

INFLUENCE OF CAN FLATNESS ON HEAT DISSIPATION OF ALUMINIUM ELECTROLYTIC CAPACITOR

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The lifetime of aluminium electrolytic capacitors highly depends on their core temperature. Heat dissipation in general applications happens by the extended cathode, which is in contact with the inner side of the can. In the case of heat sink applications, the most important heat transfer phenomenon is the heat conduction through the bottom of the aluminium can. The quantity of the dissipated heat is in direct proportion to the size of the heat transfer surface. The more dissipated heat may increase the lifetime of the capacitor. Therefore, the flatness value of the can bottom is critical. This paper presents a flatness measurement method, which can successfully replace the equipment for a more complex and more expensive 3D measurement. It discusses an implementation of a measurement environment, where data acquisition and visualization are automated by a LabVIEW-based software. In addition, this study deals briefly with the influence of production processes on the flatness value of the capacitor produced by leading manufacturers.

Keywords: aluminium electrolytic capacitor, measurement automation, heat dissipation, graphical programming environment, flatness measurement

Introduction

The aluminium electrolytic capacitor is the most commonly applied capacitor type, due to the fact that the capacitance and voltage range of the components is wide. The rated voltages change from 5 V to 550 V, while the capacitance 1 μ F to 3 F. These are applied in many fields of industry, such as energetics, power electronics, automotive application, etc. and used for energy storage, smoothing and filtering function. The lifetime of the capacitor highly depends on its core temperature. Each decrease of 10 °C doubles the lifetime [1]. Operating temperature is determined by the ambient temperature, by the applied ripple current, by the used voltage, and by the equivalent serial resistance (ESR). There are two ways for the reduction of core temperature. The first one is the extended cathode foil and the second one is the cooling of the capacitor can. Cooling in general applications is realized by applying a heat sink at the bottom of a capacitor can. This paper presents the basic construction of capacitors and the most important production steps, introduces the heat conduction between the can and the environment and describes the effect of the flatness of the can to heat conductivity. It also presents the entire measurement environment (measurement station, data acquisition and evaluation software), the database behind the measurement system that stores the results. At last, it discusses the effect of production processes to the

measured flatness, and presents the flatness of capacitors produced by leading capacitor manufacturer companies.

Structure and construction of aluminium electrolytic capacitor

The winding of an aluminium electrolytic capacitor contains two foils and papers [1]. These are rolled together tightly into a winding. The material of the anode, positive foil is aluminium with purity higher than 99.9%. The foil has been etched [2] to increase the effective surface area (and thus the capacitance of the capacitor). As a result, the effective surface area becomes typically 20–40 times larger than the plain area of the foil. On the etched surface of the foil an aluminiumoxide layer [3] has been generated electrochemically. The forming voltage of the anodized aluminium foil [4] is 30–60% higher than the rated voltage of the capacitor. The material of the cathode foil is also aluminium and itself has a thin oxide film (the forming voltage is only a few volts regardless of the rated voltage). It is typically etched to slightly increase the surface area. The anode and cathode foils are connected to aluminium tabs, which are coming out from the winding and are riveted to the aluminium terminals of the cover disk. The tab foils are not etched but are provided with an oxide layer made by

electrochemical oxidization. Before being housed in a suitable container, the complete winding is impregnated with electrolyte. After housing the edges of the can are curled down. Before being sleeved and packed, capacitors are first aged. The purpose of this stage is to repair any damage in the oxide layer and thus to reduce the leakage current to very low levels. During manufacturing there are two processes (curling and aging processes), which apply mechanical stress to the casing of capacitors.

The effect of flatness of aluminium cans on heat conductivity

In common applications with usage of extended cathode (the cathode is wider than the anode and exposed to the bottom of the winding) or different kinds of capacitor cooling (for example air or water cooling) are applied to reduce the core temperature that effects its lifetime. Earlier investigations showed that there are three types of heat transfer phenomenon between capacitor and the environment [5]: (i) heat conductivity (mostly at the bottom), (ii) radiation (mostly at the side), and (iii) convection. This paper only deals with heat transfer from the bottom of the capacitor to the environment. From the general theory of thermodynamics the heat conduction can be described by Eq.(1).

$$P = kA \frac{dT}{dx}, \quad (1)$$

where P represents power of the heat flow (W); A is the size of the tangential surface (m^2); dT/dx is the temperature gradient ($K m^{-1}$); and k stands for heat conductivity of the material ($W Km^{-1}$). In our case the linear approximation is acceptable. As already described, the rate of the heat flow depends on the size of the tangential plane.

