

An Overview of Failure Analysis of Tantalum Capacitors

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Tantalum Capacitor FA

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Introduction

A meaningful failure analysis of a capacitor (CAP) requires a thorough understanding of its construction. Capacitors can be classified into different types based on their materials and construction: tantalum, ceramics, aluminum, and so on (Table 1). Each offers a unique set of properties suited for a particular application. A simple CAP consists of a dielectric material sandwiched between two conductors with a bias applied across them. The capacitance (C) of a CAP is given by the following equation, where ϵ , A , and t are the dielectric constant, surface area, and thickness, respectively:

$$C = \epsilon A / t \quad (\text{Eq 1})$$

Miniaturization of electronic devices demands higher and higher capacitance in a smaller volume. One way to achieve higher capacitance in a small volume is to increase the “ A ” in Eq 1. This is achieved differently in different types of capacitors. In the case of tantalum CAPs, for example, it is achieved with porous tantalum anodes (high surface area/volume), which are produced by pressing and sintering tan-

talum powder, with an attached tantalum wire. An amorphous Ta_2O_5 dielectric is then electrochemically grown on this high-surface-area porous tantalum anode. The Ta_2O_5 is typically a few tens of nanometers thick. The porous anode is then impregnated with a counterelectrode layer (MnO_2 or conductive polymer), providing high capacitance in a small volume (Fig. 1). Solid-state tantalum capacitors are typically used for 100 V or below, with most of them being 50 V or lower. Wet tantalum capacitors (the counterelectrode being a liquid) allow higher working voltages, up to a few hundred volts.

In film and ceramic CAPs, thin layers of dielectric and electrode materials are stacked alternately, with alternating electrodes displaced to avoid contact between the opposing terminals. Figure 2 shows the typical construction of a ceramic capacitor. A few tens to hundreds (in ceramic CAPs) or even thousands (in film CAPs) of these layers can be stacked to obtain the desired capacitance.

Because of significant dissimilarity in the materials and construction of different types of CAPs (Table 1, Fig. 1 and 2), the cause of their failure is also

Table 1 Different types of CAPs

Type	Dielectric	Electrode/counterelectrode	Construction	Polar devices
Tantalum	Tantalum oxide	Tantalum/ MnO_2 Tantalum/conductive polymer Tantalum/liquid electrolyte	Porous tantalum anode for high surface area	Yes
Aluminum	Aluminum oxide	Aluminum/conductive polymer Aluminum/liquid electrolyte	Etched aluminum foils for high surface area	Yes
Ceramics	BaTiO_3 , ZrTiO_3 , etc.	Base metal electrode (BME), such as copper, nickel Precious metal electrode (PME), such as silver, palladium	Layered structure for high surface area	No
Film	Polypropylene, polyethylene	Metal, such as zinc, aluminum, etc.	Layered structure for high surface area	No

Source: Ref 1

different. Consequently, each condition requires a unique failure analysis (FA) approach. It is worth noting that the FA of the failed CAP is part of the overall root-cause analysis, along with circuit and application analyses. This paper provides an overview of FA for surface-mount tantalum CAPs.

