Thermal stress on capacitors: failure prevention

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Failure of capacitors affects the other components in the circuit and causes secondary failures in many cases. This article discusses the failure modes and mechanisms in capacitors of various types which are typically used in electronic systems and methods to prevent capacitor failures due to thermal stress.

Various types of passive components are used in electrical and electronic systems. Among them, capacitors constitute a major type used in large quantities. The types of capacitors used in a system are of types such as ceramic, electrolytic (aluminium and tantalum), metallised film, mica, glass, porcelain, etc. Capacitors are used in electric circuits for applications such as timing, filtering, dc blocking, decoupling, suppression of voltage transients, etc. Both SMD and normal leaded type of capacitors are used. Based on studies carried out on failed capacitors of all types [1, 3, 4, 5, 7], it has been found that major causes of failure of capacitors are heat, high voltage, humidity, chemical contamination and moisture. To the best of the authors’ knowledge, attempts have not been made to highlight the thermally induced failure mechanisms of capacitors used in electronic systems. This paper describes the thermally induced failures in various types of capacitors and methods to minimise the same. Prevention of failures of capacitors due to thermal stress is important to achieve reliability in applications where electronic systems have to operate at high temperatures, such as, non-AC applications, automotive electronics, underground applications such as drilling, mining, etc. As capacitors form the basic components for building electronic systems, this article addresses the failures in capacitors caused by thermal stress. This article is based on the analysis of thermal stress failures carried out on various electronic products, and may be considered as a case-study on the subject, with practical examples.

Capacitor failures due to thermal stress

Different types of capacitors are used in electrical and electronic systems. Among the main types of capacitors used are: ceramic, polypropylene, Al electrolytic, tantalum electrolytic, polycarbonate, polyester, etc. Capacitors are major causes of failure in electronic systems. Capacitors fail for various reasons, such as wear out, aging, reverse polarity voltage caused damage, mechanical damage during assembly, dielectric failure, high temperature induced damage during soldering, operation, testing, etc.

Electrolytic capacitors:

Electrolytic capacitors are widely used in power electronic circuits. High ripple current and high temperature of the environment in which the capacitor operates cause heating of the capacitor due to power dissipation in it [2]. Temperature is an important factor which affects the life span of electrolytic capacitors and this aspect should be considered. Electrolytic capacitors can fail due to many reasons such as high temperature during soldering, internal power dissipation due to ripple, etc., high ambient temperature, reverse voltage, voltage transients, etc. The thermally induced failure mechanism in wet electrolytic capacitors is triggered by electrolyte evaporation at high temperature. High temperatures cause hot spots within the capacitor and lead to its failure. A capacitor is not purely capacitive – the equivalent circuit of a capacitor is shown in Fig. 1. In power electronic circuits, electrolytic capacitors are exposed to high temperatures and high ripple currents. When charging and discharging currents flow through a capacitor, losses are caused by ohmic resistance which causes an increase in temperature.

In a typical capacitor ohmic losses exist in the dielectric material and the connections have resistance – this is represented as equivalent series resistance (ESR); at low frequencies this is mainly the resistance of the dielectric. There is heat generation in the capacitor due to the ESR, and this power dissipation is given by:

\[ P = I_i^2 R_c + V_i \phi \]

(1)

This power dissipation causes heating and a rise in temperature in the capacitor. This imposes a limit on the power that a capacitor can dissipate. When the power dissipation becomes excessive, the temperature rise of the capacitor exceeds its limit for safe operation and the capacitor will fail. When the temperature rises, ESR increases and causes more heating and thus the capacitor is more prone to failure. (See Fig. 1)

Fig. 1: Relationship between voltage and current in a capacitor.
There is one more factor which accounts for power dissipated in a capacitor known as dissipation factor (DF). This also represents heat generating losses within a capacitor. The dissipation factor is also known as the loss tangent (\(\tan \delta\)). \(\tan \delta\) increases with an increase in temperature and frequency. Al electrolytic capacitors have a higher \(\tan \delta\) than other types of capacitors. Hence the dissipation loss due to ripple current causes more heating in Al electrolytic capacitors.

Leakage current is another factor which has to be considered in capacitor reliability. A higher leakage current will cause a higher heat generation due to the power loss, \(\frac{V}{\delta}\) where \(\delta\) is the leakage current of the capacitor and \(V\) is the applied voltage. This heat along with the ripple current heating may lead to electrolyte evaporation and capacitor failure or thermal runaway. Long periods of storage should be avoided before capacitors are used. A long storage period will cause higher leakage current as the Al-oxide will dissolve over time in the electrolyte. Hence manufacturers recommend that Al electrolytic capacitors which have been stored for a long time should be re-formed by applying the rated voltage to restore the oxide layer which would have been dissolved and lost; this will reduce the leakage current and possibility of capacitor failure.

