Evaluation of Microchip Tantalum Capacitors

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Abstract

Microchip tantalum capacitors are manufactured using new technologies that allow for production of small size solid tantalum capacitors (down to Environmental Impact Assessment (EIA) case size 0402) with volumetric efficiency much greater than for regular chip capacitors. These technologies were originally developed for commercial mobile wireless devices, but provided the parts have adequate quality and reliability, their application would be beneficial for space systems allowing for reduction of weight and size of space assemblies and units. In this work, performance and reliability characteristics of seven types of microchip capacitors are studied, analyzed, and compared with relevant performance and reliability of regular chip capacitors. To select high-quality capacitors for space applications, procedures for destructive physical analysis (DPA), screening and qualification testing are recommended.

I Introduction

Manufacturers of tantalum capacitors developed recently new technologies to produce small size capacitors with increased volumetric efficiency that might replace time conventional design tantalum capacitors that have been manufactured for more than 30 years. Currently, tantalum capacitors with code size of 0603 and 0402 are commercially available from Vishay and AVX Corporation. Considering that tantalum capacitors have better time, temperature, and voltage stability of capacitance and are not as susceptible to cracking as ceramic (X7R) capacitors, these new technologies are expanding successfully to areas of application where ceramic capacitors were traditionally used.

Although conventional chip tantalum capacitors are considered high volumetric efficiency devices, only ~ 30% of their volume is occupied by tantalum [1] and the rest is "wasted" mostly for the lead frame and molding compound. New technologies increase volumetric efficiency further, up to ~ 45% for TM8 series manufactured by Vishay and up to 54% for TAC series devices manufactured by AVX [2].

One of the major features of the MicroTan (TM8) design is external connection of the tantalum wire to the anode terminal. Fabrication processes for the TAC capacitors which differ dramatically from the conventional processes, were "borrowed" from semiconductor industry and are based on using a tantalum substrate or wafer and diamond cutting wheels to 'singulate' devices to high levels of mechanical tolerance [2]. A principal feature of the TACmicrochip technology is that, instead of the conventional tantalum wire attached to each capacitor anode body, a matrix of anodes is pressed onto a tantalum wafer. The internal construction is simple, allows for the highest volumetric efficiency, and low parasitic inductance (ESL).

A new molded case design, T528 series, has been recently developed by KEMET Capacitance Company. This design is a further development of the face down version of chip tantalum capacitors that was originally designed to improved ripple current capability of the parts [3]. The new version increases the volumetric efficiency of capacitors by incorporating the lead frame into the bottom surface of the molded case [4]. The T528 series of polymer tantalum capacitors has low Equivalent Series Resistance (ESR) and is available with a case size 1206. Although this design is just an optimization of the traditional design, and is not as effective in increasing volumetric

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efficiency of capacitors as AVX TAC or Vishay TM8 series, it permits continuation of using of the existing manufacturing infrastructure, and allows for employment of polymer cathodes.

Decreasing the weight and size of tantalum capacitors has obvious benefits for space applications, but it brings also new quality and reliability challenges. In particular, can microchip technologies provide capacitors with the same quality as regular chip devices? Are there new degradation processes in downsized capacitors caused by the soldering-induced thermal shock? What are the voltage and temperature acceleration factors for reliability testing of microchips? The purpose of this work is to get better understanding of the design and specifics of microchips, compare their quality and reliability to regular size solid chip tantalum capacitors, and suggest requirements for DPA, screening and qualification testing of the parts.

II Experiment

Seven types of different microchip tantalum capacitors from two manufacturers were used in this study. Table 1 shows description of the parts including their specified electrical characteristics and size.

Table 1. Microchip tantalum capacitors

Gr.	Mfr	C, µF	C toler.	VR at 85C	DCL, µA	DF, %	ESR, Ohm	case	L, mm	W, mm	H, mm
1	A	33	20%	10	3.3	12	1	A (1206)	3.2	1.6	1.6
2	A	33	20%	10	3.3	20	5	R (0805)	2.1	1.4	1.4
3	A	1	20%	35	0.5	8	5	R (0805)	2.1	1.4	1.4
4	A	10	10%	10	1	8	6	R (0805)	2.1	1.4	1.4
5	B	10	10%	16	0.8	8	6	A(1206)	3.2	1.6	1.7
6	B	47	10%	10	2.35	8	1	T	3.5	2.8	1.5
7	B	4.7	20%	6.3	0.16	8	5	M	1.6	0.85	0.85

Capacitance, C, dissipation factor, DF, and equivalent series resistance, ESR, of the capacitors were measured using Agilent 4294 precision impedance analyzer at 120 Hz for C and DF and at 100 kHz for ESR. Leakage currents were measured using a PC-based data acquisition system that allowed for monitoring currents for up to 60 samples. Voltage and temperature acceleration factors were estimated based on life step stress testing (LSST) of the parts.

III Characteristics of microchip tantalum capacitors

Distributions of AC and DC characteristics.

