Capacitor Failure Modes – Lessons from Industry

Nick Aitken

Edif ERA
Cleeve Road, Leatherhead, KT22 7SA
United Kingdom
Email:nick.aitken@edifera.com

INTRODUCTION

This paper discusses capacitor failure modes which have been encountered in a variety of consumer and industrial electronic systems. These failures have come from most major capacitor types and from a large number of the main capacitor manufacturers.

Common and less well known failure modes associated with capacitor manufacture defects, device and product assembly problems, inappropriate specification for the application, and product misuse are discussed for ceramic, aluminium electrolytic, tantalum and thin film capacitors.

Knowledge gained from these failure modes is discussed in the context of the requirements of capacitors used in space applications, including the potential risks associated with the use of commercial off-the-shelf (COTS) components.

Specific issues which are discussed are:-

Thin film capacitors: - internal contamination, moisture ingress, partial discharge and corona damage, vulnerability to film supply quality issues.

Electrolytic capacitors: - electrolyte formulation, liquid sealing problems.

Tantalum capacitors: - vulnerability to surge current damage, short circuit failure modes and the importance of appropriate fusing.

Ceramic capacitors: - Vulnerability to mechanical damage during use and assembly, the importance of the correct solder fillet profile, and cleanliness requirements for the avoidance of electrochemical migration.

The pros, cons, and limitations of various destructive and non-destructive analysis techniques are also discussed, along with some of the issues surrounding supplier quality control, product stress testing, and performance validation.

Metallised thin film capacitors

A thin metal film is vacuum deposited onto a polymer sheet.
These are a self-healing capacitors where in the event of an electrical breakdown the thin metallised film is rapidly oxidised or vaporised to leave an insulating region around the breakdown area, allowing the capacitor to continue operating with a negligible effect on capacitance or equivalent series resistance (ESR). In time however metal loss caused by self-healing events can accumulate to cause an appreciable loss of capacitance which may affect operation of the circuit.
The failure mode of thin film capacitors may be short circuit or open circuit, depending on the dominant failure mechanism.
There are only a certain number of electrical breakdown events which can occur within a capacitor before there is a risk of the self-healing process no longer being effective and a short circuit failure mode occurring. During a short circuit failure mode it is possible that the polymer film will act as a fuel and burn, potentially causing the spread of fire outside of the component.

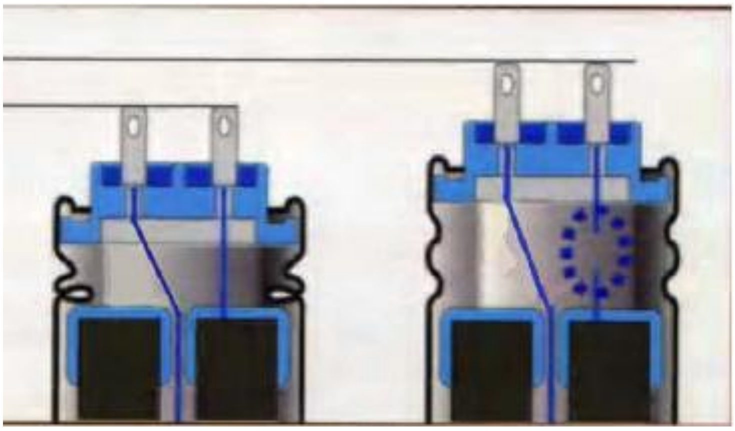

Fig. 1. Break action mechanism capacitor schematic

There are many models of thin film capacitor which are designed to have a fail-safe mechanism. These generally fall into two categories, the self-disconnect type and the thermally fused type. Self-disconnect capacitors rely on the expansion of gas within the capacitor housing (usually an aluminium case) which forces a plug of material upwards, breaking some electrical contacts. A schematic of this mechanism is shown in Fig. 1. It should be noted however that this mechanism is not always reliable, and in some instances the entire internal capacitor assembly moves together and the connections are not broken and a short circuit fault can persist, often with the risk of the spread of fire.