Definition of the flatness was adapted from Ref. [6]. It is given as the distance between the two closest tangential planes of the bottom of the aluminium electrolytic capacitor can. In the case of capacitors with higher flatness the tangential surface of the aluminium can is lower. The distance between the bottom of the capacitor and the heat sink is filled by air. It is well known that the heat conduction coefficient of the air is much lower than the aluminium. The aspect ratio between the two constants is in the order of magnitude $\sim 10^4$. Therefore the flatness of the bottom in the case of regular heat sink applications is an important value.

Theoretical background of used measurement method

There are several different methods for measuring the flatness of a surface [4]:

1. The entire surface is compared with a known reference surface (holistic methods);
2. Points on the surface are compared to a reference plane;
3. Straightness of the lines in the surface is measured.

The holistic methods (e.g. holographic and interferometric methods) are not suitable for large surfaces with more than 90 mm diameter of screw terminal capacitor [7]. The third method is too complex and time-consuming for applying in serial production. Therefore, a point-to-point method (second type) was chosen for this investigation. Of course, the expensive optical methods may be more precise (in the order of 100 nm deviations) [8], but in our case this high precision is unnecessary. On the other hand, the point-to-point method is very fast, can be used easier and cost-efficient. For point-by-point methods, the grid size is a critical issue, which determines the lowest limit for observable surface irregularities. In our case, approximately $60 cm^2$ surface area needs to be characterized. The height difference was measured between N points within the bottom. Trials were made to find the applicable grid. Finally, a 9-point-grid was chosen with circular symmetry, because the measurement time is short enough and the accuracy of the measurement is acceptable.

Least mean squares (LMS) method was used for plane fitting, because the randomly distributed measurement errors have the smallest influence to the results [9]. Eq.(2) was used for the LMS:

$$\begin{bmatrix} \sum_{i=1}^N x_i^2 & \sum_{i=1}^N x_i y_i & \sum_{i=1}^N x_i \\ \sum_{i=1}^N x_i y_i & \sum_{i=1}^N y_i^2 & \sum_{i=1}^N y_i \\ \sum_{i=1}^N x_i & \sum_{i=1}^N y_i & \sum_{i=1}^N 1 \end{bmatrix} \times \begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} \sum_{i=1}^N z_i x_i \\ \sum_{i=1}^N z_i y_i \\ \sum_{i=1}^N z_i \end{bmatrix}, \quad (2)$$

where N is the number of the grid points; x_i , y_i are coordinates within the measured surface [mm]; z_i corresponds to the measured height compared to z_1 of the i^{th} point (mm), a , b , c are constants for the fitting.

The fitted plane is described by Eq.(3).

$$z(x, y) = ax + by + c \quad (3)$$

By solving the system of linear equations, for example with Gauss-elimination the fitted plane is given. The Gauss-elimination is not necessary if the grid points are centrally symmetric. In this case, the input matrix is diagonal, so the solution of the equation system is simple. The distance between the individual points and the fitted plane was calculated. The sign of this distance describes the location of the point respect to the fitted plane. The flatness is the distance between the farthest points above and under the fitted plane. The Fig.1 shows an example of measured points and the fitted plane.

