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Article

Thermal Aging Study of an Anodized Aluminum Strip Wire for Winding and High Temperature Use

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Abstract: Electrical machines are commonly used in industries and transport and are manufactured with enameled wire coils with polymer insulation. In extreme conditions, as in aeronautics and aerospace, where temperatures exceed 280 °C, the organic insulation deteriorates and it is necessary to find another way to insulate winding wires, in order to ensure a longer life duration of the insulation system and a better operating reliability of electric motors in these environments. Ceramics are more resistant to high temperatures than polymers and the proposed study focuses on the temperature dependence of the dielectric properties of anodized aluminum strips for use in high-temperature electrical machine windings. Different dielectric parameters are measured during thermal constraint. The purpose is to determine the temperature index of the anodized strip and propose a thermal stress life model.

Keywords: electrical machine; insulation; high temperature; thermal aging; dielectrical parameters



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1. Introduction

The voltage and thermal stresses applied to the electrical insulation system (EIS) of a rotating machine increase the risk of occurrence of very unfavorable phenomena, such as partial discharges (PD). They accelerate the aging of the insulation systems [1].

The concept of aging of an insulating material can be defined by a progressive and irreversible loss of material properties. Insulators are complex structures, the material can be seen as a chemical reactor that reacts to heat, ambient oxygen and other elements, such as water; chemical transformations are generally intertwined [2–7]. In addition to this, copper conductor is widely used as a conductor of the enameled wire used in the winding of electrical machines. It oxidizes at a high temperature, resulting in degradation phenomena at the copper–insulation interface that causes premature aging of the insulation. So, for high temperatures, the copper must be protected by a nickel layer [8], for example, or another stable metal.

Electrical machines are subject to different constraints depending on their operating environment. It has been shown that, at low voltages, the organic insulation system is sensitive to thermal stress. The latter causes premature aging leading to a fault and, therefore, to a reduction in the life duration of the electrical machine [1–6].

Improving the performance of the electrical insulation system can be done in several ways. The first method consists of adding an insulating tape between each turn. This solution has been tested before and cannot be retained [9]. Indeed, adding a tape several microns thick degrades the filling coefficient of the slot and involves an actuator less compact. In addition, subjected to temperatures above 300 °C, the mica ribbon becomes friable and quickly disintegrates. It is also possible to use fiberglass or rock fiber fabric, but the electrical machine will not also be compact [9,10].

Anodized aluminum tape began to be used in electrical windings from the 1950s. In the case of transformers and certain electrical machines, the coils work perfectly for

maximum inter-turn voltages of 200 Vrms [10]. In the case of electromagnets' winding, the voltages involved at the terminals of the coils are less than 100 V [11].

The substitution of the classic organic varnish by an inorganic ceramic-type insulation represents a promising alternative for the future of “high temperature” electric actuators [12–14]. The insulation is based on alumina that has fewer good mechanical characteristics than polymers; nevertheless, it can be mixed with other compounds to improve its characteristics [15]. The Alumina with the formula Al_2O_3 (Aluminum oxide) is obtained by anodization. This is an electrochemical process that directly transforms the conductive surfaces of the conductor into an electrical insulation system (EIS). It is, therefore, not an addition of an insulating material on the conductor.

Using a strip has many advantages. It allows the obtaining of a compact actuator but also avoids the small radii of curvature encountered on a round wire, preventing the latter from being wound without breaking the alumina layer. A previous study demonstrated that for windings placed on rectangular teeth, the anodized aluminum strip offers a better filling than round ceramic wire [13]. Therefore, the current density is lower. Consequently, with the anodized strip wire, the power density may increase, by increasing the currents for the same winding volume. It has been also demonstrated, that at equivalent electrical resistance, and taking into account the higher density of copper, the use of aluminum wire will allow a reduction in mass of 50% of all the stator coils, and this is despite its higher section. It is also possible to improve the mechanical properties of the insulation and have immobilized windings by a high temperature potting cement.

Aluminum can, therefore, be considered an “eco-friendly” metal; first of all by the fact that it is extremely easy to recycle, but also by the fact that the anodizing processes are becoming increasingly efficient in terms of environmental impact [16].

