Reliability of Electrolytic Capacitors

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Introduction

Aluminum Electrolytic Capacitors („e-caps“, „electrolytics“) are vital to the function of many electronic devices. Ever-increasing requirements for energy-efficiency, the expanding utilization of renewable energy, and the growth of electronic content in modern automobiles have driven the spread of these components significantly over the past decades.

In many applications, lifetime and reliability of the electronics are directly linked to the corresponding parameters of the electrolytics [4]. While a previous article of the author [1] elucidated the topic of lifetime estimation for electrolytic capacitors, this article focuses on the reliability of electrolytics.

Construction and Manufacturing Process of Electrolytic Capacitors

Aluminum electrolytic capacitors combine voltage proofs ranging from several volts to about 750 Volts and a wide capacitance range from 1 µF to above 1 F, while offering a compact size. A highly roughened anode foil is being completely covered by a thin dielectric layer and contacted by an exact fitting cathode, the electrolyte liquid. (Fig. 1).

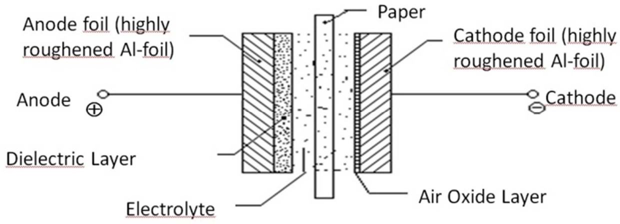

Fig. 1: Construction of an aluminum electrolytic capacitor

The manufacture process of e-caps comprises the following major production steps:

1. Etching – high purity aluminum foils of thickness 20 ~ 100 µm are the base material for the later anode- and cathode foils. The etching enlarges the total surface area of the anode material up to a factor of 140 (Fig. 2), compared to their geometric surface.

2. Forming – the anode foil bears the dielectric layer of the e-cap and consists of aluminum-oxide (Al_2O_3). It is deposited on top of the roughened anode foil by an electrochemical process called anodic oxidation or forming. The quality of the forming, i.e. the homogeneous and complete coverage of the surface area is essential for the high reliability of the components during operation. The further the forming voltage is above the rated voltage, the smaller becomes the probability of dielectric breakdown. Typical values for the ratio of forming voltage vs. rated voltage of Jianghai electrolytics range between 1.25 (low voltage) and 1.60 (high voltage). The thickness of the dielectric layer is approximately 1.4 nm/V; this amounts to about 900 nm for an e-cap with 450 V voltage proof (this is less than 1/100 of the thickness of a human hair).

3. Slitting – the etched and formed foil comes on so-called mother rolls of about 50 cm width. By slitting, the mother rolls are cut into the widths needed for the anode and cathode material.

4. Winding – attachment of electrical contact tabs to the foils (stitching, cold welding) and winding of anode, paper (spacer, multi-ply if needed), and cathode foil.

5. Impregnation – the pores of the spacer paper in the wound cell and the complete surface area of the anode foil are covered by electrolyte, the liquid cathode.

6. Assembly of the capacitor wound cell into the can, electrical connection between contact tabs and soldering or screw terminals and riveting of the can for a tight seal.

7. Post-forming („Burn-in“) to heal the cut edges of the foil.

8. 100% in-line control of the vital electrical parameters (capacitance, dissipation factor, and leakage current.