At higher temperatures, the electrolyte vapour pressure increases and the seal of the capacitor will bulge. The electrolyte vaporizes into a gaseous phase and the gas diffuses out through the seal. This causes capacitor failure due to seal failure; this is a thermal stress induced failure mechanism. An example of this failure is shown in Fig. 4. Hence to reduce thermal stress on the capacitor, ESR of the capacitor should be low and the capacitor should be as near to ideal as possible i.e., \(\delta \approx 0\), and \(\phi \approx 90^\circ\).

In practice, we can reduce thermal stress on the capacitor by following good capacitor selection guidelines based on application so that suitable voltage rating, temperature rating for the capacitor are used. Also select the capacitor with the lowest ESR, lowest \(\delta\), and low leakage current for the circuit application.

Aluminum electrolytic capacitors are used as energy storage and filtering elements in power electronic systems such as switched mode power supplies. Their advantages are availability in high capacitance values and high voltage ratings. The performance of such capacitors can affect the entire power supply. Among the failure of components in a typical power electronic system, the switching elements such as power transistors, MOSFETs, etc. and the electrolytic capacitors account for a large share of the causative components.

Electrolytic capacitors can degrade under a number of conditions such as high operating voltage greater than its rating, reverse voltage, voltage transients, large ripple currents, vibration, etc. Such operating conditions cause high levels of electrical and thermal stresses. Such stress conditions increase the ESR of the capacitor and cause a reduction in its capacitance value i.e., the capacitor degrades.

A capacitor is considered to have failed if its capacitance decreases by 20% [5]. Such capacitors, if used in power supply circuits can cause a number of problems due to their decreased ability to filter high frequency components of the voltage. Thus high levels of ripple voltages and currents will appear in the output and the DC output voltage will decrease over time. The voltage ripple will affect the digital circuits and cause malfunctions. As already discussed in the preceding sections, the high ESR and ripple currents will increase the thermal stress on the capacitor and ultimately cause its failure. The power dissipation in a capacitor due to ESR is given by

\[
P_{\text{ESR}} = I \times ESR\]

where \(I\) is the current and ESR is the equivalent series resistance. In high frequency applications this loss is important. A low loss capacitor in high frequency applications will have a lower temperature rise. If the capacitor has high ESR and high dielectric loss, it will have a high temperature rise and the dielectric is likely to breakdown at high frequencies due to thermal stress.

A high ESR will increase the impedance for the AC voltage and affect the voltage converter functioning. It has been found from various studies that heat is the major cause of failure of electrolytic capacitors, among all the causes [6]. Long periods of storage of electrolytic capacitors will cause the Al oxide to dissolve in the electrolyte. This will cause an increase in leakage current and consequent heating. Ultimately the capacitor will undergo thermal runaway failure due to thermal overstress. Hence it is necessary to re-form Al electrolytic capacitors by application of the rated voltage after long periods of storage to prevent such failures.

Surge voltages can cause high temperature and intense heating, leading to thermal stress induced failure. In electrolytic capacitors the voltage surge can cause decomposition of the electrolyte and production of gas which will increase internal pressure and lead to opening of the vent seal as shown in Fig. 4. A severe case of PCB damage observed in a case due to thermally induced capacitor failure is shown in Fig. 5.

Failure of ceramic capacitors due to thermal stress and its prevention:

Ceramic capacitors are used in electronic circuits for coupling, decoupling, DC blocking and similar applications. Such capacitors are rugged, non-polarised and work well in both AC and DC circuits, have values less than 1 nF, have higher dielectric withstanding voltage and are low-cost. Failures in ceramic capacitors due to thermal stress occur in the following situations.

- Surge voltages and leakage currents can cause thermal stress cracks and capacitor failure. At high temperature, thermal runaway can occur. If the capacitor fails due to extremely high thermal stress, the PCB on which it is mounted can get damaged as shown in Fig. 2. Fig. 3 shows

Fig. 2: Damage to PCB due to failure of electrolytic capacitor.

Fig. 3: Failure of a capacitor due to thermal overstress.
an another case of capacitor failure due to thermal stress.