Whether or not a break action mechanism is present in the capacitors, the circuit in which the capacitor is used should have adequately rated protection to isolate a capacitor which has failed to short circuit.
The metal film used in this type of capacitor is very thin (necessary for the self-healing mechanism to be effective). Typically the film is a combination of zinc and aluminium, both of which are susceptible to corrosion. Along with short circuit failure as a result of electrical over stress, open circuit failure resulting from corrosive damage is a relatively common event. The capacitor must be manufactured in a very clean environment to prevent contamination with any ionic species which might promote corrosion of the metal film. A particular problem is corrosion in the film end metallisation. Thin film capacitors are normally manufactured from a sandwich of two single sided metallised polypropylene films tightly wound together. The metal layer on the film extends to only one side or the other of the polypropylene roll with an insulating boarder at the other side. In this way the positive and negative electrodes can be established by a metalized layer on either side of the capacitor film roll. This is illustrated in the schematic below in Fig. 2. Sometimes rather than a sandwich of single side metallised films, a double sided metallised film is wound with an insulating spacer in between.

The metal contacts are frequently zinc and are made by spray coating. In small components such as X2 safety capacitors, used as filter capacitors at the mains input connections of PCBs, the connecting wires are encapsulated in the spray coating. For higher power capacitors the connecting wires are soldered to the end metallisation. A flux is required to create the solder connection and if the soldering process is not well controlled or if the end metallisation is not correctly formed it is possible for corrosive materials / ionic materials from the flux to propagate through to the thin capacitor metallisation. In time these corrosive species can damage capacitors by removing film metallization, and occasionally the corrosion isolates the film from the end metallisation causing a complete open circuit failure, possibly involving overheating as the ESR increases during the failure process.

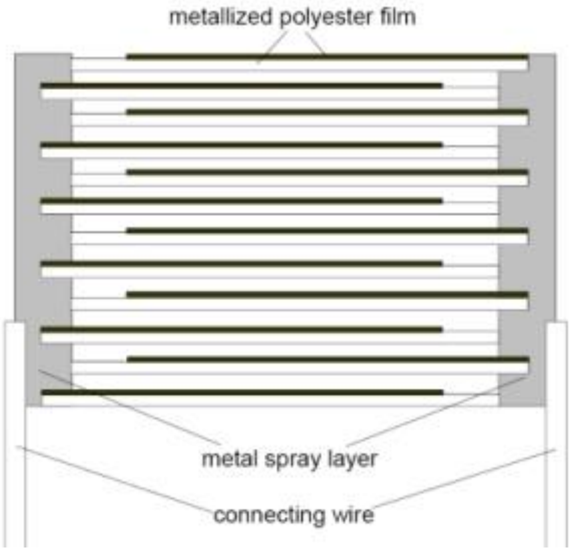

Fig. 2. MPPF capacitor schematic

Thin film capacitors are also sensitive to moisture ingress / humidity exposure. Higher power / higher voltage capacitors are usually sealed in a metal case which provides reasonable protection from humidity. However, lower value capacitors e.g. X2 safety capacitors are packaged in plastic and this can be susceptible to moisture diffusion. There is an electrochemical corrosion process which can occur if water molecules are present in the vicinity of the capacitor film metallisation [2]. In the case of capacitors being used as RF filter devices this effect may not result in a failure of the circuit. However, if the capacitors are employed in an application where their capacitance value is important, e.g. as a voltage dropper in a DC power supply, then the effect may be more important.

Electrolytic capacitors

Aluminium electrolytic capacitors have a known wear out mechanisms which normally leads to an open circuit failure / a loss of capacitance and an increase in loss factor (tan δ) / increase in equivalent series resistance (ESR). The principle intrinsic wear out mechanism is a loss of electrolyte by evaporation / diffusion through the capacitor case seal, a process which is accelerated with temperature. It is generally accepted that aluminium electrolytic capacitors follow an intrinsic ageing / wear out mechanism which is thermally dependent and governed by the Arrhenius equation, with the lifetime halving for every 10˚C increase in temperature.