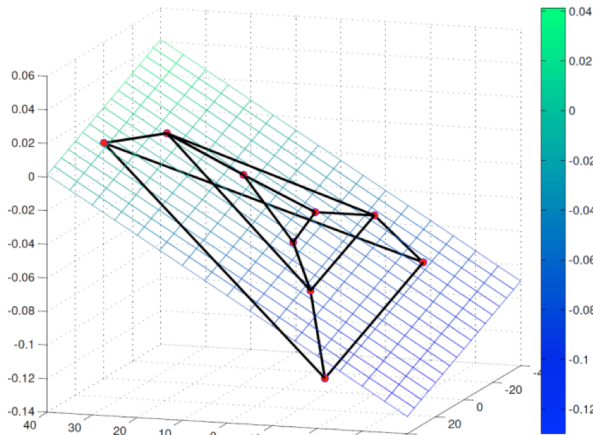


Figure 1: Example of the measured points and the fitted plane

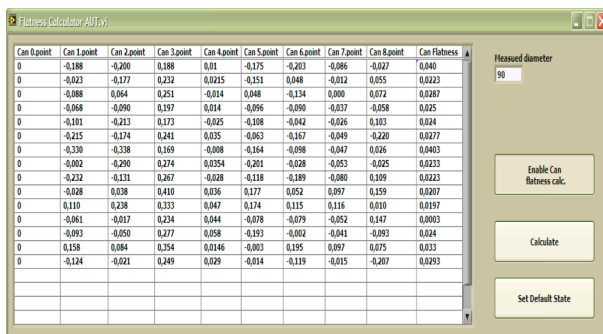


Figure 3: Graphical user interface of the evaluation software

Implemented measurement environment

The base of the hardware was a measuring pad made from stainless steel, which has an extremely smooth surface. By the LMS method, the error that comes from the tilt of the steel pad was avoided. To stay clear of the effect of the temperature gradient, the measuring equipment was kept under controlled environmental conditions. The data acquisition programme for the flatness measurement was written in LabVIEW with contains two major parts. The first one collects the data from the controlled hardware (height meter) and stores them into a local database in MS Excel format. This software communicates through an RS-232 port with the measuring equipment. The user sets the actual position, pushes a button and the module registers the results. The graphical user interface developed is shown in Fig.2 with Hungarian annotations. The software displays the number of actual measurement points and controls the entire process. For example, if the flatness value exceeds a predetermined limit, the software sends a warning to the operator.

The second module can extract the results from the database of an examined capacitor(s) or the user can import the measured values from Excel. If the results are in the input table, the evaluation module can calculate the flatness of the capacitor can. The graphical user interface of the second module can be seen in Fig.3.

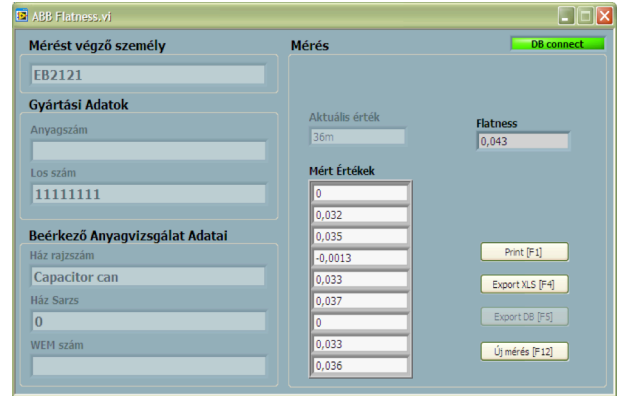


Figure 2: Graphical user interface of the data acquisition software

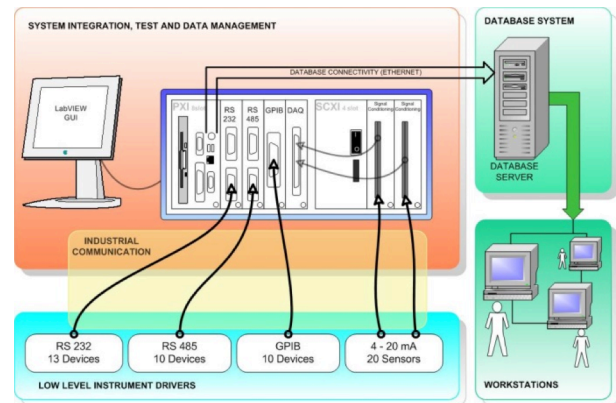


Figure 4: Architecture of the electrolyte measurements

The implemented automation environment fits into the measurement automation system (MAS) [10] being used at the Aluminium Electrolytic Capacitor Development Department of Epcos LLC. The system uses two frameworks: a LabVIEW based framework for data acquisition and an ASP.NET based framework for data management.