Nevertheless, the service life of this insulation is unknown for an application in the field of high temperature electrical machines. Therefore, the purpose of this paper is to evaluate the lifespan of anodized tape, using accelerated aging tests. Thus, the limits and conditions of use, under thermal stress, such as thermal index, will be defined, and dielectric parameters, such as partial discharge inception voltage (PDIV), breakdown voltage and dissipation factor are also measured during thermal aging. These data will be useful in the case of dimensioning a high temperature electrical machine.

2. Presentation of the Anodized Aluminum Strip

The insulation technologies of a copper conductor can be transposed to an aluminum conductor: inter-turn insulation in the shape of tape covered by a layer of varnish; however, another method of insulation, which does not exist in copper, is used for aluminum, it is called anodization. This technology consists of creating a layer of alumina (chemical formula Al_2O_3) as an inter-turn insulator, obtained by a chemical reaction from the conductor itself. The main problem with this insulation is the fragility of the alumina, as the ceramics are rigid and do not support mechanical manipulations that are too brutal [13]. The wire that was tested is in the form of a strip of 6 mm wide with a conductive part (aluminum) of 50 μm thick insulated by an alumina layer of 6 μm thick (Figures 1 and 2). To verify these dimensions, a cut of the aluminum tape was made and observed under a microscope after impregnation with a colored resin, as shown in Figure 2.



Figure 1. Anodized aluminum strip.

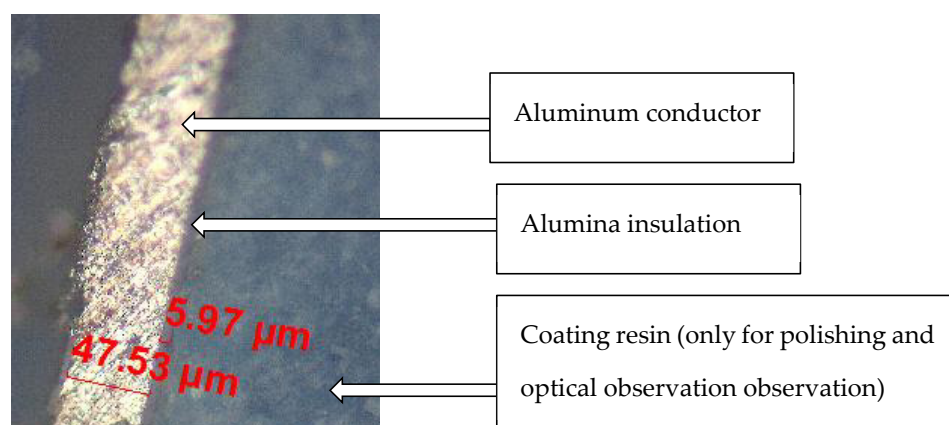


Figure 2. Microscopic section of the tape ($\times 500$).

Previous tests carried out on a configuration involving the superposition of two tapes on a flat surface showed breakdown occurring consistently at the edge of the tape [10]. The configuration adopted for the partial discharge measurements will be obtained by superimposing two ribbons (Figure 3), each mounted on a cylinder. The two cylinders are then arranged in a cross, so that the edges of each of the ribbons do not come into contact. To avoid any contact of the tape with the conductive stainless steel cylinder, a mica tape is rolled up beforehand, before placing the aluminum tape. This arrangement makes it possible to approach an inter-turn configuration while avoiding edge effects.