- Evaporation of metal contacts between the metallisation and end contacts may occur due to high current surges.
- The difference in the coefficient of thermal expansion between ceramic (≈10 ppm/°C) and Ag/Pd alloy (≈20 ppm/°C) used in the construction of the capacitor causes a mechanical shear force during soldering. Trying to make it apart; moreover, the metal being a better thermal conductor than the ceramic causes a thermal gradient which aggravates this problem.
- Rate of temperature rise during reflow soldering should be limited to within 2 °C/sec as a higher rate of temperature rise will lead to micro-cracks to appear in the capacitor.
- Rework on printed circuit assemblies by manual soldering should ensure that components are not exposed to higher than recommended soldering temperature.
- Excessive thermal stresses or thermal shocks can cause ceramic capacitors to fail due to dielectric breakdown caused by heat and this should be avoided.
- Multi-layer ceramic chip (MLCC) capacitors are prone to failure due to sudden changes in temperature to which they may be subjected, i.e., thermal shocks due to TCE (temperature coefficient of expansion) differences in the materials.
- High soldering temperatures will cause microcracks formed during assembly process to widen and this can cause the capacitor to fail. Microcracks can absorb moisture and cause short-circuits under some conditions. Subjecting MLCC capacitors to mechanical shocks will lead to microcracks in the capacitor body, which will cause moisture absorption and short-circuit. Such mechanical shocks can be caused by PCB flexure induced stress, while mounting PCBs with, capacitors of this type mounted close to points of mechanical stress.
- The MLCC is constructed out of alternate layers of Al/Pd (aluminium/palladium) alloy and a ceramic material as dielectric between them; these layers have different coefficients of thermal expansion and different thermal conductivities. When such capacitors are heated during soldering, a large force is exerted on the capacitor body and end-terminations by the differential thermal expansion. As a result of these stresses, if the capacitor is subjected to thermal shocks, microcracks appear in the capacitor at the points where the metal terminations are connected to the capacitor body. The capacitor does not fail electrically immediately, but after some time. In some cases, the cracks cause an open-circuit failure across the capacitor body, while in other cases, moisture ingress into the cracks causes an electrical short-circuit during use. Thus thermal stress causes the failure of the MLCC capacitor. This can be prevented by using a lower soldering temperature, and a smaller rate of temperature rise in reflow soldering, so that thermal shocks are avoided.
- Failure of plastic film capacitors due to thermal stress and its prevention:
  Plastic film capacitors consist of polystyrene, polyester, polycarbonate, metallised polyester, etc. materials as dielectric. Their main advantages are small size, non-polarised nature, low dielectric loss, high insulation resistance, good frequency and high temperature capacitance characteristics and self-healing property. However, some types of plastic dielectric capacitors are affected by very high temperature soldering due to changes in the plastic dielectric material which will affect its electrical characteristics when compared to ceramic capacitors. As mentioned above, polyester dielectric capacitors have self-healing properties after an electrical breakdown of the film, i.e. the film of dielectric will reform after an event which ruptures the film. They have a higher cost and size compared to ceramic capacitors of the same rating, which is a disadvantage. Polyphenylenesulphide dielectric capacitors have the lowest temperature drift among plastic dielectric capacitors. Capacitance stability with temperature is good in the case of plastic dielectric capacitors. Soldering heat and prolonged exposure to heat dissipation from neighbouring components will affect the plastic dielectric.
  High temperatures can also be caused by internal heat dissipation due to voltage surges, high voltage application, excessive leakage current, etc. All these aspects should be considered in an electronic circuit while using such capacitors. Metallised film capacitors are widely used due to their low dielectric loss and high breakdown voltage. In such capacitors, it is reported [8, 9] that for AC and DC applications, failures occur due to thermal effects. In AC applications, the thermal failure may convert to a combustion failure; hence it is necessary to ensure that in the event of a failure, hot capacitors are isolated from the circuit to prevent fire. Stress induced cracks which occur in the brittle ceramic dielectric capacitors due to thermal or mechanical stresses do not occur in plastic dielectric capacitors as the dielectric is resilient and this is an advantage in favour of the plastic dielectric capacitors.
- Failure of solid tantalum capacitors due to thermal stress and its prevention:
  In solid tantalum capacitors, the tantalum oxide film has imperfections on the surface (hillocks and valleys) caused by impurities, manufacturing processes, damage to the oxide film, etc. This leads to bursts of current flowing in the capacitor [6]. The leakage current and fault current increase in the capacitor due to such flaws. It has been found by analysis that local heating occurs in the tantalum oxide film at such imperfect sites, due to high current density at such points when a higher current flows. Sometimes current surges occur due to increase in leakage current. All these phenomena lead to failure of the capacitor.
Failures in tantalum capacitors can be prevented by derating the capacitor voltage, limiting the environmental temperature rise and using the recommended current limiting series resistance as specified by the capacitor manufacturer. During manufacture of the capacitor, the tantalum – tantalum dioxide composite material undergoes a high temperature step to oxidise the Manganese compound to its oxide. This high temperature exposure causes damage in the dielectric and reanodising step does not heal the damage fully. Thus weak areas exist in the tantalum oxide layer. Current density can become high in these weak spots and cause heating, under some conditions. This over-heating and consequent thermal stress can cause latent damage to the dielectric over time. Such weak spots can cause catastrophic failure of the capacitor during use [4].