The measurement part contains automated data acquisition measurements, which are connected to the electrolyte (conductivity, pH, viscosity, etc.) and different kind of capacitor tests. (Lifetime, surge voltage and storage test, etc.). The experiments on the electrolyte are controlled by an NI-PXI, which is connected to the database (Fig.4). PXI stand for PCI eXtensions for Instrumentation. These platforms are used as a basis for building of electronic test equipment, automation system, etc. PXI chassis can handle many modules for example plug-in data acquisition (DAQ) cards, communication cards like RS-232, and different analogue and digital I/O boards. The capacitor measurements are controlled by computers and not by the NI-PXI, because the current implementation measures the low and high voltages separately.

The ASP.NET part of the system was developed for data management and evaluation. This is a software module that contains useful tools that facilitate data handling. Data management module simplifies the registration of the constructive properties of the capacitor (like anode foil, cathode foil, type of can, cover disk, etc.) and helps the data storage of applied

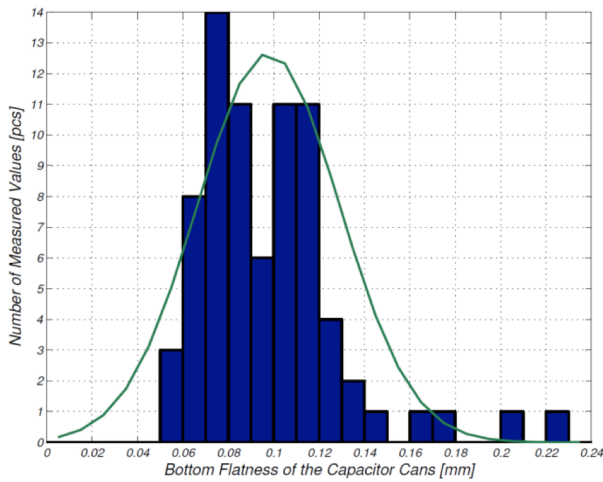


Figure 5: The measurement results from Incoming Inspection Department

Table 1: Results of the ripple current measurement

Average Flatness (mm)	Average of Temperature at equilibrium state (°C)
0.102	90.6
0.259	90.9
0.509	91.5

voltage and current, ambient temperature, etc. The evaluation part supports the evaluation process by generating a standardized report. The user can tailor the reports according to its needs by the Report Generation tool. The desired data appear in a representative way and even the trends of the parameters can be shown.

The goal of the MAS is to automate the previously manual measurements and eliminate paper-based registration. There are many advantages like making the measurements more precise, more reliable and fault tolerant, running multiple measurements in parallel, which all contribute to speed up the research and development of new component and devices.

Change of flatness value during the manufacturing

The flatness of the capacitor can is measured at the incoming inspection and at the final measurement of the production. The initial value of the flatness of the capacitor is determined by the incoming aluminium cans. These parts are produced by cold extrusion of aluminium slugs, so the irregularities of the cans is in the order of magnitude $\sim 10 \mu\text{m}$, which is negligible for our purposes.

The Fig.5 shows the flatness values measured at the incoming inspection of the capacitors. It can be seen that the mean of the measured flatness values is 0.09 mm. As mentioned above, the flatness is mainly affected by two procedures: curling and aging. During curling the can is closed hermetically by curling back the edges of the aluminium can. This curled edge sinks into the rubber ring of the cover disk. As a consequence,