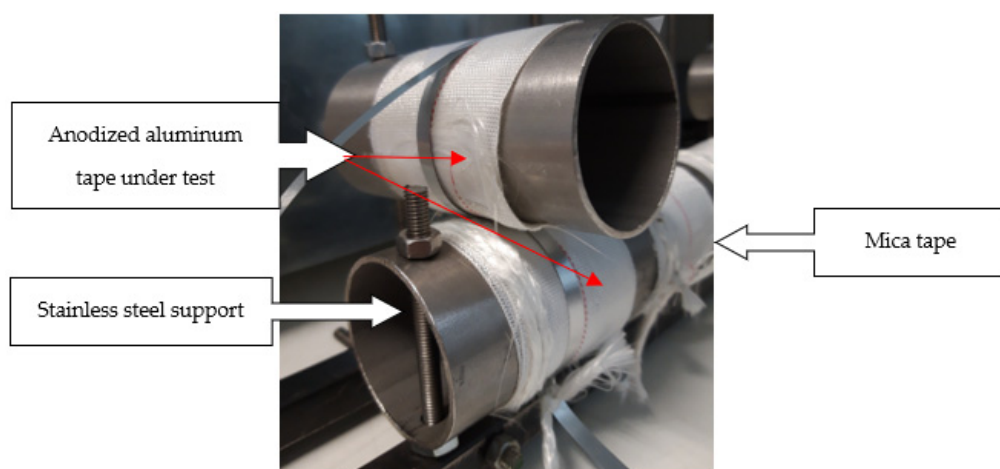


Figure 3. Crossed samples configuration.

3. Dielectric Properties Characterizations

3.1. Partial Discharge Inception Voltage Measurements

3.1.1. Measurement Device Description

The measurement circuit of the partial discharge inception voltage (PDIV) used is based on the IEC 60270 standard [17]. It mainly includes an object under test, which can be considered as a capacitance (capacitance of the sample under test), a coupling capacitor C_k , a high ac voltage source (50 Hz) with a low level of background noise (Figure 4). It includes a HV transformer and a low pass filter. This filter reduces the noise coming from the external circuit. The coupling capacitor allows one to keep the voltage stable on the measurement side. In the ideal case it keeps the voltage constant during partial discharges; for this, its capacitance should be higher than that of the sample in order to have negligible impedance. It also permits to the partial discharges current to flow in the coupling device.

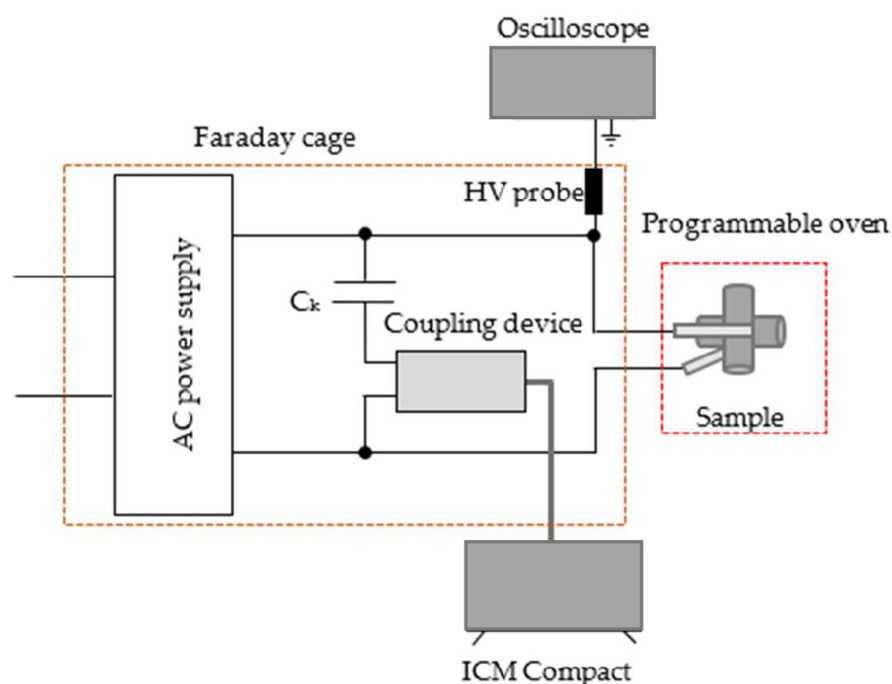


Figure 4. Partial discharge inception voltage measurement system.

All these measurement circuit elements are put into a Faraday cage in order to reduce electromagnetic noise.

The objective of this first test is to know the behavior of the PDIV when the anodized strip is subjected to increasing thermal stress. To do this, ten samples of the aluminum tape are placed in a programmable oven, with two openings allowing the passage of connection cables, necessary to carry out measures.