Aluminium electrolytic capacitors are also known to suffer failures related to premature degradation because of the use of incorrectly formulated electrolyte solution. This is a capacitor manufacturing quality issue, where on occasion manufacturers introduce a defective electrolyte solution which results in a premature ageing and failure. The electronics industry suffered heavily from this effect between 1999 and 2007 and it was known as capacitor plague (7). Since this time the issue has been less common but still occurs. It can be difficult to detect as the effect can take several years to manifest. Thermally accelerated ageing of capacitors / electronic products can reveal an issue during product testing, but it is not usually possible to test every capacitor batch during ongoing production. The defective electrolyte does not allow the correct aluminium oxide (Al_2O_3) thickness to be maintained (this is the dielectric layer of the capacitor), and an excess thickness of aluminium hydroxide ($Al(OH)_3$) develops.

Thus the incorporation of aluminium electrolytic capacitors in electrical or electronic systems represents a certain risk to reliability which may be greater than for other electronic components.

The failure mode of electrolytic capacitors is relatively slow and manifests over periods of months rather than seconds which can be the case with short circuit capacitor failure modes. Therefore condition monitoring may be practical and useful for these components.

Aluminium electrolytic capacitors also suffer from a degradation mode associated with storage time / idle time whereby the leakage current increases due to loss of Al_2O_3 dielectric (the dielectric thickness is maintained in part by the electric field in use). Following a prolonged idle period / storage time the capacitor should be subjected to its rated voltage for a number of minutes in order to “re-form” the dielectric layer and reduce leakage current.

Tantalum capacitors

Tantalum capacitors are a high charge density capacitor technology which are preferred to aluminum electrolytic capacitors for certain applications including military, aviation and space application because they do not have an intrinsic wear out mechanism.

Tantalum capacitors come in two forms – wet and dry. A simplified description of the process flow used to make dry tantalum capacitors is that they are formed by sintering tantalum powder around a tantalum wire (which connects to the positive electrode of the chip package), to create a high surface area matrix of tantalum metal (Ta, the anode). The sintered tantalum surface is then oxidised under controlled conditions to grow a layer of tantalum pentoxide (Ta_2O_5, the dielectric). This structure is then further coated in a layer of manganese dioxide (MnO_2, the cathode). The resulting structure is coated on the outside with MnO_2 followed by carbon and finally silver which is connected to the negative electrode of the chip package. Dry tantalum capacitors are typically packaged in an epoxy resin.

Wet tantalum capacitors use a liquid or gel electrolyte which is typically sulphuric acid. The tantalum anode "slug" is formed using the same process as for the dry device but without the MnO_2 layer. The tantalum slug is then suspended in a hermetically sealed metallic case surrounded by the wet electrolyte.

Tantalum capacitors do have some limitations, principally their susceptibility to damage caused by surge current or reverse bias, and the fact that the most common failure mode for dry tantalum capacitors is short circuit, Fig. 3. Therefore it is important that tantalum capacitors are adequately protected in the circuit. For example, by incorporating resistors to avoid surge current during power on, and incorporating appropriate fusing such that a short capacitor failure does not result in risk of overheating or burning or disable a critical circuit. Voltage surge suppression may also be used to reduce the likelihood of a short circuit failure.

The resilience of dry tantalum capacitors to damage by surge current is significantly compromised by mechanical stress [1], and this may be in the form of stress induced from the assembly (e.g. board warpage), or environmental stress e.g. mechanical shock and vibration, and this should be borne in mind when incorporating capacitors in circuits use in space applications.

In recent years COTS tantalum capacitor datasheets and application advice notes from the manufacturers recommend that the capacitors are de-rated by 50% from their headline voltage specification. In part this recommendation is because resilience to surge current and over voltage can be reduced by the temperatures used during PCB assembly. Some capacitor manufacturers suggest "proofing" dry tantalum capacitors after the soldering process [3]. Thermal expansion stresses are thought to cause crack formation in the tantalum pellet during the cooling phase of the solder reflow process and proofing has the effect of "growing" fresh dielectric at these crack sites.