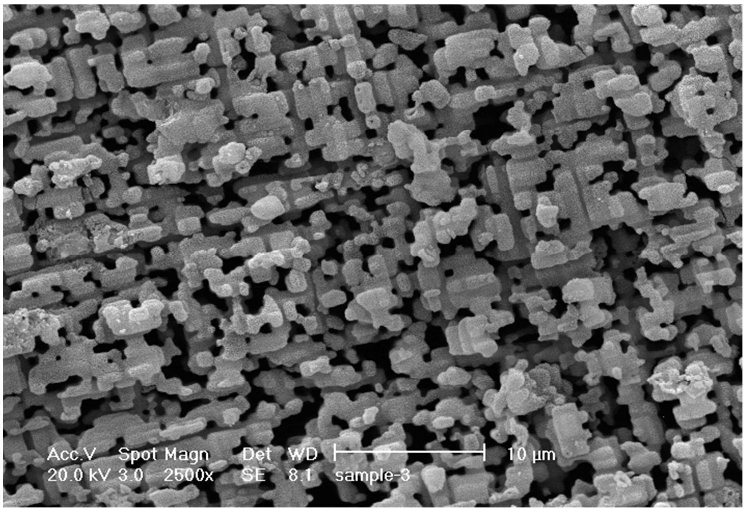

Fig. 2: Top view of the etched anode foil

Fig. 2 shows the electron micrograph of the surface of an etched high voltage anode foil. The homogeneous distribution and the large free diameter of the etched pits allow for good coverage by the oxide layer and full access of the electrolyte to the complete surface are of the anode foil. Already at this early stage of the production it is determined whether the resulting e-cap will be suitable for demanding, professional industrial applications with high requirements to reliability, ripple current capability, and long lifetime.

In particular, process steps 2 and 7 have great influence on the reliability of e-caps under operation. Jianghai pursues the target of maintaining a sufficiently high distance of the forming voltage from the rated voltage and a reasonable dwell-time during post-forming to ensure high reliability. As the forming voltage is commonly not indicated in the datasheets, the final user of the components has a hard time to use this parameter as a performance indicator. By asking the e-cap supplier and by comparing the leakage current ratings, the end user may draw his conclusions with respect to the design philosophy of the e-cap manufacturer. In times of rising material and energy prices, even some well-known manufacturers resort to lowering the forming voltages of running series. From a quality perspective, Jianghai considers these “cost-optimization measures” being not acceptable.

Lifetime vs. Reliability

Electrochemical aging mechanisms limit the lifetime of e-caps to a value that can be estimated depending on temperature, ripple current and voltage during operation. During this lifetime, random failures may occur at any time. The absolute number of these failures depends on the size of the observed total lot. The existence of random failures is usually not related to the aging process, but it is rather the consequence of hidden, internal weak spots (e.g., in the spacer paper, the foil, or in the vicinity of the electrical connections). Often, these failures happen without any pre-warning and end up in a short circuit. Increased leakage currents as a result of a damaged dielectric layer may lead to such a big formation (that goes along with the buildup of hydrogen gas) that the overpressure opens the safety vent. Then, the e-cap dries up and fails with low capacitance.

The 100% end measurement of capacitance, leakage current and ESR on all produced components and the conduction of additional tests on samples drawn from all mass production batches ensure the high quality level of the products. Hence, early failures in the application are a rarely observed exemption [2].

There exist many definitions of the term „reliability" and depending on whether you ask a statistician, mathematician or an engineer, you may obtain a different answer. A common sense approach to defining reliability could be: the probability of an electronic device for satisfactorily fulfilling the requirements of its mission within a defined time period.

The typical time course of reliability density for e-caps follows the so-called "bathtub curve" [3]. The failure rate ("FIT rate") λ designates the number of failures per unit time (failure density, measurement unit FIT = "Failures in Time" in $\frac{10^{-9} failures}{h}$).

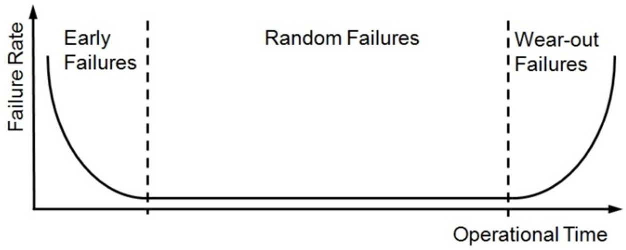

Fig. 3: Failure Rate vs. Time – "Bathtub Curve"

The bathtub curve in Fig. 3 shows three distinct consecutive segments:

1. The early failure period ("infant mortality") with a decaying FIT rate λ
2. The period within the normal lifetime has a constant FIT rate λ that describes the occurrence of random failures
3. The final segment with increasing FIT rates λ that originate from wear-out and changes beyond acceptable limits at the end or after the end of the regular lifetime

The so-called „failure rate" that is given in conjunction with the definition of the „useful life" refers to the outlier percentage, i.e. the relative amount of components that have parameters out of specification at the end of the lifetime test and must not be confused with the failure rate for random failures.