Distributions of characteristics of microchip tantalum capacitors that include capacitance, C, dissipation factor, DF, equivalent series resistance, ESR, leakage currents, direct current leakage (DCL), and scintillation, breakdown voltage (VBR)_scint and surge current, VBR_SCT, breakdown voltages were measured, analyzed and compared with similar distributions of regular solid chip tantalum capacitors. The data for regular chip capacitors (approximately 60 lots) were obtained over the several last years working with various lots of military and high-reliability commercial tantalum capacitors used in space projects.

Figure 1 shows distributions of AC characteristics and leakage currents for seven lots of microchip capacitors used in this study. For all lots all AC and DC characteristics were within the specified limits. However, in lots Gr.2 and Gr.3 a substantial proportion of parts had DF and ESR values greater than the majority of the population thus indicating bimodal distributions and the presence of “out-of family” parts.

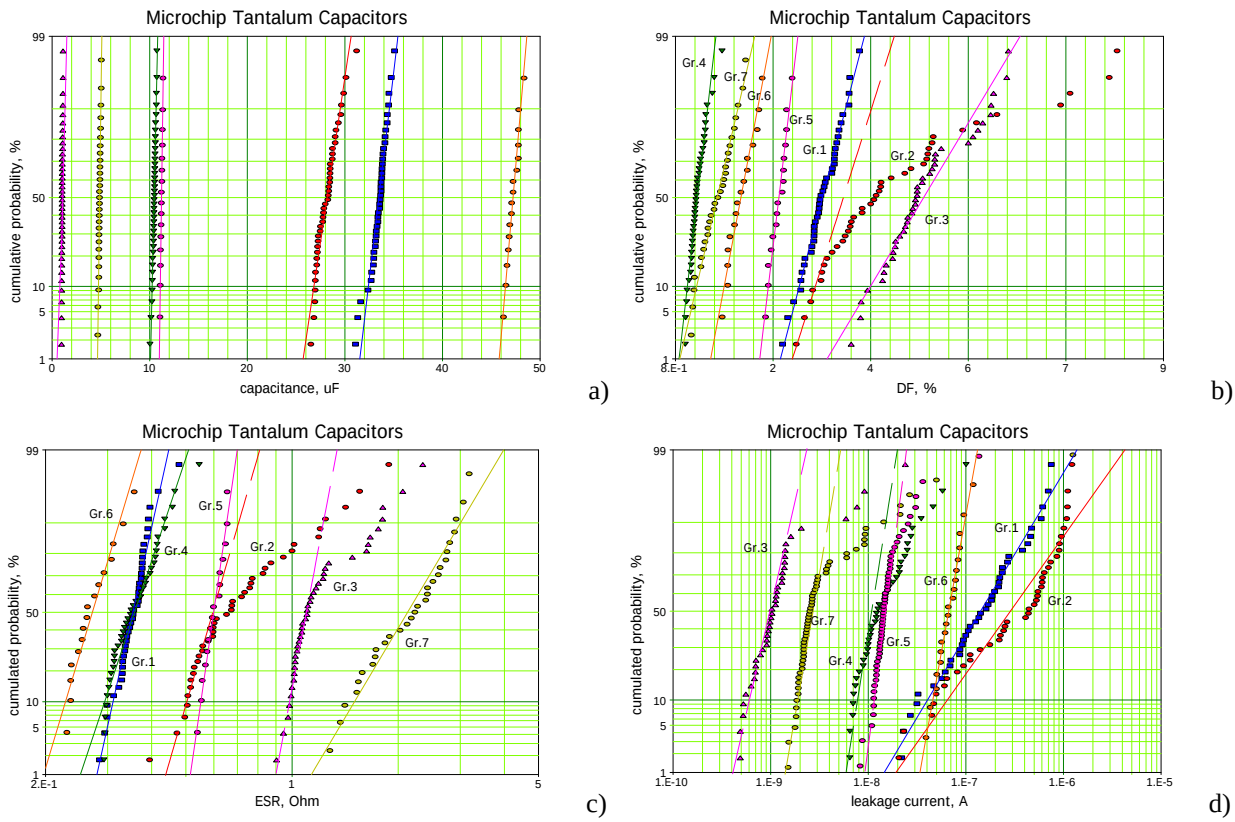


Figure 1. Distributions of capacitance (a), dissipation factors (b), equivalent series resistance (c), and leakage current (d) for seven groups of microchip tantalum capacitors.

Data for dissipation factors indicate that maximum values of DF were well within the specified limits. The value of margin that was calculated as $M_{DF} = (DF_{nom} - DF_{avr} - 3\times STD)/DF_{nom} \times 100$ indicates that in all cases except Gr.3, the margin exceeded 50% that is typical for high-quality parts. Note, that average margin for CWR grade military capacitors is ~ 64%. Values of ESR margin for all lots except for the smallest-size parts, Gr.7, were above 50%. Note that margins in Gr.4 and Gr.5 parts exceeded substantially 50% thus indicating that the nominal values of ESR for these lots are overrated.

