig. 2. For the PCB boards, they become soft, turn black, and have cracks during the aging process. The aged solder mask is resolved and evaporated, and the copper layer is exposed outside. The failure of the solder mask results in the crack on the board, the change of the parasitic capacitance, the breaking of internal copper connection, and losing the insulation function.

For the insulator in the test, it is the Polyimide for above 130 °C applications. The thermal aging process in the insulator is the thermo-oxidative degradation, and the aged insulator turns darker compared with the new one [10].

In the partial discharge (PD) test, the inception voltage at which PD is triggered is measured in Fig. 3. For the samples at 200 °C, the inception voltage measured at the beginning and after 2400 hours of aging do not change significantly. Notice that in some samples, the solder mask in the PCB has already disappeared and the copper layer is exposed in the air. However, the insulation layer still provides good insulation between the boards and the inception voltage does not change significantly. Therefore, the conclusion that the inception voltage decreases with the insulation degradation cannot be made at this point, especially for this specific insulator. The variation of test results at each time attributes to the measurement error.

B. Core Degradation

The core test of the transformer P1 includes the primary inductance and resistance test, as in Fig. 4(a,b,c,d).

The primary inductance indicates the effective equivalent permeability of the core. It decreases significantly in Fig. 4(a) and (b). Fig. 5 is the mean primary inductance values of the samples at two different temperatures and their corresponding degradation curves based on curve fitting. Their curve along with the test time t is

$$L_{\mathrm{m}200} = 0.6471 + 0.3547 \times \exp\left(-0.0009429t\right) \qquad (1)$$

$$L_{\mathrm{m}180} = 0.6737 + 0.3211 \times \exp\left(-0.0003021t\right) \qquad (2)$$

where $L_{\mathrm{m}200}$ and $L_{\mathrm{m}180}$ are the normalized mean primary inductance at 200 °C and 180 °C, respectively.

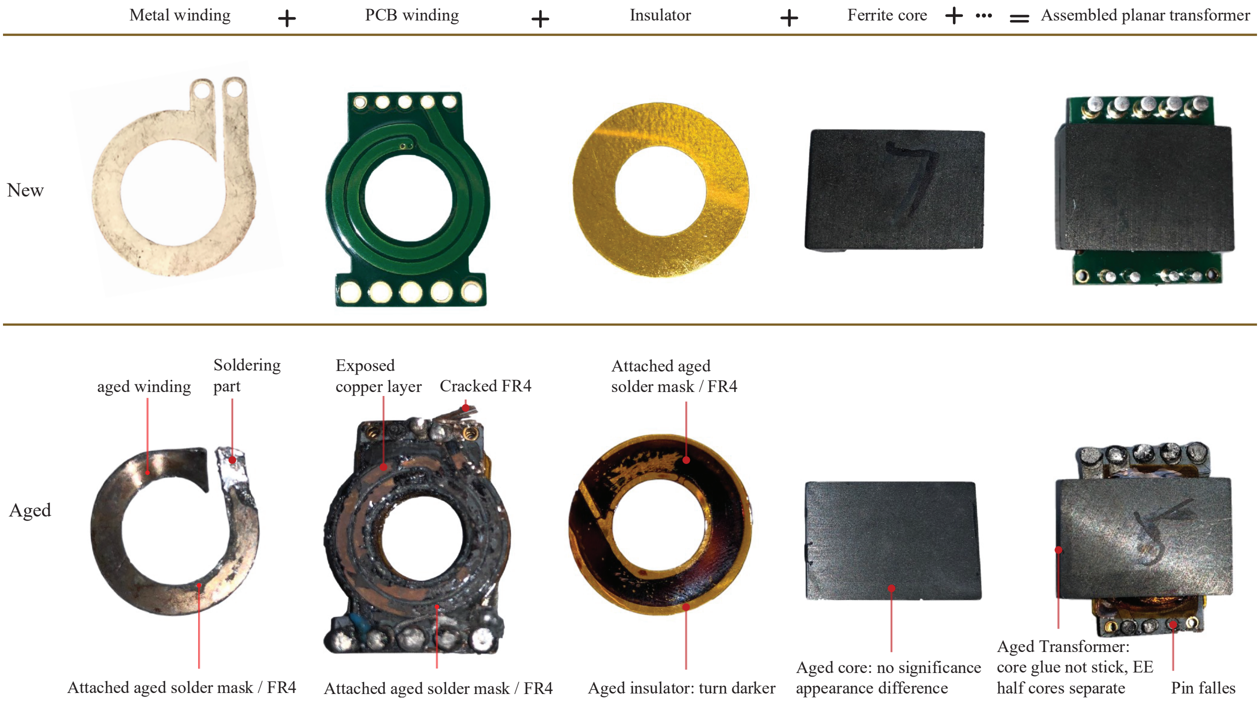

Fig. 2: The optical observation of the new and aged transformer and components. The aged transformer is with 200 °C, 5688 hours thermal stress.