After closing the oven, it is programmed. First, the temperature is increased by 25 °C for 15 min, then paused for 10 min to take the measurements; the temperature is increased up to 450 °C. These measurements, with novel samples, are reproduced for each temperature by step of 50 °C up to 450 °C.

As soon as the desired temperature is reached and stable, the voltage is increased slowly until the appearance of PD on the ICM Compact measuring device, the corresponding voltage is noted on the oscilloscope; it represents the PDIV.

Based on this measurement system, the breakdown voltage is measured according to the IEC 60851-5 [18].

3.1.2. Results

The PDIV mean values data are shown in Figure 5. Three areas emerge from this figure:

- For a temperature $T < 100$ °C (area 1): the PDIV increases. This can be explained by the drying of the samples; there is no ambient humidity above 100 °C. In addition, during the anodizing process, after the formation of the alumina layer, the clogging of the pores of the insulating layer is achieved. A phenomenon of hydration of the alumina then occurs on the surface layer. This hydration involves a change of state of the alumina, which is then transformed into alumina monohydrate ($\text{Al}_2\text{O}_3(\text{H}_2\text{O})$) [19].
- For 100 °C $< T < 350$ °C (area 2): PDIV is stable. Heating the sample up to 100 °C causes partial drying of this monohydrate layer, thereby causing this increase in PDIV [20].
- For $T > 350$ °C (area 3): The PDIV decrease phenomenon can be explained by the alumina transition changes that always occur at these temperatures [20,21].

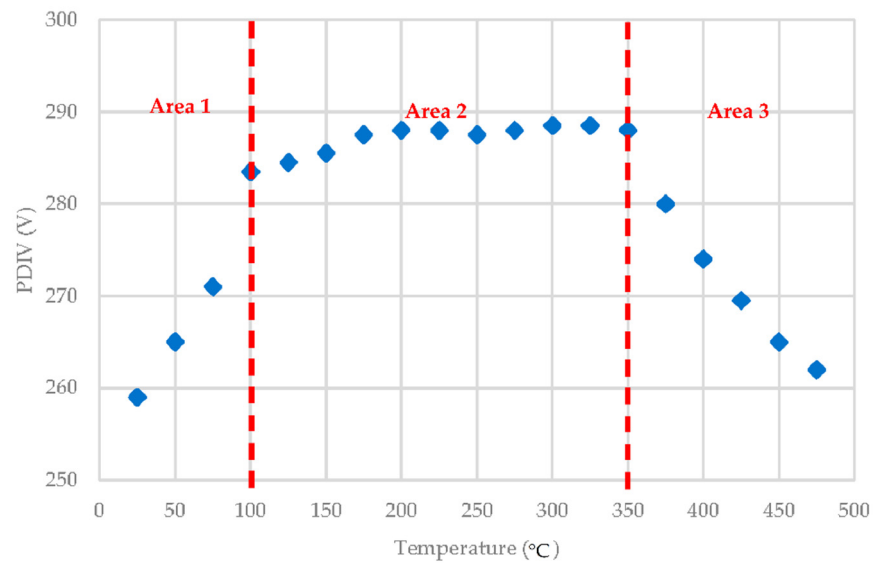


Figure 5. Temperature dependence of the discharge inception voltage (PDIV).

The mean values of the breakdown voltage data are presented in Figure 6. The analysis of the results can lead to same observations with PDIV data.