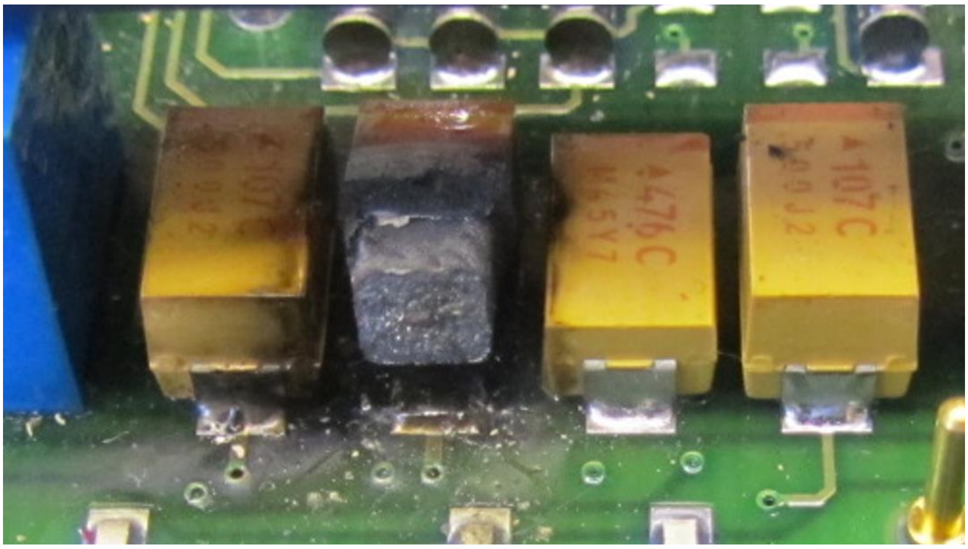

Fig. 3. Example of tantalum capacitor failure

For high reliability applications, or applications where a 50% derating has not been applied then a post assembly proofing step should be considered.

Wet tantalum capacitors are often preferred for high reliability military and aerospace applications, and they have some advantages over dry tantalum capacitors in superior resilience to reverse bias voltages (for tantalum cased devices), lower DC leakage, reduced likelihood of a short circuit failure mode, and high operating temperatures of up to 200˚C. However operating environments with high vibration levels have been seen to damage wet tantalum capacitors. The tantalum pellet which is a relatively high density item is supported in the case by the anode connection wire along with a polymer insulating ring which locates the pellet centrally in the case and prevents contact with the cathode electrode. The arrangement is shown in Fig. 5. Two distinct failure modes have been observed for this type of capacitor – open circuit failure where mechanical stress has caused the anode connection wire to fracture, and high equivalent series resistance (ESR) failure where vibration has caused abrasion of the tantalum pellet against the insulating ring resulting in contamination of the electrolyte with tantalum pentoxide. The open circuit failure mode results in an almost complete loss of capacitance. The high ESR failure can result in self heating of the capacitor which leads to an increase of internal pressure in the case and loss of electrolyte as the case seal fails and areas local to the capacitor are contaminated with acidic liquid. Therefore the orientation of wet tantalum capacitors with respect to the primary axes of vibration is important, as is the mounting of the capacitors on the circuit board, both when the capacitor is powered and unpowered.

Fig. 4. Buildup of tantalum pentoxide following wet tantalum capacitor vibration testing