Variations of mean values of ESR with capacitance and CV for 63 lots of regular chip and seven lots of microchip tantalum capacitors are shown in Figure 2. As expected, ESR decreases with capacitance; however, a better correlation is observed between ESR and CV values. Variations of ESR with CV can be approximated using an empirical relationship:

$$ESR = \frac{16.64}{(C \times V_R)^{0.71}},$$

where C is in μF, VR is in V, and ESR is in Ohm.

Comparison between regular chip and microchip capacitors shows that, for similar values of C, microchips have somewhat greater ESR and in some cases the difference might be rather substantial, up to 1.5 Ohm. Obviously, downsizing of the parts limits the thickness of manganese and silver epoxy layers and the capability of manufacturing of parts with low ESR. However, ranges of ESR variations for both types of the parts are overlapping and some microchip capacitors have ESR values close to the values that are typical for regular chip capacitors. A better process control and use of new polymer cathode materials might allow for further decreasing of this critical parameter for tantalum capacitors.

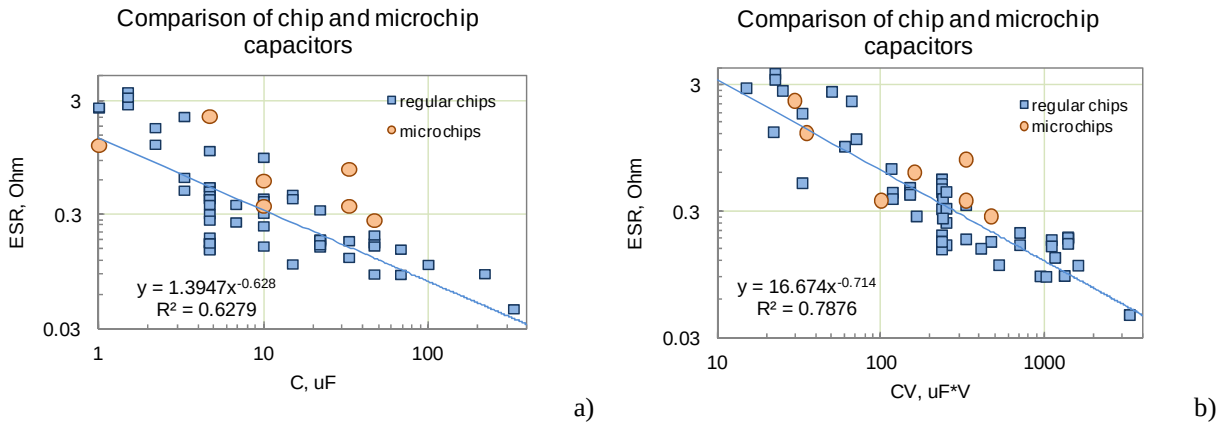


Figure 2. Variation of mean values of ESR with capacitance (a) and CV values (b) for regular chip and microchip tantalum capacitors.

Median values of leakage currents were in the range from ~4×10-7 A (Gr.2) to ~10-9 A (Gr.3) that is from ~10 to 500 times less than the nominal values for DCL. This is also within the range of DCL_{50}/DCLnom values for regular chip tantalum capacitors. Distributions of DCL for Gr.5, Gr.6, and Gr.7 capacitors were much tighter than for other parts. Using the three sigma limit that is suggested to select space-grade, level T, capacitors per MIL-PRF-55365, only a few samples would be rejected in 3 out of 7 tested lots.

Figure 3 shows variations of leakage currents in commercial and military-grade regular chip tantalum capacitors with CV values (for parts below 600 μF×V) in comparison with microchip capacitors. All lots of microchips, except Gr.1 and Gr.2, had DCL values within the range that is typical for regular parts. The two lots of microchips with excessive currents had the same nominal values of C and VR, but different size of package, so most likely the reason for excessive DCL in these parts is not related to packaging, but rather to some flaws in the process of oxide formation.

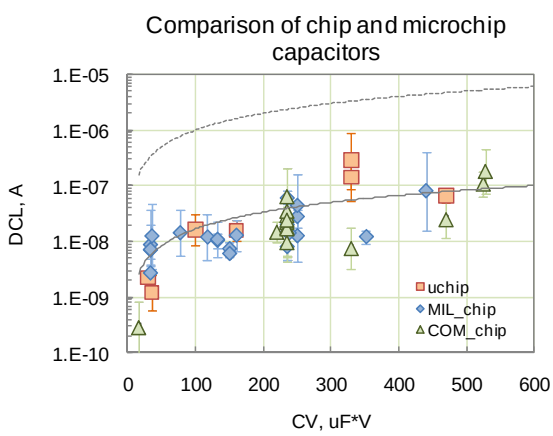


Figure 3. Comparison of leakage currents in regular chip and microchip tantalum capacitors. The solid line indicates linear approximation of the data for regular chip capacitors and the dashed line corresponds to the maximum current calculated as 0.01CV.

Distributions of scintillation breakdown voltages are shown in Figure 4. In all cases the distributions could be accurately enough approximated with two-parameter Weibull functions. The spread of breakdown voltages was from 20 V for parts rated to 10 V to 121 V for capacitors rated to 35 V.