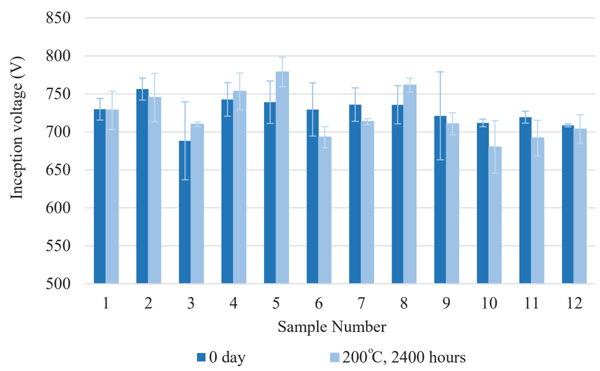

Fig. 3: Insulation test results of the planar transformers P1 with the thermal stresses 200 °C. The inception voltage in the partial discharge tests is measured and the threshold of the partial discharge is 10 pC. Three tests are performed each time, and the average value and standard deviation are given.

One possible explanation attributes to the aging of the core glue. The special glue is used to stick the upper and lower cores of the transformer. It contributes a tiny air-gap between the cores, as in Fig. 6. For the glues used in transformer P1, its volume expands with the degradation and turns from the dark to white. The air gap g increases gradually, and the equivalent permeability and the primary inductance of the core decreases. This explanation can also be used for the decrease of the primary resistance.

Another possible explanation of the primary inductance decrease is the degradation of the core material itself. The core material of P1 is also possible to lose the permeability and become less lossy at the same time. The primary resistance is the representative of the core loss and winding loss. Although the winding resistance increases, their core loss decreases so much that the overall primary resistance decreases.

C. *PCB Winding Degradation*

The PCB winding test of the transformer P1 includes the leakage inductance and short-circuit resistance test, as in Fig. 4(e,f,g,h).

The increase of the short-circuit resistance in (g) and (h) indicates the degradation of the PCB and one-turn metal winding. The copper oxidation is their major aging process. It increases the resistivity, and also changes the appearance of the mental winding to a much darker color, as in Fig. 2.

Finally, the leakage inductance does not change significantly during the test. Neglecting the secondary effect, the leakage inductance depends on the physical structure and dimension of the transformer core and windings only. The air-gap and material character of the core and windings do not impact the leakage inductance significantly. Therefore it is relatively stable during the transformer degradation.

III. End-of-Life Criteria and Lifetime Models

A. *End-of-Life Criteria*

To indicate the end-of-life of the planar magnetics, it is necessary to choose the failure indicating parameter and end-of-life criteria. They are open questions because there is no systematic research on the degradation and failure of planar magnetics until now. The failure indicating parameters includes the primary inductance, the winding resistance, stray