### Failure of solid tantalum capacitors due to thermal stress and its prevention:

Plastic film capacitors consist of polystyrene, polyester, polycarbonate, metallised polyester, etc. materials as dielectric. Their main advantages are small size, non-polarised nature, low dielectric loss, high insulation resistance, good frequency and high temperature capacitance characteristics and self-healing property. However, some types of plastic dielectric capacitors are affected by very high temperature soldering due to changes in the plastic dielectric material which will affect its electrical characteristics when compared to ceramic capacitors. As mentioned above, polyester dielectric capacitors have self-healing properties after an electrical breakdown of the film, i.e., the film of dielectric will reform after an event which ruptures the film. They have a higher cost and size compared to ceramic capacitors of the same rating, which is a disadvantage. Polyphenylenesulphide dielectric capacitors have the lowest temperature drift among plastic dielectric capacitors. Capacitance stability with temperature is good in the case of plastic dielectric capacitors.

Soldering heat and prolonged exposure to heat dissipation from neighbouring components will affect the plastic dielectric. High temperatures can also be caused by internal heat dissipation due to voltage surges, high voltage application, excessive leakage current, etc. All these aspects should be considered in an electronic circuit while using such capacitors. Metallized film capacitors are widely used due to their low dielectric loss and high breakdown voltage.

### Capacitor type

<table>
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<th>Capacitor type</th>
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<tr>
<td>Plastic dielectric capacitors</td>
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<tr>
<td>Porcelain/glass</td>
<td>Cracking of dielectric.</td>
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Table 1: Thermally induced failure mechanisms in capacitors.
is used in the case of Pb-free soldering. This causes an additional thermal stress on the components. The higher soldering temperature by itself does not cause any failure; due to mismatch in the coefficients of thermal expansion (CTE) of the different materials used in the packages, mechanical stresses are induced in the package and its integrity will be affected.

Delamination between layers of component package parts such as metal lead-frame and plastic can lead to susceptibility to moisture ingress, pop-corn failure leading to cracks in the plastic package, corrosion of metal parts, etc., which can cause failure of the component under high humidity conditions and over time.

Table 1 summarises the thermally induced failure mechanisms in capacitors.

Recommended methods for prevention of capacitor failures due to thermal stress:

Several methods can be applied at various stages to reduce the effect of thermal stress on capacitors to reduce the incidence of failures. Some of the important techniques are mentioned below.

Board layout, selection, component placement, assembly and soldering precautions

- Mount capacitors away from hot components in circuit boards by using suitable printed circuit board layout techniques.
- Mount a heat radiating shield between a capacitor and a hot component.
- Wet electrolytic capacitors are especially prone to heat induced damage and should be protected.
- Select capacitors with low ESR and low dielectriclosses.
- Derate capacitors suitably, especially the voltage rating, as per applicable standards and as specified by the manufacturer.
- Use protective circuit methods such as using a resistor in series with the capacitor in the circuit, as recommended by the manufacturer.
- Avoid exposing the capacitors to extremes of temperature, thermal shocks and excessive ripple current.
- Avoid excessive soldering temperature for capacitors; use the recommended temperature profile.
- Avoid mechanical shocks and force of any kind which may cause any kind of damage to the capacitor, hair-line cracks, etc., which may cause failure after some time during field use.
- Ensure the capacitors are connected with the correct polarity in the circuit in the case of polarised capacitors.

Conclusion

In this paper we have discussed the thermally-induced failure mechanisms in capacitors of various types which are generally used in electronic systems. The basic properties of the different types of capacitors have been described. The effect of thermal stress on capacitors due to various causes has been explained. The effect of failure of capacitors on the other components such as PCBs and the amount of damage which can be caused has been demonstrated through examples based on case studies. A few examples of damage caused to capacitors due to thermal overstress have been discussed in this paper; these are based on case studies.

References


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