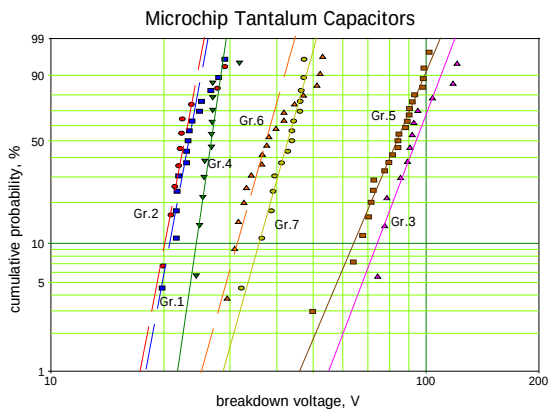


Figure 4. Scintillation breakdown voltages in microchip tantalum capacitors.

The margin values of VBR corresponding to the one percentile of the distributions, VBR1, *[M1 = 100×(VBR1 – VR)/VR]*, exceeded 50% for all lots suggesting adequate quality of the parts. Breakdown voltages in capacitors from Mfr.B were substantially higher than the rated voltages with the margin exceeding 150 %. This indicates that a very conservative approach was used for voltage rating of these parts, and these parts are most likely capable for reliable operation at voltages much higher than the rated. Obviously, derating conditions for these parts can be much less than the typically required 50%.

Normalized to VR average scintillation breakdown voltages for commercial and military-grade regular chip tantalum capacitors are plotted against CV values in Figure 5. Values of VBR_scint/VR for microchip capacitors are also plotted in this chart and are within the spread of data for regular chip capacitors. However, normalized breakdown voltages for Gr. 1 to Gr.4 capacitors are at the bottom levels of the spread, whereas parts from Gr. 5 to Gr.7 are among the best performers.

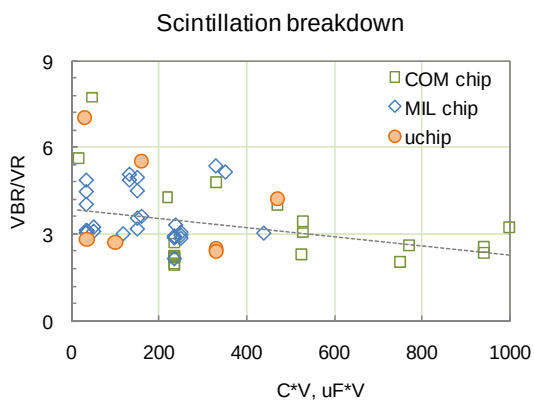


Figure 5. Comparison of normalized breakdown voltages in commercial chip, military chip, and microchip tantalum capacitors.

Anomalous dependencies of the current spike amplitude with the applied voltage were observed in several cases during surge current testing of 4.7 µF 6.3 V capacitors. As voltage increased, at a certain point the current dropped and then continued increasing, but with a lesser rate indicating an increase in Reff (see Figure 6). A similar anomaly was observed previously [5] during testing of small-size CWR06-style capacitors. Most likely the effect is due to significant mechanical stresses associated with high surge currents. These stresses might cause formation of microcracks and delaminations between the cathode layers (manganese oxide – carbon - silver epoxy 1 – silver epoxy 2 – metal terminal) resulting in an increase in ESR that limits the amplitude of the current spikes. The effect is prevailing for relatively small-size parts likely due to a thin plastic package that does not create large enough compressive stresses in the structure that would suppress tensile transient stresses caused by surge currents.

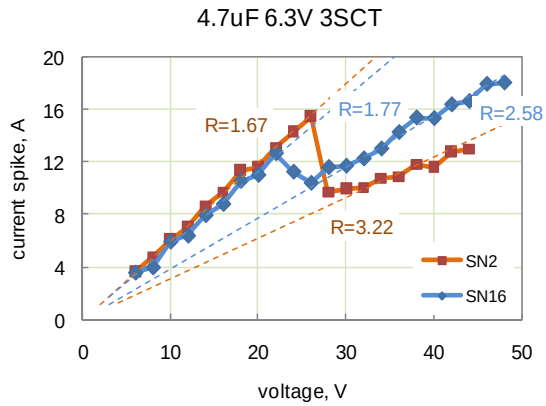
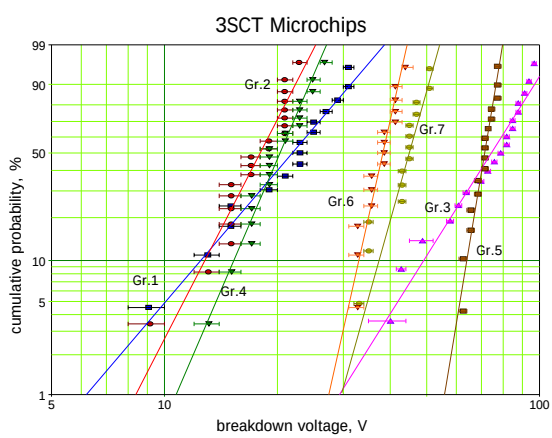


Figure 6. Anomalies in variation of surge current spike with voltage during surge current testing of Gr.7 capacitors.