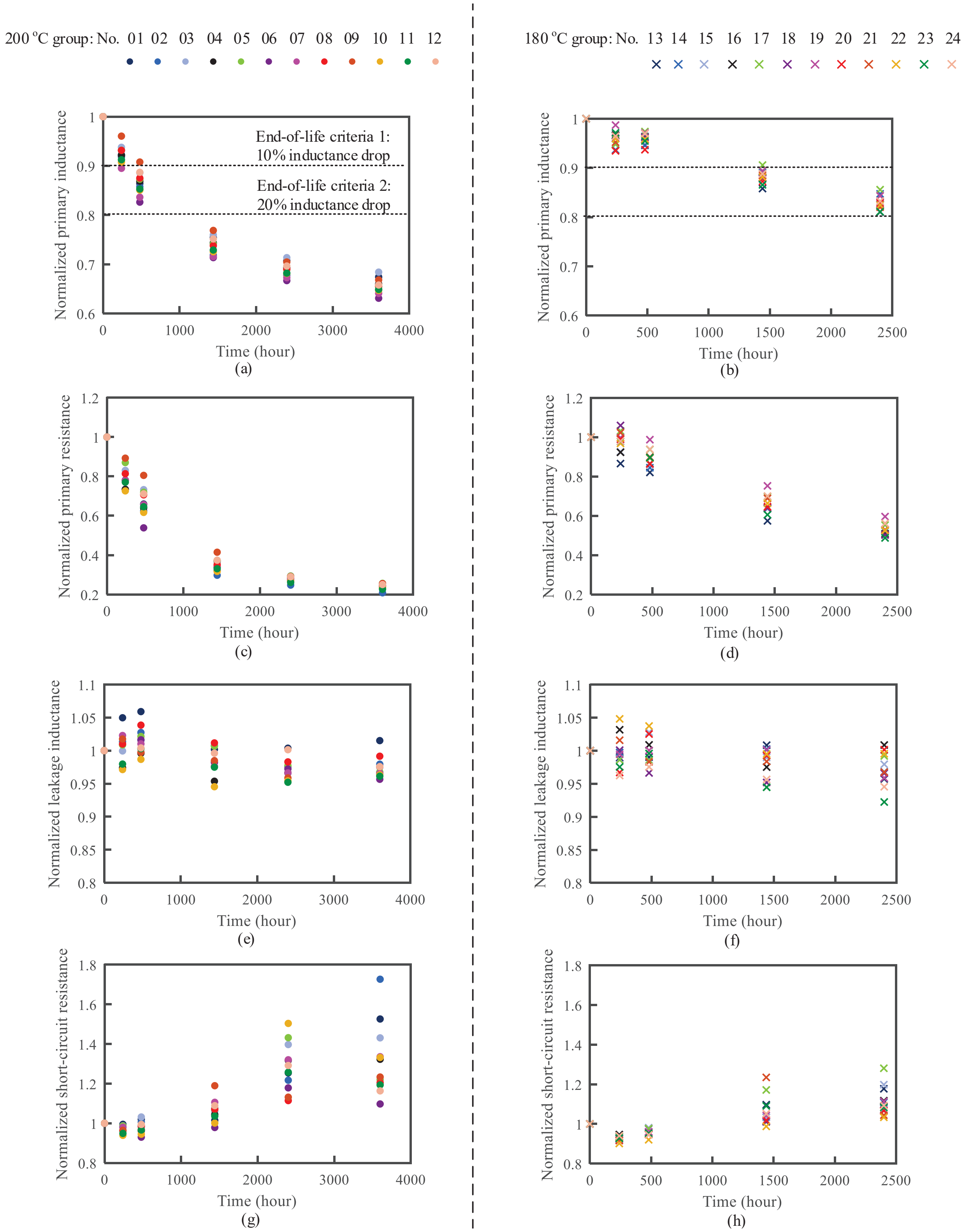

Fig. 4: Parameter changes of the planar transformer P1. (a), (c), (e), (g) are the normalized primary inductance and resistance, leakage inductance, and short-circuit resistance at 200 °C, and (b), (d), (f), (h) are at 180 °C, respectively.

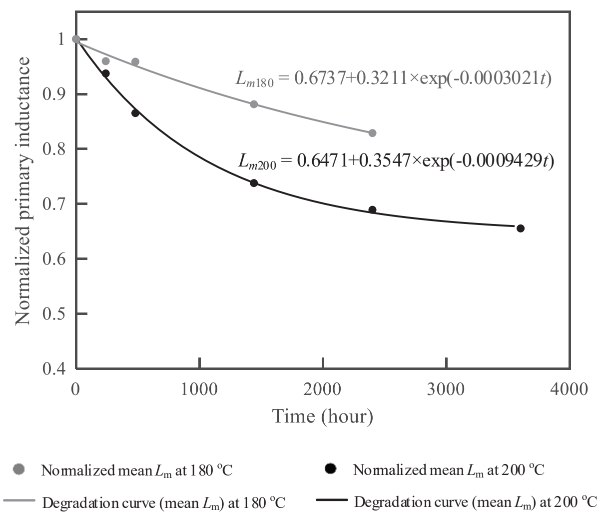

Fig. 5: Mean normalized primary inductance and the corresponding degradation curves at 180 and 200 °C, respectively.