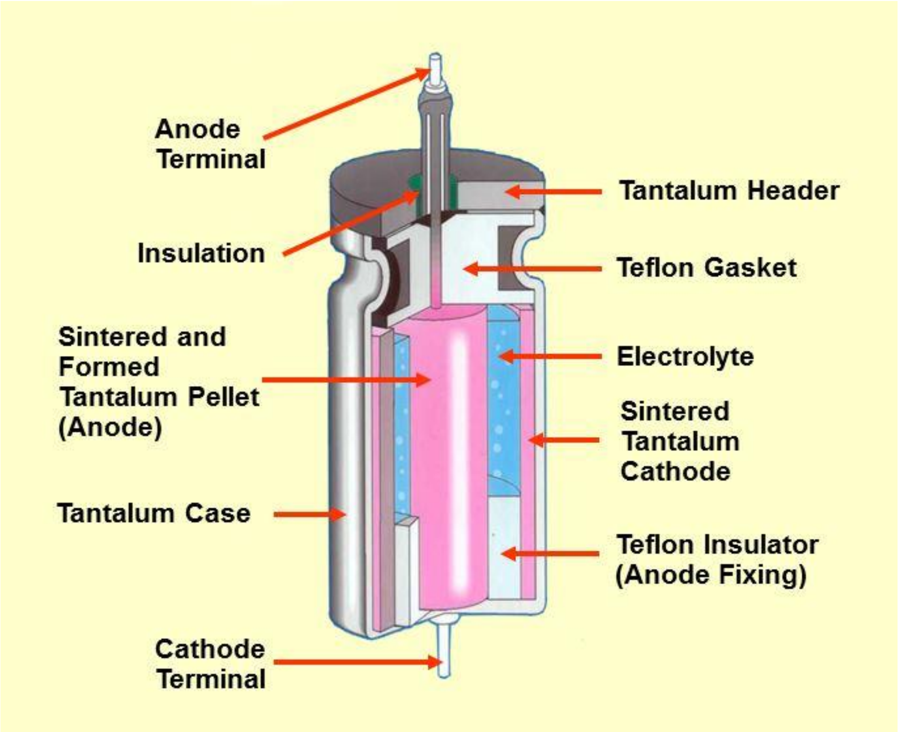

Fig. 5. Schematic of wet tantalum capacitor

Ceramic capacitors

Multi-Layer Ceramic Capacitors (MLCCs) do not have any intrinsic wear out mechanisms but are vulnerable to short circuit failure modes caused by mechanical stress including vibration. They may also suffer from latent defects which are introduced during the PCB manufacturing process.

Short circuit failures can result in local heat dissipation and burning, therefore the circuit protection should be designed such that a MLCC short circuit failure is confined as far as possible to the component in question and burning or fire does not spread.

The most common mechanism of failure is crack propagation in the ceramic initiating at the device end caps, which leads to a short circuit.

MLCC failures are often seeded during PCB manufacture because of mechanical stress induced by the PCB assembly tooling, or thermally induced stress during the PCB soldering process which can also be exacerbated by incorrect solder fillet profile. The location of MLCCs on a PCB can be a factor in reliability as components placed near to the PCB edge can be subjected to excess mechanical stress during PCB de-panelling. Therefore it should be verified that the de-panelling process, and the component mounting / PCB mounting system does not impart excess mechanical stress. The same applies for other PCB components and connectors.

MLCCs for automotive and aerospace applications will have a reduced likelihood of failure due to cracking, as these components are designed with a softer resin material in the capacitor end caps which reduce the mechanical stresses on the actual ceramic device area. The use of these components will reduce the likelihood of cracks being seeded during manufacture and reduce the susceptibility of the devices to thermal cycling and environmental vibration when in operation. A schematic illustrating this feature is shown in Fig 66, which is taken from a capacitor manufacturer's website (Murata).

MLCCs are often screened for cracking following environmental stress testing. Typically micro sectioning is conducted on the capacitors to reveal any cracks. However, this analysis technique in itself can induce cracks in the devices. Although it is a slower and potentially more expensive process a high resolution CT x-ray analysis of components can provide a more reliable assessment of cracking in MLCCs.

MLCCs are often subject to a permanent DC bias when in use, and this can lead to electrochemical migration which can cause a short circuit failure mode, particularly where there is silver present in the component interconnects. With respect to space applications, the adoption of COTS components which are ROHS compliant increases the likelihood of silver being present. Operation in a high humidity environment will exacerbate this effect. The effect may be mitigated by using conformal coated PCBs, but a conformal coating is not a guarantee against the effect. Furthermore electro migration may occur beneath the components, accelerated by the presence of trapped flux residues, and in this case visual inspection of components (e.g. as part of high temperature and humidity stress testing) will not detect the defect. An example of this effect is shown in Fig. 7.