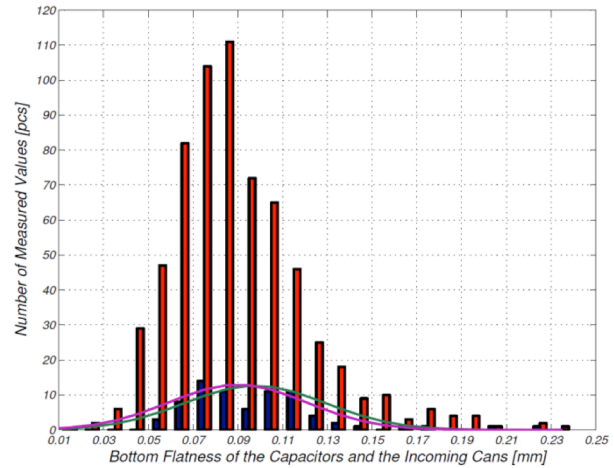


Figure 6: The effect of the production processes to the flatness of capacitor

the cover disk presses down the winding. It can affect the flatness value, since for example concave shaped aluminium can turn into a convex shape. During aging, the flaws of the anode foil are repaired by applying voltage to the capacitor and placing it in an oven. As a side effect gas is generated. The pressure of the generated gas can change the geometry of the can. From the distribution of the flatness values the effect of Epcos production steps (coloured curves in Fig.6) can be estimated. The results show that the different production steps do not influence significantly the bottom flatness of the capacitor at the Epcos.

Experimental results regarding to core temperature measurements

Two experiments were completed for investigating the importance of the flatness value of the capacitor can. Sample capacitors were produced with different bottom flatness values. The aluminium cans were made to be convex. These were ordered directly from the supplier and the used parts were sorted out. Regular heat sinks were assembled to the bottom of the parts. The tangential planes of the heat sinks were flat ($\sim 2 \mu\text{m}$) due to their grinded surface. The heat sinks were fixed to the bottom of the samples with the bottom screw of the capacitors. The mechanical stability of the fixation was made with torque wrench. Also guaranteed the same fixation level in each case. During the tests, forced air-cooling was not used. Heat conductive wires were applied to the core of the samples, which allowed us to measure the core temperature of the capacitors directly. The core temperature measurement system is shown in Fig.7.

In case of the first measurement, sample capacitors with very similar equivalent serial resistance (ESR) and leakage current were selected. These parts were taken to 85°C oven and rated voltage (450 V) was applied to them for 100 h. This preparation is necessary to avoid the different behaviour of the leakage current of the capacitors (isolated from each other to avoid the heat transfer). During the experiment a sinusoidal current

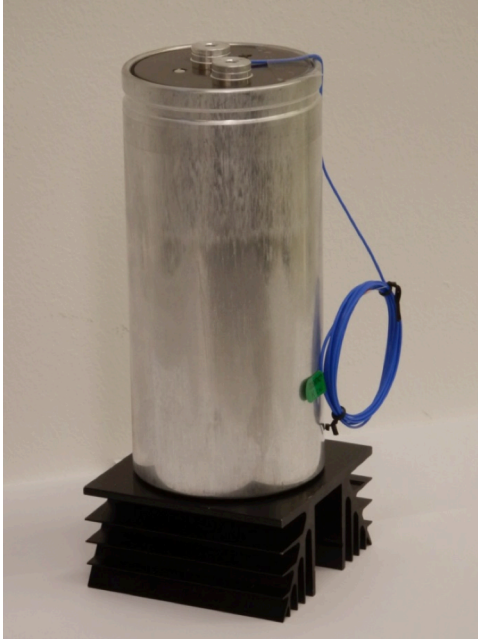


Figure 7: Core temperature measurement of a capacitor

was applied at 50 Hz. The current and the temperature (the upper category temperature) of the test are specified by the data sheet of the capacitor. In this case the examined capacitor was B43586A5278Q ($C = 2700 \mu\text{F}$, $UR = 450 \text{ V}$, $I(85^\circ\text{C}, 100 \text{ Hz}) = 12 \text{ A}$), the applied current (multiplying with the frequency factor) was 10.8 A. The selected samples were placed into an oven at 85°C and a rated voltage of 450 V was applied. The core temperature was measured during the test. The equilibrium temperature was measured and compared. Test was started with the remaining three prepared samples. In case of the second measurement the behaviour of the capacitors was tested against transient heat. The parts were heated up to 85°C and removed from the oven after 10 hours. The core temperature of the capacitors was measured during cool down time. The recorded core temperature curves (Fig.8) show exponential decay. The time-constant of the decay depends on the flatness value of the bottom. As a comparison, the flatness values for screw terminals capacitors from leading manufacturers were inspected. Table 2 summarizes the flatness results by leading manufacturers.