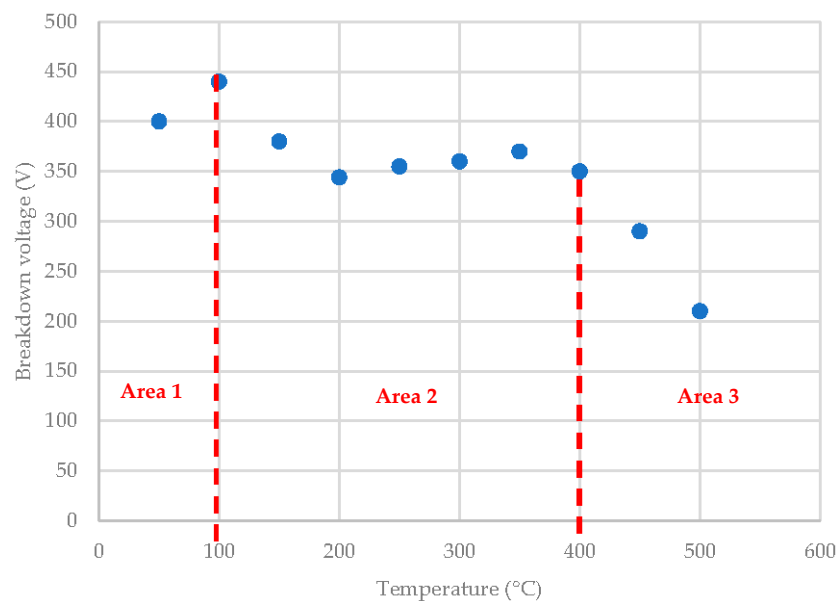


Figure 6. Temperature dependence of the breakdown voltage.

3.2. Dissipation Factor Measurement

When two conductors are insulated by a dielectric, a capacitor is formed, and the value of its capacitance C_p depends on the dielectric material used and the distance between conductors. The losses at the level of the dielectric are presented by the dielectric loss factor $\tan(\delta)$, named dissipation factor, which is a function of C_p and the resistance of the dielectric R_p .

This makes it possible to determine whether the insulator maintains a capacitive behavior. When a dielectric has high losses, it plays the role of insulator.

3.2.1. Measurement Device Description

The measurement is made by an “Agilent E4980A” measuring device by choosing a frequency $f = 10$ kHz in accordance with the chart of the device in order to have an

optimal precision of the readings of 0.1%. The same heating procedure followed for PDIV measurements is used and tests were achieved for five samples. For each temperature C_p and R_p are measured. The value of tangent delta is deduced by:

$$\text{tg}(\delta) = \frac{1}{2 \times \pi \times f \times C_p \times R_p \omega} \quad (1)$$

with:

C_p : parallel capacitance (F).

f : measurement frequency (Hz).

R_p : parallel resistance (Ω).

3.2.2. Results

The results are presented in Figure 7. They are correlated to the PDIV and breakdown voltage data. At the beginning of the rise in temperature, a desorption phenomenon occurs. This phenomenon makes it possible to improve the dielectric performances in this zone. The dielectric properties are improved, and losses begin to decrease after 100 °C, that represents the water (H_2O) evaporation temperature and air drying, but they increase sharply from 350 °C due to the phase change of the alumina. The slope of the increase is illustrated by red dotted line. Similar changes in the dielectric behavior of alumina have also been observed previously [22,23]. For higher temperatures, the dielectric properties are modified due to thermal agitation and the presence of H_2O molecules at the interface between the air and the insulation following a chemical reaction between Al_2O_3 and O_2 gas (in air).

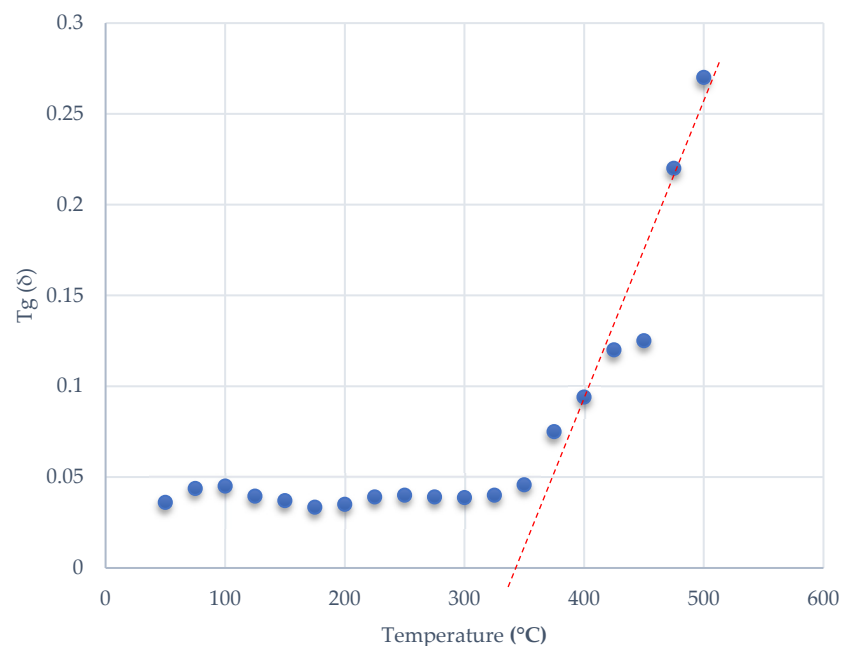


Figure 7. Temperature dependence of the dielectric loss.