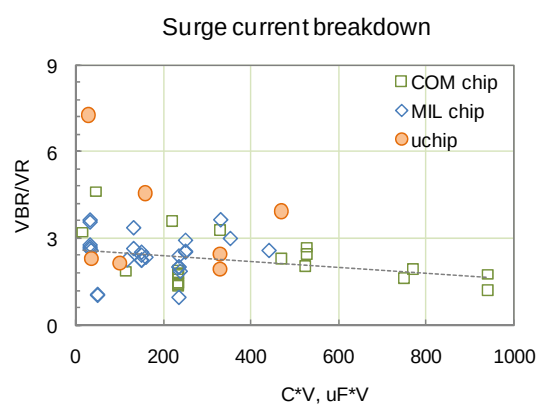
After step stress surge current testing, fractures were observed in Gr.7 capacitors, and their appearance is consistent with the surge-current-induced crack formation model. The fracturing resulted in a separation between the protective polymer strip and cathode terminals that resulted in open circuit conditions. This mechanism is likely beneficial for power supply systems where the parts are typically used because open circuit failures might be less damaging for the system compared to a short circuit failures that are typical for regular chip capacitors. To make sure that fracturing of the parts does not happen as a result of surge current testing, a thorough visual examination and measurements of ESR and delta analysis should be carried out as a part of the surge current testing procedure for the smallest size microchip capacitors.

Distributions of surge current breakdown voltages for seven lots are shown in Figure 7a. Note that similar to scintillation breakdowns, capacitors from Gr.5, Gr.6, and Gr.7 had very large margin values (more than 150%) that substantially exceeded similar values even for military-grade capacitors and indicates underrating of these parts.

Variations of the normalized breakdown voltages with CV for regular chip and microchip capacitors that have relatively low CV values are shown in Figure 7b. Similar to scintillation breakdown surge current breakdown voltages in parts from the three groups, Mfr.B exceeded their rated voltages by a factor of more than 3.5, which is much greater than for similar military chip capacitors.



a)



b)

Figure 7. Distributions of surge current breakdown voltages (a) and variation of normalized surge current breakdown voltages in commercial and military regular chip capacitors and microchip capacitors with CV values (b).

Life step stress testing.

Four types of microchip capacitors were used for life step stress testing (LSST) that was carried out at voltages that typically varied from 1.5VR to 3VR and duration at each step from 20 hr to 40 hr. Temperature during the testing was in the range from room to 125 ˚C. All capacitors during life testing had fast acting 125 mA fuses connected in series and their condition was monitored using a PC-based data acquisition system that recorded test conditions and voltage drop across the fuses. Test results were analyzed using ALTA-7 software available from ReliaSoft.

A Weibull-exponential cumulative damage model was used to assess parameters of distributions and predict the behavior of capacitors at the use-level stress conditions, V = VR. According to this model, the characteristic life of capacitors can be presented as an exponential function of the voltage acceleration (V/VR):

$$\eta = \exp\left(\alpha_0 + \alpha_1 \times \frac{V}{V_R}\right), \qquad (1)$$

where α_0 and α_1 are parameters of the model.

Based on this equation, the voltage acceleration factor can be presented as:

$$AF_V = \frac{\eta(V)}{\eta(V_R)} = \exp\left[\alpha_1 \times \left(\frac{V}{V_R} - 1\right)\right] = \exp(B \times u), \qquad (2)$$

where u = V/VR-1

This means that coefficient α_1 is equivalent to the voltage acceleration constant B that is used in MIL-PRF-55365 to calculate acceleration factors of the Weibull Grading Test (WGT). Model parameters, α_1, α_2, and β were computed using ALTA-PRO software by utilizing the maximum likelihood estimation method.

Figure 8 shows results of LSST for 40 samples of Gr.2, 33 µF 10 V, microchip tantalum capacitors that was carried out at 85 ˚C and voltages varying from 16 V to 24 V in 40 hr steps with 4 V increments. The slope of the Weibull distribution for the use level was 0.19 suggesting that similar to regular chip tantalum capacitors, failures of the microchip capacitors can be considered as infant mortalities up to the end of life, in this case ~10^9 hours. These parts were not screened by WGT explaining the presence of "instant" initial failures (within a few seconds) during the first step after application of 16 V at 85 ˚C. The calculated voltage acceleration constant, B = 14.1, was within the range observed for the regular chip capacitors [6].