Failure Modes and Mechanisms

The normal failure mode of a regularly aged e-cap is a parametric failure due to low capacitance or increased ESR (Fig. 4, light green boxes).

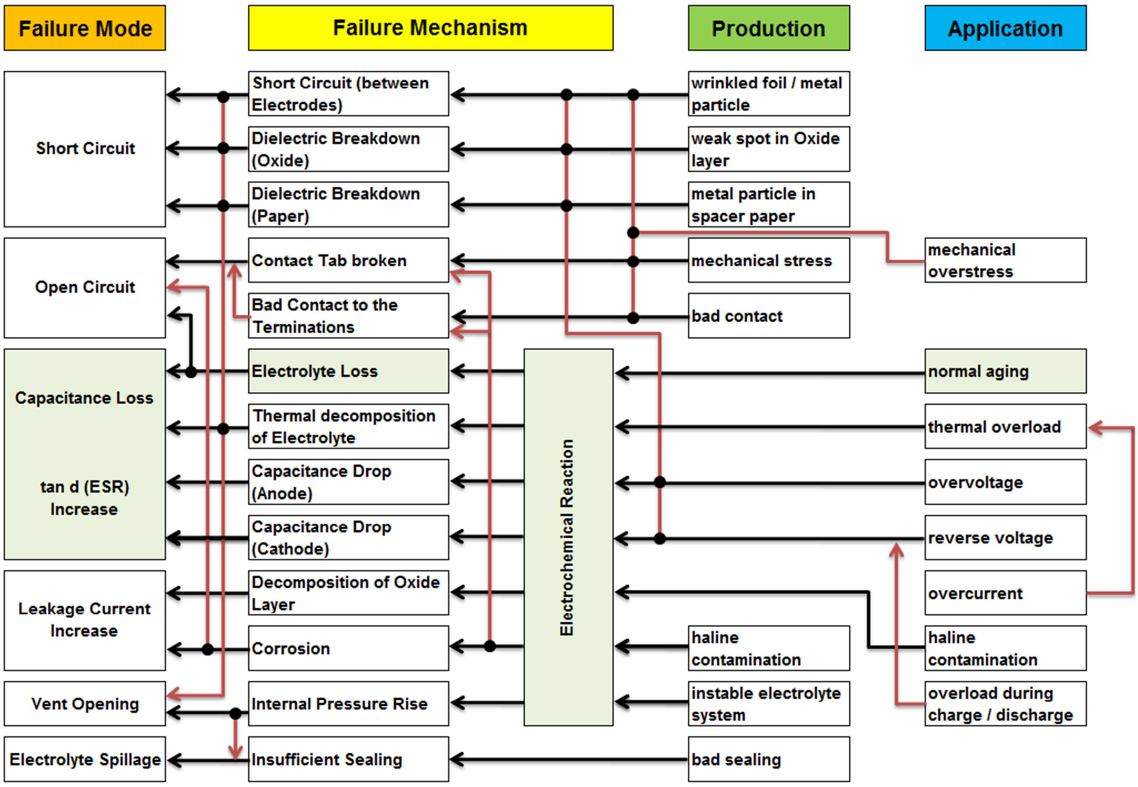

Fig. 4: Failure Modes and Failure Mechanisms

The failure mechanisms shown in the overview (Fig. 4) may originate from production or application related causes. In the field, production-related failures are rarely observed, because the purity of the base materials and the quality level of the mechanical production processes have been continuously improved over the past years. Often, failures can be traced back to arise from unfavorable operating conditions, because an overload in the application (e.g., ambient temperature, ripple current, operating voltage, vibration, mechanical stress, …) could sometimes neither be predicted nor be prevented.