4. Thermal Aging

IEC 60505 establishes the basis for estimating the aging of EIS under different constraints [4]. Generally, standards specify the procedures that should be followed, during the development of testing or assessment methods, to establish the life of a specific insulation system. Currently, in the field of electrical machines, the standards only apply to winding wires insulated with polymers. There is no standards for non-organic (ceramic) enameled wire insulation used in the winding of electrical machines.

The degradation phenomena are not the same as in the case of ceramics, in particular for the anodized wire. It was, therefore, necessary to embark on various preliminary tests to try to find the method of accelerated thermal aging in order to estimate the thermal index of the anodized strip.

Actually, the enameled wires are classified by thermal index. Its determination is achieved according to IEC 60270 and IEC 60851-5. It is the temperature, expressed in degrees Celsius, for which the time taken to reach a specific point in the degradation process is 20,000 h. This concept is based on the Arrhenius law that describes the variations of the rate of a chemical reaction as a function of temperature. This law has been verified on a large number of chemical reactions, but it remains an empirical law that has many limitations. It works well enough to extrapolate results when the temperature difference remains reasonable. In the field of aging of materials, the Arrhenius law is often used to predict the lifetime of a material subjected to a thermal stress at given temperature T_1 from accelerated aging tests carried out at temperatures above T_1 .

4.1. Test Description

To limit the duration of accelerated aging tests, it is necessary to apply short cycles at high temperatures. The durations and temperatures of the thermal cycles correspond to the thermal endurance graph defined by standards IEC 60216-1 and IEC 60216-3 [24,25]. In accordance with this standard, the samples must be exposed at least to three temperatures. For each temperature, ten thermal cycles are provided. The lowest temperature should lead to a time of more than 5000 h until failure. An exposure temperature producing values below 100 h is generally considered too high. Exposure temperatures should not differ from each other by more than 20 °C.

Based on the curve of Figure 7, the thermal index of the aluminum tape is supposedly equivalent to the temperature that corresponds to the crossing of the tangent of the second part of the curve with the abscise axis (red line drawn). This temperature (350 °C) defines the limit from which the dielectric characteristics of the insulation begin to be modified. The extrapolation of the standard has allowed us to determine the thermal cycles specifications for the anodized tape:

- 24 h cycles under 460 °C,
- 72 h cycles under 440 °C,
- 168 h cycles under 420 °C.

For each temperature, 10 aging cycles are planned. The aging can be stopped before the 10 cycles if, during the proof tests, the percentage of defective specimens exceeds 50%. According to the standard, the limit point, which characterizes the estimated lifetime, corresponds to the destruction of 50% of the aged samples after a proof test under a specific voltage for 10 s. Following the PDIV measurement, this voltage is fixed at 150 V as there is no standard for this new wire.

The measurements are taken at room temperature, after the oven has cooled down naturally, in order to avoid thermal shocks. During any interruption of the test, the samples are left at 25 °C in the oven to reduce any influence from the environment while remaining at a temperature that does not accelerate aging.

4.2. Results

The different cycles have been carried out. It has been observed that the insulating layer has undergone degradation. An example of a sample microscopic section that has undergone thermal degradation is illustrated on Figure 8. Indeed, it can be seen that the thickness of the alumina insulating layer has decreased. Let us recall, as illustrated on Figure 2, it was 6 μm before aging. This decrease is not “natural”; one would have expected, on the contrary, that the oxidation increases with the temperature.



Figure 8. Microscopic section of the strip after seven cycles of 72 h at 440 °C.