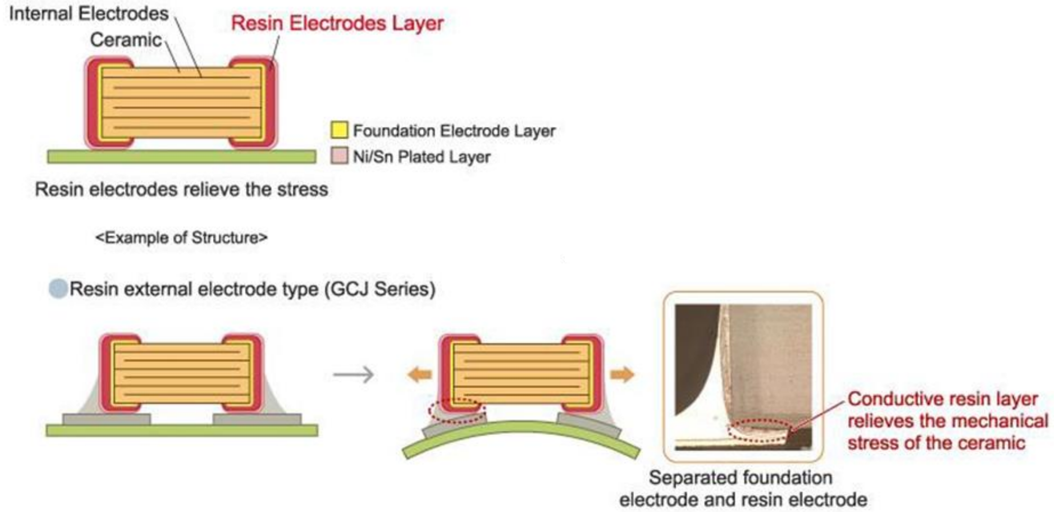

Fig 6. MLCC schematic illustrating resin electrodes

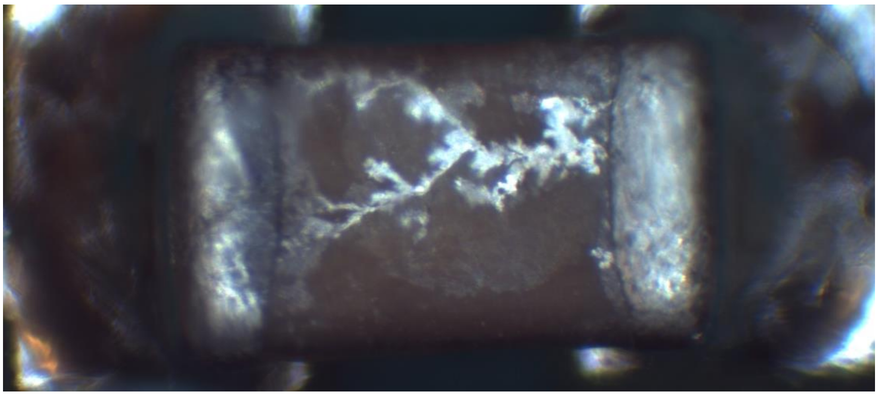

Fig. 7.Dendritic growth on MLCC

CAPACITOR FAILURE ANALYSIS AND QUALITY SCREENING TECHNIQUES

There are a wide variety of analysis techniques which are relevant to the assessment of capacitors. Some of the most useful techniques along with their relative merits and limitations are discussed below.

MLCCs

As the most common MLCC failure mode is cracking, the principle analytical techniques used in failure investigation and component screening are sectioning and CT X-ray imaging.

Sectioning must be conducted with caution as the sectioning process itself can induce crack formation in the sample. Therefore the capacitor should be cut out of the circuit along with the printed wiring board using a high speed diamond saw leaving a reasonable distance between the cut and the component, and the section should be mounted and potted using a material which will not impart stress to the component. During grinding to the plane of interest a fine grade abrasive should be used.

Several sequential planes should be analysed through the device, paying particular attention to the onset of cracks from the inside edge of the solder fillet.