Conclusion

It is possible to measure the flatness of a capacitor can with the presented and implemented measurement environment. The expensive 3D measurement equipment can be replaced with this cost-effective method. The measurement and evaluation software was implemented in LabVIEW programming environment, which perfectly fits into the previously presented measurement automation system, which is currently being used at the aluminium electrolytic capacitor

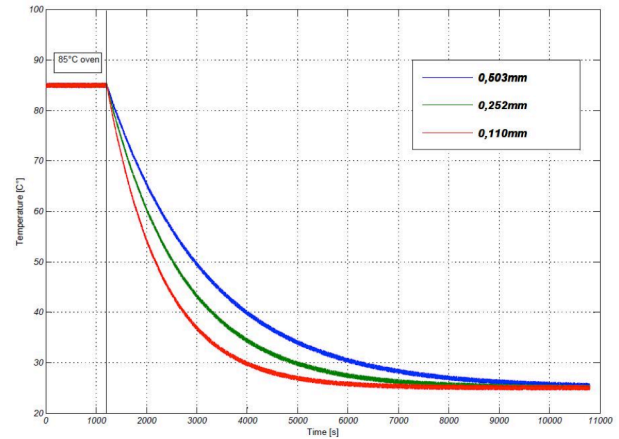


Figure 8: The behaviour of core temperature in case of different bottom flatness values

Table 2: Flatness results for products from leading manufacturers

Company	Capacitor Series	Flatness (mm)
Epcos	B43586	$0.095 \pm ???$
Hitachi	FXR	$0.158 \pm ???$
Kemet	ALS	$0.225 \pm ???$
Nichicon	NT	0.330

product development department of Epcos. The faults of previously manual measurements have been lowered with the help of automation and data acquisition software. This study discussed the basic construction of a capacitor and highlighted the critical construction steps from the aspect of flatness. In addition, it reveals the flatness values of other capacitor manufacturers' products.

Acknowledgments

The authors gratefully acknowledge the support of the Hungarian State and European Union under the "Green Energy – Cooperation of the higher education sector for the development of green economy in the area of energetics" project (TÁMOP-4.1.1.C-12/1/KONV-2012-0017), and the support of the TÁMOP-4.2.2.A-11/1/KONV-2012-0071.

REFERENCES

- [1] TDK Corporation, Aluminium Electrolytic Capacitors, 2013
- [2] PARK D., KIM H.: Electrochemical Etching of Aluminium through Porous Alumina, Analytical sciences, 2001, 17(supplement), a73–a76
- [3] CHURCH H.F.: The dielectric properties of anodic aluminium oxide films, Proc. IEE – Part B: Electronic and Communication Engineering, 1962, 109, 399–403

- [4] CHEN C., MASS W., HUTCHINS G.: Anodization of aluminium electrolyte capacitor foil, U.S. Patent 4,481,084, 1984
- [5] PARLER S.G. JR.: Thermal Modelling of Aluminium electrolytic Capacitor, IEEE Industry Applications Society Conference, 1999
- [6] ISO/TS 12781-1: Geometrical Product Specifications (GPS) – Flatness – Part 1: Vocabulary and parameters of flatness, 2003
- [7] DE GROOT P.J.: Grating interferometer for flatness testing, *Optics Letters*, 1996, 21(3), 228–230
- [8] MEIJER J.: Accuracy of Surface Plate Measurements – General Purpose Software for Flatness Measurement, *Annals of the CIRP*, 1990, 39, 545–548
- [9] HAITJEMA H., MEIJER J.: Evaluation of surface plate flatness measurements, *European Journal of Mechanical Engineering*, 1993, 38(4), 165–172
- [10] KOVÁCS L., FODOR D., KLUG O., ENISZ K.: Measurement Automation System for Aluminium Electrolyte Capacitor Development, *IEEE Instrumentation & Measurement Magazine*, 2013, 16(3), 38–43