Electrical failure modes of tantalum CAPs can be

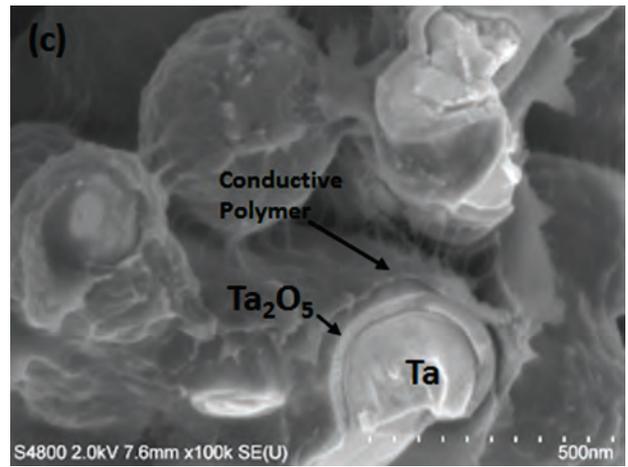
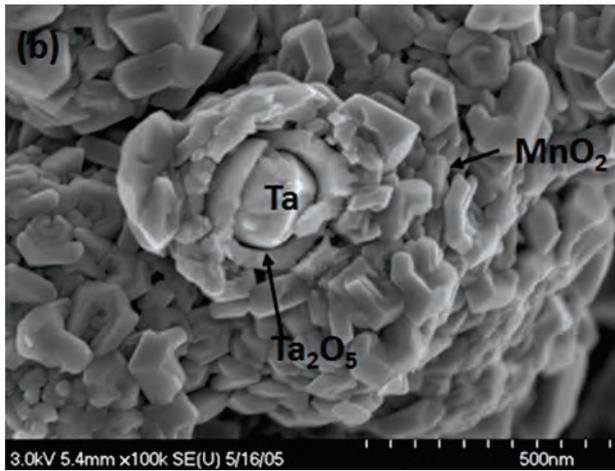
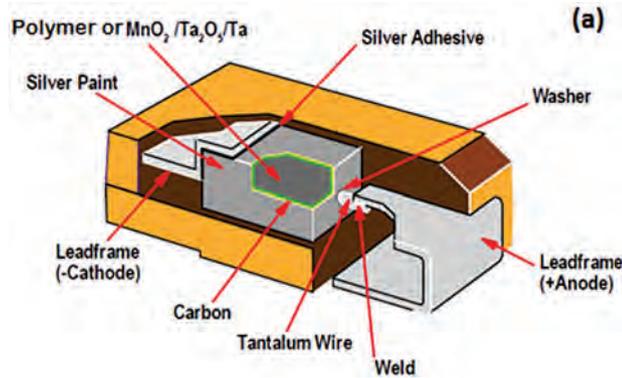


Fig. 1 (a) Typical construction of a tantalum CAP. The tantalum/dielectric/counter-electrode inside the tantalum anode is shown (b) for MnO_2 and (c) for a conductive polymer tantalum CAP. Source: Ref 1

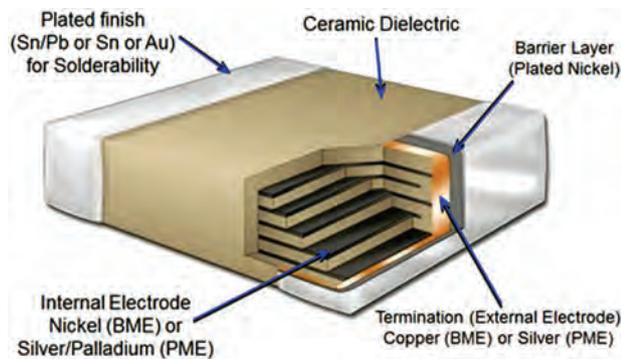


Fig. 2 Typical construction of a ceramic capacitor. BME, base metal electrode; PME, precious metal electrode. Source: Ref 1

divided into three broad categories: high leakage/short, high equivalent series resistance (ESR), and open/low CAP, with the high leakage/short accounting for most of the failures. Each of the failure modes has its own possible causes, and therefore, the FA approach is determined by the type of failure, as discussed below. Prior to any destructive analysis, it is essential to obtain as much relevant physical and electrical data as possible without further damaging the CAP. Background information and the conditions

the CAP was exposed to, such as board mounting, storage, application parameters, environmental conditions, time to failure, and so on, should be collected and analyzed as well, because FA of the failed CAP alone may not provide the root cause. Figure 3 lists the most common causes (divided into application and production) that can contribute to a tantalum CAP failure. It is worth noting that failed capacitors resulting from application conditions or production anomalies may be very similar.