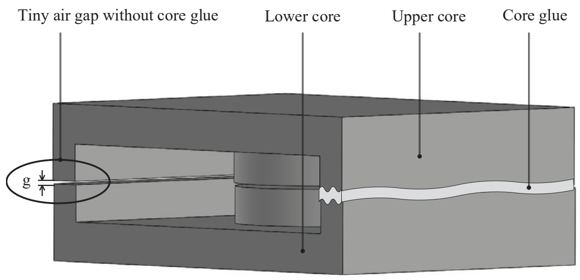

Fig. 6: The planar transformer cores and the core glue between them. Normally both the left and right limbs are with the core glue in between, however the glue in the left limb is not drawn to show the tiny air-gap length g.

capacitance, leakage inductance, etc. Normally the inductance affects the current and operation mode, the resistance increases leads to the overheating, and the stray capacitance causes the current ringing, respectively.

For the end-of-life criteria, there are absolute value, slope of change, and change percentage, respectively. Magnetic components are normally with significant manufacture tolerances. For instance, the loss density and permeability of the core is with 3% to 40% tolerances, depending on different manufacturers. Moreover, when assembling two pieces of half cores, the core glue is used in between. It introduces small slit and the air-gap g between the cores. Those two factors cause the variation of the main inductance L_{m} of different samples. Therefore, using a absolute value criteria to indicate their failure is difficult. Using slope of change as the criteria is with physical meaning. For some parameters the slop increases with degradation which indicates the accelerated aging till failure. However no parameters is with this feature in out test. Finally, the degradation change percentage α_{d} is used as the the end-of-life criteria, and the primary inductance L_{m} is chosen as the indicating parameter. α_{d}=10% and 20% are assumed to indicate the end-of-life of the planar magnetics. Once L_{m} drops below the range, the circuit is possible to operate abnormally, and the current ripple exceeds the limitation.

B. Lifetime Model

The Arrhenius equation is widely adopted for the lifetime modeling under thermal aging [12]

$$L = L_0 \times \exp[(\frac{E_{\mathrm{a}}}{K_{\mathrm{B}}})(\frac{1}{T+273} - \frac{1}{T_0+273})] \tag{3}$$

where L, L_0, T, and T_0 are the real and rated lifetime and temperature of the component, E_{a} is the activation energy with unit eV, K_{B} is the Boltzmann's constant ($8.62 \times 10^{-5}\mathrm{e}V/K$). The Arrhenius model was proposed by Svante Arrhenius in 1889. It assumes that the wear-out of the device is driven by the temperature-dependent chemical reaction. Depending on different application scenarios, failure mechanisms, and device under investigation, the formula is regarded as an empirical relationship, and its activation energy E_{a} are normally obtained from the curve fitting of the field data.

Based on the Arrhenius model, the lifetime calculation procedure of transformer P1 is introduced below.

- Choose the end-of-life criteria: from the test results in Fig. 4, assume the decrease of L_{m} will cause significant current ripple and affect the circuit operation, α_{d}=10% and 20% are chosen as the end-of-life criteria;
- Determine end-of-life time: perform curve fitting of L_{m} in Fig. 4(a,b), use α_{d}=10% and 20% as the criteria and find the related failure time of each sample at each temperature;
- Plot Weibull probability: plot the end-of-life time of each sample in the Weibull paper, the result of α_{d}=10% is in Fig. 7;
- Obtain B1/B10 lifetime: in the Weibull plot, the B1/B10 lifetime is the interact point between the probability line and the 1%/10% unreliability line, respectively. The B1/B10 lifetime indicates that 1%/10% of the samples fails when the planar transformer reaches its lifetime. The B10 lifetime points at each temperature are pointed out in Fig. 7 and are used for the lifetime calculation.
- Calculate lifetime model: based on the B10 lifetime of different temperatures, calculate the lifetime using Arrhenius model (3), as in Fig. 8.

The calculated B10 lifetime of P1 using α_{d}=10% is

$$L = 240 \times \exp[(\frac{1.1}{K_{\mathrm{B}}})(\frac{1}{T+273} - \frac{1}{473})] \tag{4}$$

using the end-of-life criteria α_{d}=20% is

$$L = 770 \times \exp[(\frac{1.1}{K_{\mathrm{B}}})(\frac{1}{T+273} - \frac{1}{473})] \tag{5}$$

The lifetime L is in unit of hours, and temperature is with Celsius. These lifetime models are with the rated lifetime 240 and 770 hours at 200 °C for α_{d}=10% and α_{d}=20%, respectively. Using the models, at 140 °C, the lifetime of