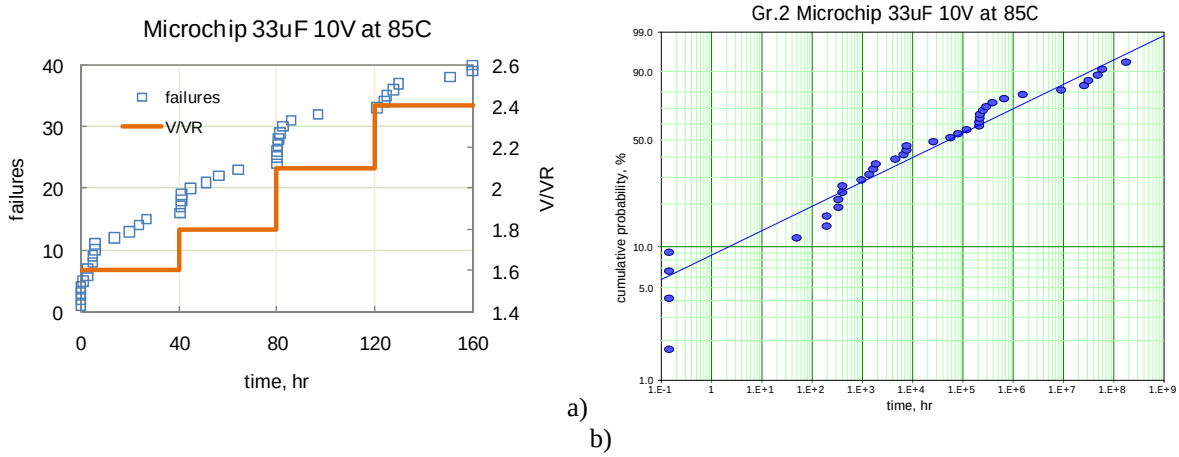


Figure 8. Experimental (a) and calculated for the use-level Weibull distributions of times to failures for Gr.2 capacitors.

Life step stress testing for Gr.4, Gr.6, and Gr.7 capacitors was carried out at three temperatures, 22 ˚C, 85 ˚C, and 125 ˚C. Results of calculations of the LSST data for the use level of stress for three types of capacitors are shown in Figure 9. In most cases the distributions could be approximated using unimodal Weibull functions. However, early failures in 4.7 μF 6.3 V parts deviated from the unimodal distribution that was used to describe failures of the majority of the capacitors. These distributions had β exceeding 1, which indicates wear-out failures and are likely related to extremely high level of breakdown voltages in these parts suggesting a high quality dielectric. Most likely, the early failures were due to the presence of defects in the oxide, whereas the majority of the parts with defect-free oxides failed after a rather long incubation period and within a relatively short time interval. Obviously, for an ideal, defect-free dielectric all capacitors would break at the same voltage and after the same period of operation, thus resulting in wear-out failures that occur simultaneously. In similar cases it is important to assure that the incubation period is large enough (e.g. three mission life times).

Note that the presence of wear-out mechanisms was also observed for low-voltage polymer tantalum capacitors [7]. This might limit the capability of Weibull grading test that is based on the assumption that all failures of tantalum capacitors are defect-related infant mortality failures for selecting high-quality new technology capacitors.