CT X-ray imaging can be used to screen for cracks in MLCCs. This technique has the advantage of being non-destructive, and the disadvantage of being a slow technique (although probably faster than sectioning). However, there is a limit to the size of feature which can be resolved, and therefore it is possible that very short / fine cracks are missed.

Scanning acoustic microscopy (SAM) is very effective at detecting cracks in dense materials, such as ceramic capacitors. Unfortunately because any cracks are likely to form underneath the capacitor end caps this makes the technique impractical to use. To image a material at high resolution requires a high frequency transducer (e.g.>100MHz), and at this frequency the sound energy is easily scattered and attenuated, making an acoustic measurement of any features underneath the endcap metal difficult.

Thin Film capacitors

There are several analysis techniques relevant to thin film capacitors.

Dye penetration testing can be used to pinpoint leaks in the case. For plastic packages this is particularly relevant in the region where the electrical connections exit the package.

Moisture content inside the capacitor housing is critical. Water analysis by Karl-Fischer titration can be used to calculate the moisture level in various materials. This might include the metallised film itself, potting material (if any) which is present around the film, and insulation oil.

The level of ionic material inside the capacitor housing is also important. In the analysis of failed devices and screening of devices the amount of ionic material present in the end metallisation, on the film surface itself, in any insulating oil, and in any potting material, is relevant to the reliability of the device, and this can be measured by ion chromatography (IC) testing.

Partial discharge measurement can be used to screen capacitors. Partial discharges cause localised metal loss and over time this can accumulate and result in a significant loss of capacitance. This technique can be difficult to use with larger value capacitors however, as the high currents involved make measurement of the small partial discharge charge spikes more demanding.

Basic optical microscopy under transmitted light will often reveal the mechanism behind any thin film metal loss. For example it is often possible do differentiate between high voltage breakdown or partial discharge breakdown, or corrosive damage. If metal loss effects are more subtle then scanning electron microscope analysis (SEM) can provide useful diagnostic information. The resultant SEM images can give information on whether areas of metal loss are a result of electrical breakdown or corrosive processes, and in some instances SEM energy or wavelength dispersive x-ray analysis can reveal what species are involved in a corrosive process.

Aluminium electrolytic

Analysis of electrolyte formulation and the makeup and structure of the aluminium electrode surface are the most common requirements with respect to discriminating between reliable and unreliable aluminium electrolytic capacitors, along with analysis of the quality of the case seal. The principle intrinsic wear out mechanism of electrolytic capacitors is loss of electrolyte through diffusion / evaporation.

In differentiating between electrolyte formulations IC can be of value. For example, assessing the presence / absence / concentration of phosphate which is used as a stabiliser, as well as assessing relative levels of organic acids. Infrared spectroscopy (IR) can also be used to compare electrolyte from reliable and unreliable batches, or be used a “gold standard” to screen batches / guard against counterfeits.

Electron microscope inspection of the aluminium surface can reveal differences in the microstructure and hence the surface area. SEM -EDXcan be used to measure the ratio of aluminium to oxygen which gives an indication of whether the alumina surface (which is the dielectric layer) has been converted to aluminium hydroxide which is a degradation mechanism characteristic of an incorrectly formulate electrolyte.

Tantalum

Dry tantalum capacitors are susceptible to failure as a result of mechanical damage, and degradation of the dielectric layer due to fine cracks which reduce the resilience to surge current / inrush current. Cracks can form during solder processing, probably during the cooling phase as compressive stress affects the tantalum / tantalum pentoxide matrix.

Due to the highly complex and fine three dimensional structure direct observation of mechanical defects e.g. by sectioning may not be practical, and the resolution and contrast afforded by X-ray CT scanning insufficient. There may be an obvious mechanical crack in the tantalum pellet which normally occurs at the corners, and this can be identified by sectioning, however there may also be much smaller fault sites in the dielectric which are susceptible to electrical breakdown at voltages at or below the rated voltage and these will not be revealed by sectioning.