Nondestructive Analysis

It is important that the failure analyst understands the type of CAP failure, because the definition of *failure* varies. In all cases, the CAP's as-received condition should be compared to its specifications. Moreover, the results of the nondestructive testing techniques help determine the path forward to ascertain the root cause of the failure.

Ideally, the failed CAP should be initially examined on the circuit board. This allows confirmation that the CAP was mounted with the correct polarity. Examination of the CAP (on the circuit board) and

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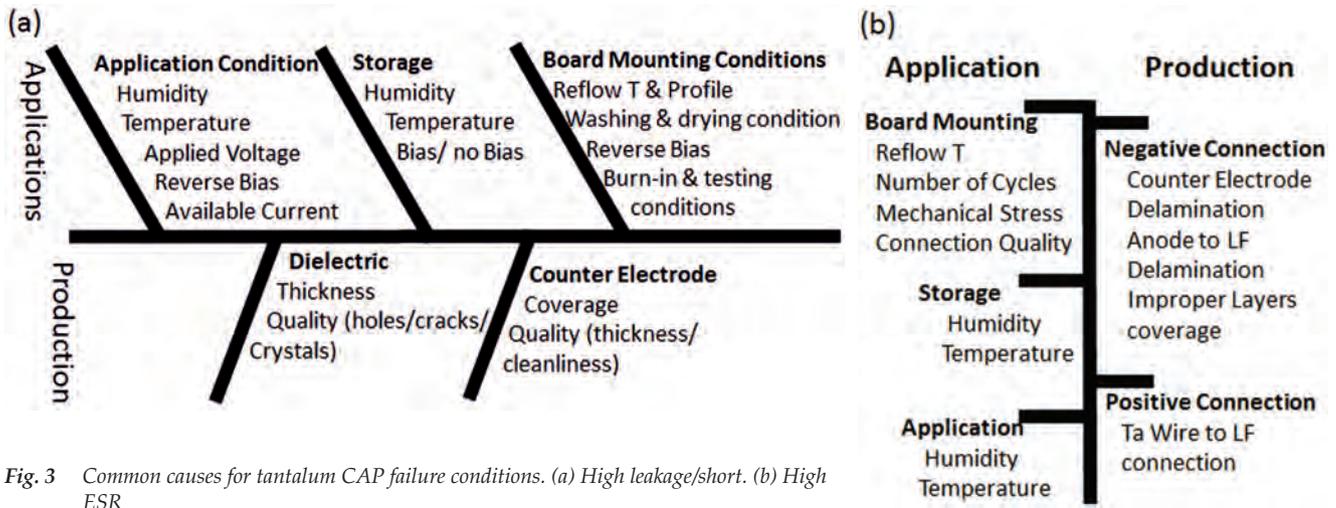


Fig. 3 Common causes for tantalum CAP failure conditions. (a) High leakage/short. (b) High ESR

its surroundings could help identify if there was any external stress involved. Analyzing the solder joints allows identification of any possible manual rework. Next, external and internal construction of the CAP should be examined. External examination of the CAP is typically conducted using a stereomicroscope, which can reveal defects such as mold-epoxy cracking, discoloration, thermal/mechanical damage, rework, and so on. Ensuring that the external defect is the cause of the failure and not the result of the failure is critical, because it can lead to a wrong root cause. A real-time x-ray inspection allows examination of the internal construction of the CAP and any anomalies present (anode misalignment, poor positive or negative connections, etc.). With improving x-ray resolution and faster computing power, x-ray tomography is becoming a helpful tool in analyzing the internal construction of a CAP.^[2]

After physical and x-ray inspection, the electrical parameters of the as-received CAP must be recorded as well. This should be done in a way that does not further damage the CAP. Needless to say, the CAP must be electrically isolated from the circuit. All major tantalum CAP manufacturers have a specific way of marking their CAPs, which typically provides manufacturer, capacitance, rated voltage, date/lot code, and polarity. Ensuring that the failed CAP is not a counterfeit is becoming an important factor.