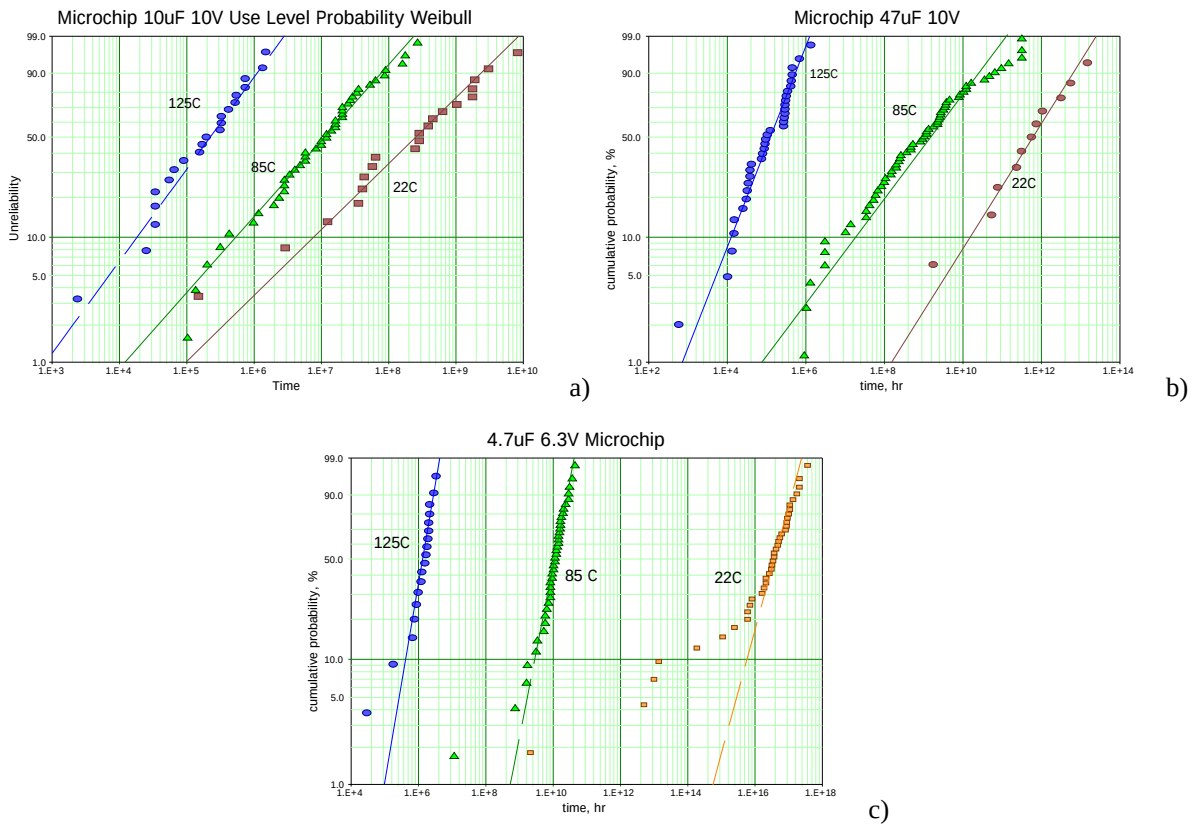


Figure 9. Calculated use-level Weibull distributions for times to failures for three types of microchip capacitors at temperatures 22 ºC, 85 ºC, and 125 ºC.

Parameters of the cumulative damage model for all parts are shown in Table 2. In all cases, except for Gr.7 shape factors of Weibull distributions were below 1. Results for Gr.7 capacitors indicate wear-out mechanism of failures that apparently became more pronounced as temperature rises. Note, that the table indicates β(22 ºC) = 1.05 based on estimations for the top 70% of the failed parts.

At 85 ºC the acceleration constant, B, is close to the value accepted by MIL-STD-55365 (B = 18.77) for Gr.4 capacitors only. In all other cases the acceleration constant is much less, in the range from 6 to 14, which is consistent with the results for regular chip capacitors reported in our previous work [8]. This confirms that the

existing procedure for calculation of reliability characteristics of tantalum capacitors in many cases overestimates the rate of failures and can result in significant errors.

Table 2. Parameters of the cumulative damage exponential model for microchip capacitors.

Lot	T, °C	QTY	β	α_0	α_1 = -B	η(VR), hr	WGT FR, %.1000hr
Gr.2	85	40	0.19	26.98	-14.12	3.85E+05	1.6E-02
GR.4	22	20	0.51	33.53	-13.43	5.39E+08	
	85	43	0.62	35.05	-18.23	2.01E+07	6E-03
	125	21	0.81	36.39	-23.70	3.25E+05	
Gr.6	22	11	0.51	38.42	-10.56	1.25E+12	
	85	60	0.34	31.87	-9.92	3.39E+09	4.7E-04
	125	34	0.82	18.44	-6.26	1.95E+05	
Gr.7	22	38	1.05	46.16	-7.89	4.17E+16	
	85	40	1.4	29.40	-6.02	1.43E+10	1.2E-11
	125	18	1.62	18.48	-4.16	1.66E+06	

Table 2 has also failure rates calculated at 85 °C for conditions simulating Weibull grading test per MIL-PRF-55365 (WGT FR). First, failure rates were calculated for conditions simulating testing for 40 hrs at 1.5VR and then the data were divided by 20000, which is the acceleration factor accepted by the military standards. Obviously, this acceleration was not confirmed by our data. However, this method is currently used for all high-reliability parts and these estimations were made to compare microchip and regular chip capacitors. The results indicate that microchip capacitors can be screened to a high FR levels, level B (0.1%/1000hr) and greater, up to the highest T-level (0.001%/1000hr) reliability.

Temperature dependencies of characteristic life times at the rated voltages are shown in Figure 10. In Arrhenius coordinates the data were approximated with straight lines and the slopes of these lines allow for estimations of the life time activation energies, E_a. Based on these calculations, values of E_a are spread over a wide range, from 0.66 eV for Gr.4, 1.37 eV for Gr.6, and to 2.15 eV for Gr.7 capacitors. This range is consistent with the available literature data [8].

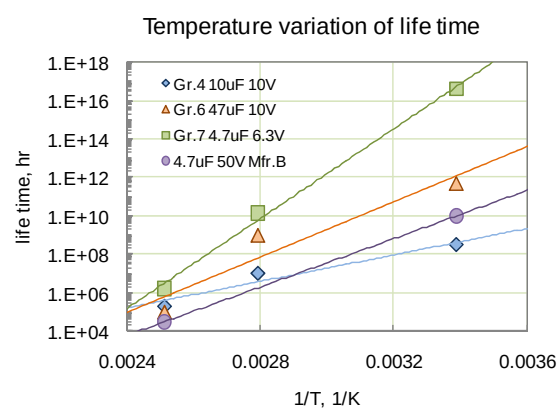


Figure 10. Temperature dependencies of characteristic life times based on results of life step stress testing at different temperatures.

IV Selection of high-quality microchip tantalum capacitors.