Estimation of Failure Rates

Even when using best materials and world-class manufacturing processes in conjunction with an effective QA-system, random failures of components do exist in the field. In the context with the estimation of failure rates, the MIL-HDBK-217F is often referred to in literature, even though the handbook relies on component reliability data that has been devised some decades ago. The numerical values of the component failure rates found there often exceed the field failure rates observed with current Jianghai series by a factor of 10 ~ 100. Even in spite of these findings, the MIL-HDBK-217F data and the calculation schemes found there provide some insight into the dependency of failure rates on ambient temperature and actual operating voltage (Fig. 5). The failure rates are being normalized to operation at an ambient temperature of 40 ℃ and at 50 % of the rated voltage.

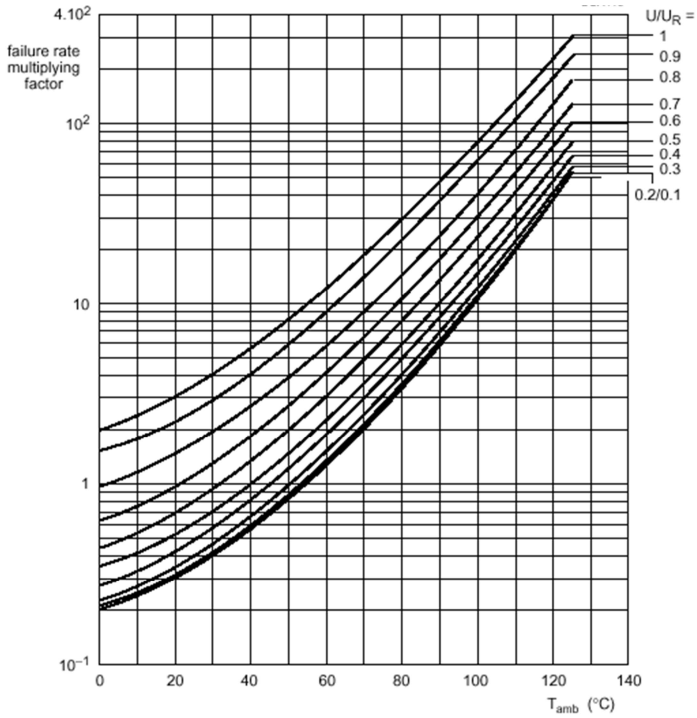

Fig. 5: Failure Rate Multiplying Factors (MIL HDBK-217F)

In order to obtain trustable reliability data from laboratory trials, a tremendous effort would be necessary. Experimentally gained test data from billions of unithours would be required, i.e. some 1 million e-caps should be tested at high labor cost. Jianghai rather uses the information on actual field failures at customers together with the typical application information (temperature, ripple current, operating voltage). Utilizing field data, the production data on quantities and types by technology, and laboratory test results, FIT-rates can be estimated at a reasonable effort. The order of magnitude for the estimated field failure rates is 0.5 ~ 20 FIT.

From the FIT-Rates, the MTBF (Mean Time Between Failures) can be easily calculated as its reciprocal: MTBF = 1 / FIT. Please note that the MTBF figure does not constitute a guaranteed minimum time until the first failure is observed, but rather indicates the mean time when about 37 % of the initial e-cap population are alive (similar to the radioactive decay, the distribution function for the failure of components obeys an exponential distribution).

Factors affecting Reliability

Reliability (and also lifetime) of e-caps of any brand and type depend in a non-linear way on temperature, ripple current and operating voltage. Small changes in any of these parameters show great impact on the overall performance of these components. A carefully designed circuit is essential for obtaining the required reliability level of a device:

- Complexity – reducing the component count enhances the reliability.
- Stress – Temperature, ripple current and operating voltage, sometimes in combination with mechanical stress like vibration, requires compromises with respect to cost and size. Whenever possible, the thermal stress should be kept to the minimum: for each 10 K of temperature increase, the failure rate of e-caps doubles!

- Reliability of individual components – when selecting components, their individual reliability should be considered taking into account their cost. High reliable components are usually bearing a higher price tag.