The first thing to check electrically is the direct current resistance (DCR) of the tantalum CAP, which is typically done with a multimeter. (The available current should be kept very low.) A DCR of less than ∞ indicates that the CAP has a high-leakage or a short-circuit condition. Next, the capacitance, dissipation factor (DF), and ESR should be checked (typically by using an LCR meter) at the appropriate frequencies (see the manufacturer's data sheet), typically at 0.5 or

1 V rms. It is important to note that the capacitance, DF, and ESR of a shorted CAP will not meet the specifications. Leakage measurements must be done very carefully because the CAP could "self-heal" in the process. The exact mechanisms for self-healing are different for the MnO₂ and polymer CAPs.^[3,4]

High-Leakage/Short Failures

If the CAP has a DCR less than ∞ , then there is a conductive path between its positive and negative terminals. Assuming that the CAP has been isolated from the circuit, either the leakage path is through the tantalum anode (the dielectric has been compromised) or a conductive path has been formed between the positive and negative terminals, bypassing the tantalum anode. The CAP should be examined to ensure that no bridging is present externally. There could be a number of reasons that lead to either possibility, as shown in Fig. 3(a), which can be broadly divided into application or production.

Knowing the location of the fault site inside the CAP before performing any destructive analysis is very valuable, especially for large case sizes and multiple-anode CAPs. Figure 4 shows the thermal image of a high-leakage CAP subjected to the rated voltage and a very small amount of current applied for a very short period of time. Localized internal heating at the fault site results in a slight increase in localized temperature, which is recorded by the thermal imaging system. Thermal imaging in combination with x-ray analysis allows pinpointing of the fault location. This approach increases the FA success rate and reduces FA time. The CAP can then be cross sectioned to the fault site, and the anode and the counterelectrode layers can be analyzed for any anomalies. If the CAP has no physical anomaly, its DCR is in the hundreds

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of kilo- to mega-ohms range, and no thermal hot spot is observed, then the leakage should be measured at the rated voltage (see the manufacturer's specification) to ensure that the part indeed has high leakage.

Based on the failure mode, the tantalum CAP could be chemically stripped to examine the tantalum anode's integrity and the dielectric quality.^[5] Tantalum dielectric is typically electrochemically grown at two to three times the CAP's rated voltage to provide a more robust dielectric. Flaws in the dielectric, such as a crystalline oxide (Fig. 5), could be examined by stripping away the counterelectrode layers. Crystalline oxide nodules weaken the amorphous dielectric and provide a conductive path. The presence of a few of these sites could be isolated by the healing mechanism of the tantalum CAP. With everything else being the same, crystalline oxide is more pronounced for high-voltage CAPs (typically 35 V and higher), and the presence of a significant number of these sites could be a problem. Over the years, many processes have been developed to minimize/eliminate crystalline oxide growth.^[6,7]

Tantalum CAPs, like any other electronic component, could also fail due to their application conditions (Fig. 3a). As a polar device, the tantalum CAP can withstand a small amount of reverse bias for a short period of time; however, it is not very forgiving when subjected to reverse polarity. If a CAP is suspected to have experienced reverse bias, it may be possible in

some cases to do a reverse knee voltage test on sister CAPs taken from the same circuit.^[8] This could help show if the CAPs have been subjected to reverse bias.

Stability of the circuit is also an important factor. High current and voltage surges can also damage the dielectric, which can lead to a failure. Localized heating will appear as evidence of both abusive application conditions and a weak dielectric. Ensuring that an appropriate CAP is used for a particular application is yet another factor to be considered.

In general, surface-mount tantalum CAPs are not hermetically sealed and therefore can absorb moisture. The presence of significant moisture inside the CAP during reflow can create a large amount of steam inside the CAP, which, in some cases, can crack the mold epoxy and allow more moisture to penetrate into the internal elements. Extended exposure to high humidity and temperature during storage and/or application could also result in chemical/electrochemical migration of the conductive species inside the CAP, resulting in a leakage path.