Design and manufacturing materials of microchip capacitors were analyzed to better understand specifics of these parts and potential reliability issues. The effect of compressive stresses on leakage currents and degradation of performance caused by soldering-induced thermal shock have been studied and will be reported in a separate paper. Suggestions for DPA, screening and qualification of microchip tantalum capacitors based on results of analysis of possible reliability issues are summarized below.

1. *Destructive physical analysis (DPA):*
   - 1.1. A special attention should be made to the shape and size of silver epoxy used to form cathode contacts during visual examinations of microchips with protective strips.
   - 1.2. Radiography should be included for DPA to assure proper alignment of elements, adequate thickness of plastic packages, manganese layers, and sizes of the contact areas between silver-epoxy and terminations.
2. *Screening:*
   - 2.1. Two-side radiography should be used during screening. To avoid exposure of manganese cathode, maximum thickness of MnO^2 layer should be less than 50% of the thickness of molding compound. To assure proper cathode interconnections, the contact area between silver epoxy and cathode terminals as it is seen from the top radiographic views should be not less than 10 mils and not less than 5 mils on a side view.
   - 2.2. Surge current testing should be mandatory for all types of microchip capacitors, including the smallest, size code M, parts. To make sure that the parts are not damaged (fractured) as a result of surge current testing, a thorough visual examination, measurements of ESR, and delta analysis should be carried out as a part of the surge current testing procedure.
   - 2.3. Weibull grading test should be carried out using a verified voltage acceleration factor and maximum percent of defective parts should be limited. A procedure that verifies the presence of electrical contacts during the testing should be developed and implemented.
3. *Qualification testing:*
   - 3.1. Surge current and scintillation breakdown voltages should be measured to obtain the baseline distributions and characterize quality of the lot.
   - 3.2. The range of temperatures during temperature cycling should be increased from currently used -55 ºC to +125 ºC to -65 ºC to +150 ºC and the number of cycles from 10 to 100. Post-TC electrical measurements should include breakdown voltages.
   - 3.3. Life testing should be carried out at 105 ºC and 1.1VR for 2000 hours using parts soldered onto printed wiring boards (PWBs) of a standard size and material.
   - 3.4. Resistance to soldering heat testing should include post-test measurements of breakdown voltages. A terminal solder dip testing at 325 ºC should be required if the parts are allowed to be soldered manually (or reworked).
   - 3.5. Additional analysis should be done to evaluate the necessity of the flex-stress testing similar to Multilayer Ceramic Capacitors (MLCCs) (e.g. AEC Q-200 but modified as appropriate).
   - 3.6. Considering that tantalum capacitors are sensitive to mechanical stresses, to assure a necessary margin between the critical level of stress that degrade performance of the parts and stresses caused by soldering onto PWBs, qualification tests should include measurements of leakage currents under a stress of 10 MPa.

V Summary

1. Seven types of different microchip tantalum capacitors from two manufacturers were characterized by distributions of AC and DC characteristics including scintillation and surge current breakdown voltages. A comparative analysis of distributions with the relevant distributions of approximately 60 lots of regular chip tantalum capacitors showed that five out of seven lots had margins that are typical for high quality regular size capacitors.
2. Margins of breakdown voltages for all microchip capacitors exceeded 50% that is typical for high quality parts. Surge current breakdown voltages in three groups of capacitors had margins in the range from 170% to 330%

that exceeds performance of military-grade chip capacitors. This indicates that a very conservative approach was used for voltage rating of these parts, and these capacitors are most likely capable for reliable operation at voltages much higher than the rated.

3. An increase of ESR was observed during surge current testing of the smallest size microchip capacitors. The effect is likely due to a thin plastic package that does not create compressive stresses sufficient to suppress tension caused by surge currents.
4. Reliability characteristics, as well as, voltage and temperature acceleration factors were evaluated using life step stress testing technique with the following results:
   - 4.1. At 85 ^{o}C the acceleration constant, *B*, varies in the range from 6 to 18, which is consistent with the results for regular chip capacitors and for some lots deviates substantially from the accepted standard constant (B_s = 18.77).
   - 4.2. Failure rates calculated at conditions simulating Weibull grading test per MIL-PRF-55365 showed that microchip capacitors can be screened to a high FR levels up T-level (0.001%/1000hr).
   - 4.3. Based on temperature dependencies of characteristic life times activation energies for different lots were in the range from 0.66 eV to 2.15 eV, which is consistent with the data for regular chip capacitors.
   - 4.4. In all cases, except for Gr.7, shape factors of Weibull distributions were below 1. Results for Gr.7 capacitors indicate wear-out mechanism of failures that apparently became more pronounced as temperature raises. Wear-out failures do not affect the useful life of microchips as long as there is a substantial margin between the mission duration and the onset of failures. The presence of wear-out failures might be specific for high-quality new technology products and requires new approaches for screening and qualification.
5. To assure high quality and reliability of microchip tantalum capacitors, the existing procedures for DPA, screening and qualification testing should be adjusted to accommodate specifics of design of microchip tantalum capacitors.

VI Acknowledgments

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VII Reverences

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