Component performance degrades at high temperatures. The process can generally be described by Arrhenius' law, which expresses lifetime as an exponential function of the reciprocal of absolute temperature [60216-3]:

$$L_t = \frac{1}{A} \cdot e^{-\frac{E_a}{RT}} \quad (2)$$

with:

L_t : lifespan under thermal stress in hours.

A : material constant, to be estimated from experimental data (s^{-1}).

E_a : activation energy, to be estimated from experimental data.

R : is the universal gas constant $8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$. T : operating temperature (K).

Arrhenius' law is based on observations of chemical reactions: the more the energy in the system increases, the more the chemical elements present tend to exceed their energy barrier, which degrades their lifespan.

The thermal endurance curve has been determined and plotted in Figure 9. By applying the definition of the thermal class given in the IEC 60270 standard, this curve allows us to determine the temperature index by interpolating the line up to 20,000 h, the temperature that anodized tape can withstand is 350 °C.

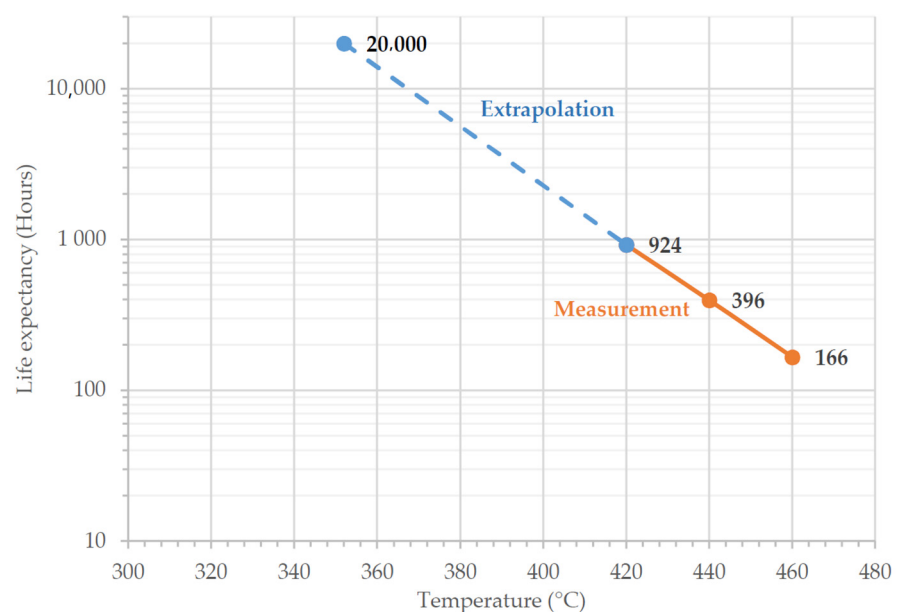


Figure 9. Thermal endurance graph of the anodized strip.

The lifespan parameters of equation 1 are estimated from the three used temperatures during thermal aging 460 °C, 440 °C, and 420 °C: $A = 16,447 \times 10^{-11} \text{ (s}^{-1}\text{)}$ and $E_a = 184,080 \text{ (J/mol)}$.

5. Conclusions

The behavior of the anodized aluminum strip dielectric parameters under thermal constraints is studied in this paper. The insulation of the conductive tape is obtained by the electrolytic process of anodization made continuously on the strip. Previous work has made it possible to compare the electrical characteristics, and the analysis of the life cycles of the coils based on this tape, to other round wires insulated with ceramics or polymers. The purpose of this study is to determine its thermal endurance and establish its life expectancy and thermal index for high temperature electrical machines application.

At first, the dielectric characteristics under the effect of temperature are studied, in particular the dielectric losses, the PD appearance voltage, and the breakdown voltage. The use of alumina makes it possible to increase the operating temperature range. However, they possess low mechanical strength and lower PDIV than many organic insulators. Therefore, the use of this type of conductor in an electrical machine operating at high temperatures, and powered by a voltage converter, requires rethinking the structure of the conventional machines currently produced.

The thermal class of the anodized aluminum tape is 350 °C. It will be interesting to perform more tests with other temperatures to confirm the lifespan equation. However, this life span is clearly higher than the conventional polymer and opens various novel applications for electrical motors.

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