High-ESR Failures

The cause of high ESR can be divided into two main categories: a loose connection or an increase in the resistivity of the material (Fig. 3b). Again, before performing any destructive analysis, the high-ESR condition must be verified at the appropriate frequency, and, more importantly, proper connections between the testing probes and the CAP terminals must be ensured. The presence of any conformal coating or flux on the solder joint, improper solder/adhesive joints, oxidation of the terminals/solder joint, inappropriate probes, and so on could falsely show a higher ESR than the actual value.

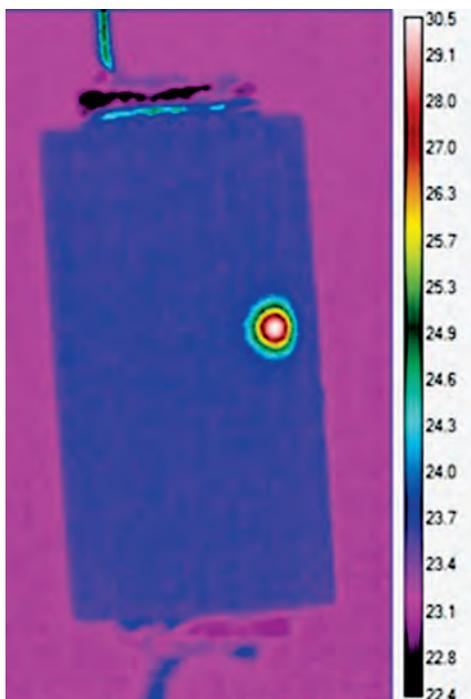


Fig. 4 Thermal image of a tantalum CAP shows a hot spot indicative of a fault site.

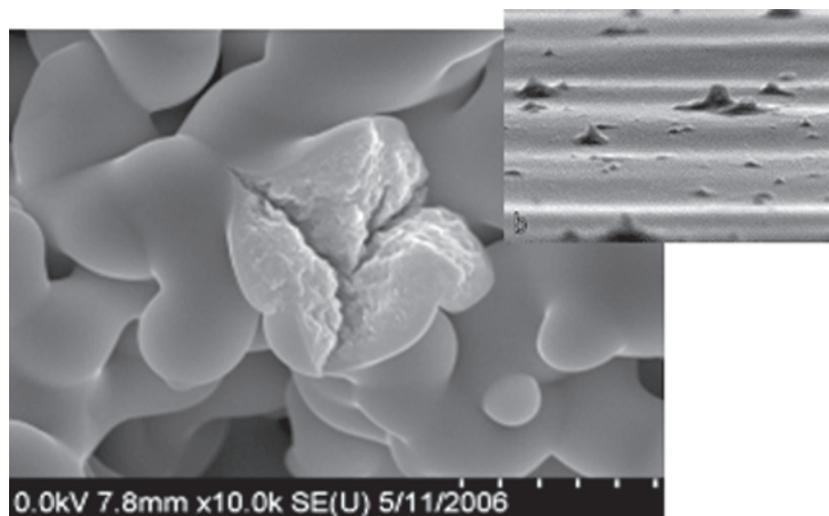


Fig. 5 Crystals on tantalum anodes. Source: Ref 6

The ESR of a CAP is impacted by the mechanical/thermomechanical stresses it is exposed to during pick-and-place, board mounting, reflow, and application lifetime. These stresses can compromise external and/or internal connections, resulting in high ESR. The materials used in the construction of a typical tantalum CAP have very different coefficients of thermal expansion, and exposure to a high temperature for an extended period of time could create thermomechanical stresses, resulting in ESR problems.

Exposure to high relative humidity at elevated temperature can result in oxidation of the external leads, causing high ESR. Because these are not hermetically sealed CAPs, moisture could penetrate inside the CAPs at high humidity and elevated temperature, resulting in oxidation of the terminals and cracking/delamination in the counterelectrode layers.