Electrical testing can be used to reveal whether dry tantalum capacitors have “degraded” during soldering, specifically by conducting electrical scintillation tests. These tests involve applying a small constant current to a capacitor and monitoring voltage rise vs. time. The scintillation voltages for a capacitor can be used to indicate the dielectric quality / dielectric fault distribution for that component and compared against pre soldered components / gold standard components.

CAPACITOR QUALITY CONTROL ISSUES AND COTS COMPONENTS

The use of COTS capacitors in industries where reliability is critical and servicing / replacing parts is costly or even impossible, carries certain risks. Based on the many failure investigations carried out by Edif ERA over >20 years the main risks are associated with medium term degradation mechanisms occurring at a higher rate than would be expected based on the component datasheet, caused by subtle variation in manufacture and materials. Such degradation mechanisms might not be detected during burn in tests and for example:-

- Trace levels of ionic contamination have been introduced during thin film capacitor electrode metallisation leading to metal corrosion and premature failure.

- The supply of polypropylene film used in thin film capacitors has been compromised following a large natural disaster which forced manufacturers to obtain the film from a single factory.

- Miniaturisation of thin film capacitors which led to susceptibility to electrochemical corrosion in high humidity environments and this effect was highly random with some batches showing low reliability but rogue failures also occurring in reliably batches.

Issues have been seen in high voltage oil impregnated capacitors which were linked to the manufacturing environment.An increased failure rate was observed in parts from South East Asia which were assembled during periods of high humidity. In this case the vegetable based impregnation oil had absorbed a greater amount of moisture which was not then adequately dehydrated prior to sealing of the capacitor housing.

Dry tantalum capacitors which do not have an intrinsic wear out mechanism should be expected to have a low failure rate. However, care should be taken to de-rate the components with respect to the magnitude of any inrush current and in particular the de-rating should take into account the magnitude of any inrush current in conjunction with the level of mechanical stress which the parts are subjected to during that time. Dry tantalum capacitors can be made more resilient to inrush current damage by proofing following the solder assembly, which essentially involves applying a controlled DC voltage at or close to the rated voltage which has the effect of "re-growing" / forming tantalum pentoxide at the site of any faults in the dielectric layer. Capacitors can be screened by electrical scintillation testing which can reveal whether a component has a higher level of dielectric fault sites than known "good" components.

Summary

The purpose of this paper was to share experience in capacitor failure modes observed in a range of industries and applications, and to point out where certain failure modes may be of greater concern with respect to the adoption of COTS components in space applications.

In this respect the widest variety of failure modes are associated with thin film capacitors, and many of these failure modes are difficult to screen by using burn in tests, and in some cases even using accelerated stress testing. For example problems with thin film capacitors have been found to be associated with the climate at the time of manufacture, with subtle changes in contamination levels, and with seemingly random differences between the same components where certain parts are more susceptible to failure in high humidity environments.

Tantalum capacitors are popular in aerospace applications with lower failure rates than other capacitor types, and no intrinsic wear out mechanism. The principle concerns with this type of capacitor are associated with mechanical stresses making the device more susceptible to surge current / inrush current damage than expected, and the requirement for the parts to be de-rated. Wet tantalum capacitors have been seen to fail following operation in a high vibration environment.

Aluminium electrolytic capacitors have an intrinsic wear out mechanism, and because of the delicate chemical balance which must be maintained at the dielectric / electrolyte interface are susceptible to premature failure as a result of manufacturing issues affecting electrolyte composition, and these issues may not become apparent for several years of operation.

Multi-layer ceramic capacitors have been seen to be unreliable as a result of the ROHS compliance requirements of COTS components, where the silver used in the ROHS compliant soldering system undergoes electrochemical migration leading to short circuit failure.

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AUTHOR

Nick Aitken, MSc, CEng, MIET, Senior Consultant, Forensic Engineering, Edif ERA

Nick has a Masters Degree in Physics and over fifteen year of experience working in the areas of scientific equipment development, sensor and instrumentation development, and semiconductor process development. He has now turned his troubleshooting experience gained in several branches of high tech industry to Reliability and Failure Analysis consultancy with Edif ERA where he has been working since 2010.