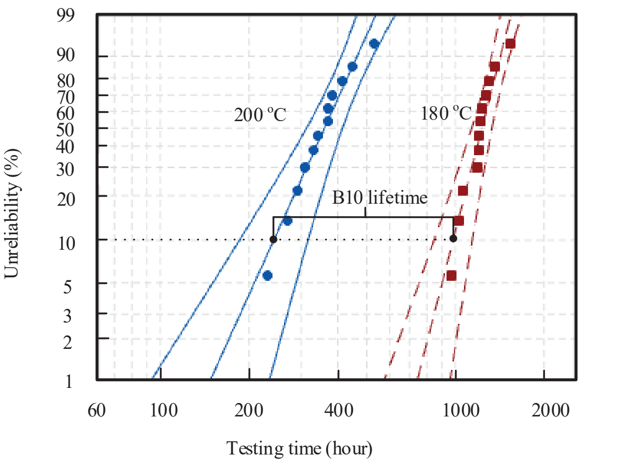

Fig. 7: The probability plot of the planar transformer with the degradation criteria percentage α_{d}=10% as end-of-life criteria. The data is from the test results in Fig. 4(a,b). The Weibull distribution is applied, the two-sided confidence interval with 95% confidence level is also plotted. B10 lifetime at 200 °C and 180 °C are 240 and 980 hours, respectively.

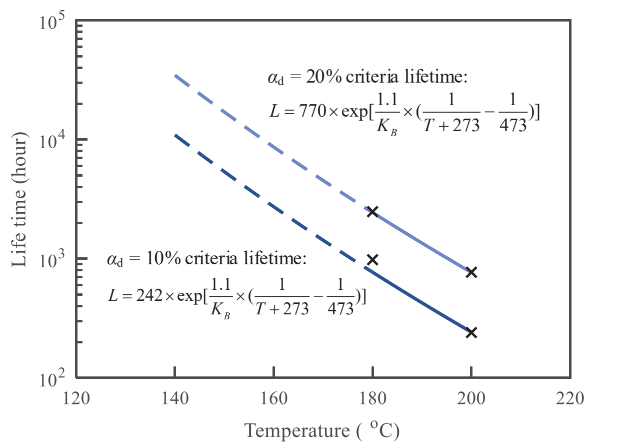

Fig. 8: B10 lifetime calculation based on the Arrhenius model, 50% confidence level. For the α_{d}=10% criteria lifetime, two B10 lifetime points at 200 °C and 180 °C from Fig. 7 are used. Between this temperature range the lifetime is with validation and therefore with solid line, while out of this range is with dot line. Obtaining B10 lifetime points of α_{d}=20% follows the similar way. E_{a} = 1.1 for both two lifetime equations. It is obtained from the curve fitting of the two equations simultaneously. K_{B} is the Boltzmann's constant ($8.62 \times 10^{-5} \mathrm{eV}/K$).

the planar transformer P1 under the 10% and 20% primary inductance drop criteria are 10,800 hours (1.2 years) and 34,800 hours (4.0 years), respectively. 140 °C is usually the maximum temperature of the PCB material using FR4 substrates. In the tested planar transformers, they are with much higher temperature grade PCB boards. Therefore if the same core glue is still applied for FR4 PCB transformers, the degradation of the core glue should be taken into the consideration for the system-level reliability evaluation.

Finally, in the above case, the failure indicator L_{m} and the end-of-life criteria α_{d}=10% and 20% are all based on the assumption. The choose of the failure indicators causes a significant difference in the lifetime results. Therefore, a proper lifetime modeling requires a suitable lifetime model and end-of-life criteria at the same time, which heavily dependents on the failure mechanism of the device, the application area, and the field requirements in terms of the parameter control, functionality, efficiency, etc.

IV. Conclusions

This paper presents the degradation analysis and lifetime assessment of planar magnetics. Various parameters of the planar transformers, e.g., inception voltage of the PD test, primary inductance, short-circuit resistance, etc. are tested. Based on the test results, the degradation and the likely failure mechanisms of the insulator, core, and PCB are analyzed. For the tested planar transformers, the PCB degradation and deadhesion of the core glue are likely to be the primary failure cause. It can be used to guide the chosen of the PCB thermal grade and core glue. The lifetime modeling procedure is presented while the end-of-life criteria are chosen based on the primary inductance drop percentage. At 140 °C, with 50% confidence level, using 10% and 20% primary inductance drop as end-of-life criteria, the predicted B10 lifetime are 1.2 years and 4.0 years, respectively. Further investigation of the proper end-of-life criteria based on application requirements and failure mechanisms are needed.

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