From the perspective of tantalum CAP production, most of the ESR issues arise from the counterelectrode (negative connection) layers, including delamination between the layers, a thicker-than-normal layer, a missing layer, and so on. The ESR issues are rarely associated with a positive connection problem, which typically results from a poor connection of the tantalum wire to the positive leadframe. A thorough x-ray analysis could reveal some of these internal construction issues. Optical or scanning electron microscopy analysis of a sectioned CAP will be more helpful in determining the root cause. A sectioned CAP can also be microprobed to clarify which layer is contributing to the high ESR of the CAP. This must be done very carefully, because destructive analysis techniques such as sectioning can introduce sample-preparation artifacts.

Low Capacitance/Open

Under normal conditions, the capacitance of a tantalum CAP does not change significantly, and this failure mode is not very common. In general, a significantly lower capacitance at customer-incoming inspection would be an indication of a wrong or mislabeled CAP. Lower capacitance of a CAP in application could be an indication of a shorted CAP. Exposure to high humidity and temperatures could increase the capacitance somewhat, and conversely, drying could reduce the capacitance. A tantalum CAP could read open if it was shorted. Open failure could also result from a compromised or noncontinuous positive leadframe and wire connection. X-ray imaging would help to examine the internal construction, and cross-sectional analysis could help identify the cause.

Summary

Leakage, ESR, and low-capacitance failure modes of

surface-mount tantalum CAPs have been reviewed. The nondestructive and destructive analysis approaches for each of these failure modes have been discussed. The most common causes for each of these failure modes and their determination techniques have been reviewed.

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About the Author

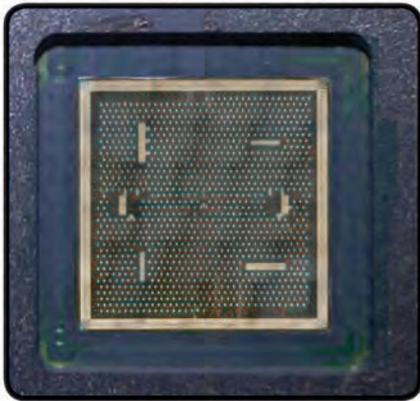


Javaid Qazi, currently the Manager of Technical Services at Kemet Electronics, has held various positions at Kemet since 2005. His group focuses on developing materials chemistry processing property relationships and failure analysis to improve existing capacitors and develop new ones. He has 39 publications, including review and invited articles. Dr. Qazi holds a B.S. degree in metallurgical engineering from the Middle East Technical University, Ankara, Turkey; an M.S. in polymers and polymer composites from the University of Sheffield, Sheffield, United Kingdom; and a Ph.D. in materials science and engineering from the University of Idaho. He held a postdoctoral position at Clemson University before joining Kemet Electronics.