Successful Application of Electrolytic Capacitors

The majority of field failures observed with e-caps are not related to classical random failures. Beyond the scope of influence of the e-cap manufacturer, the end user is obliged to safeguard proper operating conditions by ensuring robust design, careful handling and manufacture processes and moderate environmental influences. See the below list for some hints on the successful application of e-caps:

<u>Transport and Storage</u>

E-cap cans (pure Aluminum) and e-cap seal (rubber) are soft and elastic. Obviously damaged (indented) components should thus not be utilized. Contamination by halines (in particular Bromide for sterilizing oversea shipments) are regrettably often found. This applies both to the shipment of individual components as well as to the transport of finished goods.

<u>Mounting and Assembly</u>

Pushing, pulling or bending of the terminals (in particular with radial e-caps) has to be avoided. Severe damage to the inner contacts of anode or cathode foil may result.

Glue, molding compounds and lacquers must be free from halines. In the vicinity of the e-cap's seal, an opening to the ambient should be maintained to prevent the build-up of a microclimate in a confined space beneath (risk of corrosion). Conducting tracks shouldn't be routed below any e-cap. Electrolytics must never be used as a „handle“ for a PCB.

<u>Soldering</u>

The soldering temperature limits specified by the manufacturer must be kept to avoid damages (bulging, lifetime loss or thermal destruction of the electrolyte). This applies in particular to the processing of SMT e-caps in a lead-free reflow process (higher temperature soldering profiles).

<u>Operation</u>

When switching on or off, voltage transients from inductive loads beyond the forming or reverse voltage may occur. Even if only applied once, these type transients cause permanent damage to the electrolytic capacitor and must be avoided by proper design.

Mechanical overstress during operation (e.g., self resonance) may cause breaking of connecting tabs. Gluing the e-caps to the PCB or placing them at a different location may solve the issue.

Any increase of ambient temperature by 10 K doubles the failure rate and halves the lifetime. Placing e-caps away from heat sources (heat sinks, power inductors,…) is thus benefitial.

Summary

By their individual reliability, aluminum electrolytic capacitors influence the reliability of the electronic devices they are mounted in. A thorough knowledge of some of the key parameters of these components are necessary to ensure the reliable design of electronic devices.

The definition of reliability and the most important influence factors on reliability are explained. A collection of practical hints helps as a guideline to the successful application of electrolytic capacitors.

The applicability of the general guidelines depends on the specific product type and the particular application. Consultations with the supplier are essential to get guidance throughout the design project and to confirm any estimates.

References

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Company Profile

Jianghai Europe Electronic Components GmbH with office and warehouse in Krefeld (Germany) supports the European customers of Nantong Jianghai Capacitor Co., Ltd. (Jianghai) in Nantong, China. Jianghai has been founded in 1959 at the location of the present headquarter – about two hours by car north of Shanghai. In the early years, Jianghai developed and produced specialty chemical products (e.g., electrolyte solutions). In 1970, the production of electrolytic capacitors was launched and during the following years, low and high voltage anode foil production facilities complemented Jianghai's portfolio. Being the no. 1 producer in China, Jianghai is one of the world's largest manufacturers of radial, snap-in and screw terminal electrolytic capacitors.

Author

Dr. Arne Albertsen was born 1965 in Eutin in the north of Germany and he studied physics with a focus on applied physics at Kiel University. Following diploma (1992) and doctoral thesis (1994), both on a subject from biophysics, he pursued an industrial career at Haase Energietechnik, a medium-sized enterprise that had specialized in landfill and renewable energy technologies. He held positions in R&D, product management, division head and assistant to the CEO before he started to work with leading manufacturers of electronic components like BCcomponents, Vishay, and KOA, in 2001. He worked in managing positions in design-in and sales and marketing for passive and active discrete components until he joined Jianghai Europe Electronic Components GmbH in November 2008. In his current position as manager sales and marketing, Dr. Albertsen is responsible for the support of European OEM accounts and distributors.

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