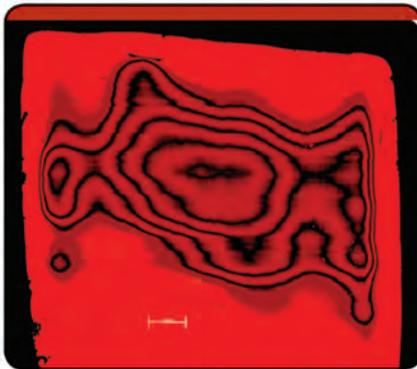
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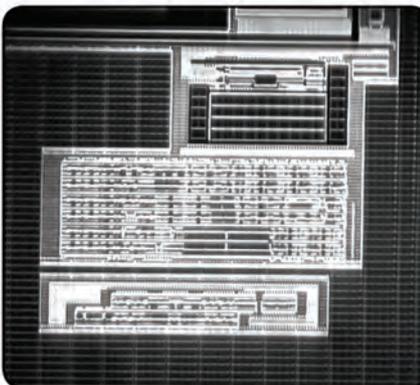
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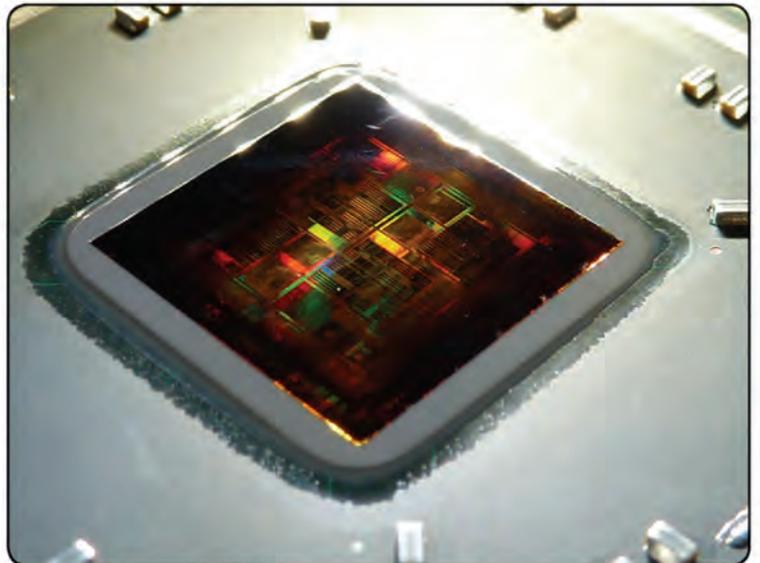


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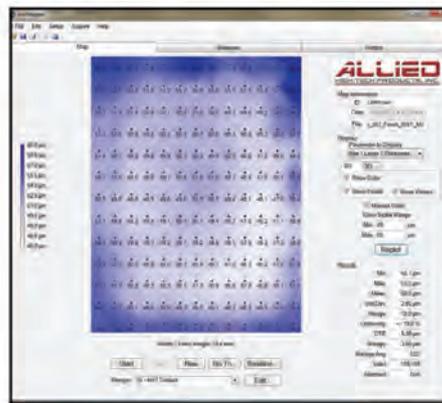
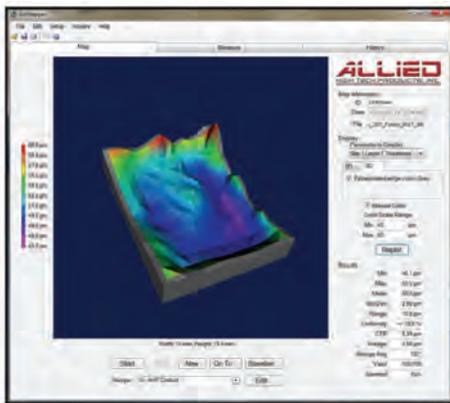


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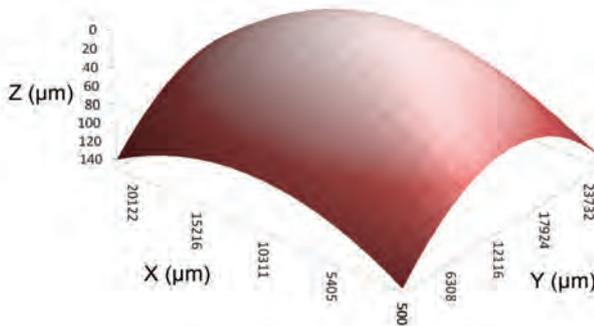
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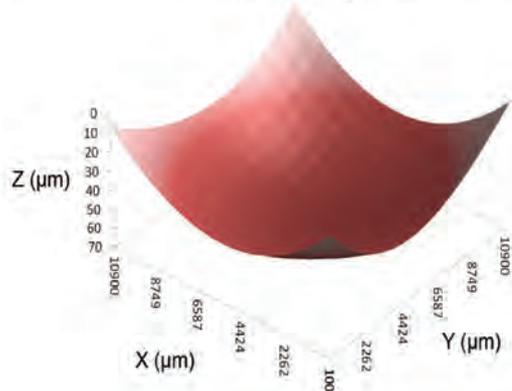
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