A Study of Solder Joint Failure Criteria

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Abstract

One of the challenges in an experimental study of solder joint reliability is to determine when cracks occur in a solder joint or when a solder joint fails. Cracks in a real solder joint are difficult to identify using an X-Ray system. Cross-sectioning and scanning electron microscopy (SEM) is a destructive method. A common non-destructive test method is to monitor resistance increase in a solder joint or a daisy-chain. However, no scientific research has been done in establishing the relationship between the crack area of an interconnection and the change in resistance of the interconnection. This paper proposes a method of defining failure criteria as the resistance increase in a solder joint exceeding a threshold. The threshold is determined by *k* times the range over the natural variation in resistance measured by a measurement system. The natural variation by random cause is judged using X-bar and R charts. The principles of defining failure criteria are to be able to detect failure of solder joints as early as possible with minimum false detection due of measurement system error/variation. An experimental study confirmed that a full crack of an interconnection occurs when the increase of resistance in the interconnection is 10 times the natural variation of resistance change. The results of this study could be used to narrow the definition of failure in consensus standards IPC 9701A, JESD22-B111, and IPC/JEDEC-9702.

Keywords: Solder joint, failure criteria, measurement capability, crack, X-bar and R charts

1. Introduction

It is well known that solder joint failures are a result of crack initiation and growth. Therefore, failures of solders can be divided into two stages: the crack initiation stage, which starts with the first load cycle and ends when a detectable crack is present; and the crack propagation stage, which starts with a detectable crack and ends when the joint is open (or electrical discontinuity).

One of the major challenges in an experimental study of solder joint reliability is to determine when cracks occur and to monitor the propagation of cracks in a solder joint. It is extremely difficult in reality to characterize the initiation and propagation of cracks [1]. The fact is that cracks in a solder joint are difficult to identify through a non-destructive method such as a conventional X-Ray system, because of limited resolution. Cross-sectioning and scanning electron microscopy (SEM), and dye-and-pry cannot be used for in-situ monitoring crack initiation and propagation because they are destructive methods. Furthermore, without knowing where a crack is, it is difficult to decide which plane should be cross-sectioned since cracks can happen anywhere within the three dimensions of a solder joint while SEM pictures are normally cross-sectioned in the vertical plane (two-dimensional). Therefore, researchers who have studied the reliability of solder joints so far rely on detecting electrical discontinuity through measuring the resistance change in a solder joint or a daisy-chain, based on the assumption that an electrical discontinuity will occur if there is a crack or cracks in a solder joint detaching fully the interconnection path.

Now the question is what defines an electrical discontinuity? Different researchers have used different criteria, for example, a resistance threshold of 450Ω [2], an increase in resistance of 10Ω or greater [3], the resistance change of 5Ω [4]. The majority of the studies such as in references [5-9] use criteria defined in one of five standards [10-14], depending on the kind of reliability test. For temperature cycling testing, the industry-wide guideline was IPC-SM-785 (released in 1992). The guideline has been replaced by the requirements standard IPC-9701 in 2002 and its revision A in 2006. In IPC-SM-785, electrical discontinuity is defined as exceeding the resistance threshold of 1000 Ω for a period of 1 μs or more; and solder joint failure is defined as the first such electrical discontinuity followed by 9 or more events within 10% of the number of temperature cycles to the first event. IPC-9701A defined the aforementioned criterion for the event detector monitoring systems; in addition, it added criteria for data logger systems. However, preference was given to event detector use. For a data logger, the electrical discontinuity is defined as a 20% resistance increase from the initial resistance value and the failure of a solder joint is defined as the first such event within five or more consecutive scans with this increase. Note that less than 1 minute per scan is required for a data logger.

The industry-wide specification for drop testing is JESD22-B111 released in 2003 and for monotonic bend testing is IPC/JEDEC-9702 released in 2004. The electrical discontinuity specified in JESD22-B111 is a resistance threshold of 1000 Ω lasting 1 μs or longer if an event detector is used, and resistance threshold of 100 Ω if initial resistance value is less than 85 Ω, and 20% increase in resistance if initial resistance is larger than 85 Ω when a high speed data acquisition system is used. The high-speed data acquisition system should have a scan frequency of 20 kHz or faster (or a sample rate of 50,000 samples per second or greater). The failure of a solder joint is defined as the first such event followed by three additional such events during five subsequent drops. Solder joint failure specified in IPC/JEDEC-9702 is 20% resistance increase. The failure criteria defined in these specifications are summarized in Table 1. Similar reviews have been made by Qi, et al. [15].

In a sense, all of these criteria are subjective, because, at this time, the relationship between the crack area of an interconnection and the change in resistance of the interconnection has not been established. Henshall et al. [16] compared three different electrical failure criteria, 20% resistance rise, 500 Ω threshold, and hard open (infinite resistance) and concluded that use of the IPC-9701A standard failure criterion of 20% resistance rise provides the most sensitive measure of failure among those studied.

There are two types of errors that can occur in defining failure using an increase in resistance or resistance threshold. A type I error is false detection, meaning an increase in resistance exceeds a threshold defined in a failure criterion but the truth is there is no crack in the solder joint. This may be due to minor electrical noise in the test setup, cables, and environments, which happens often when an event detector is used as acknowledged in IPC-9701. A type II error is false pass, made when a crack occurs in the solder joint but the change in resistance does not reach the threshold defined in the failure criteria. IPC-SM-785 states that a solder joint with a full crack may not exhibit an electrical discontinuity or even a significant increase in resistance because “a failed solder joint is normally surrounded by solder joints that have not yet failed and therefore the solder joint fracture surfaces make compressively loaded contact.”

In this paper, failure criteria for a solder joint is proposed to be defined as the resistance increase exceeding a threshold. The threshold is determined by *k* times the natural variation in resistance change measured by a measurement system. The natural variation by random cause is judged using X-bar and R charts. The principles of defining failure criteria are to be able to detect failure of solder joints as early as possible with minimum false detection due to measurement system error/variation.

Table 1. Comparisons of Solder Joint Failure Criteria

<table>
<tr><th rowspan="2">Standard</th><th rowspan="2">Test</th><th colspan="2">Failure definition</th></tr>
<tr><th>Event detector</th><th>Data logger</th></tr>
<tr><td>IPC-SM-785 (1992)</td><td>Temperature cycling</td><td colspan="2">The 1st event of resistance exceeding 1000 Ω for lasting >1 μs, followed by >9 events within 10% of the number of cycles to initial failure</td></tr>
<tr><td>IPC-9701 (2002) & IPC-9701A (2006)</td><td>Temperature cycling</td><td>The 1st event of resistance exceeding 1000 Ω for lasting >1 μs, followed by >9 events within 10% of the cycles to initial failure</td><td>20% resistance increase in 5 consecutive readings</td></tr>
<tr><td>JESD22-B111 (2003)</td><td>Drop test</td><td>The 1st event of resistance > 1000 Ω for a period of >1μs, followed by 3 additional such events during 5 subsequent drops.</td><td>1st detection of resistance value of 100 Ω if initial resistance is <85 Ω, or 20% increase in resistance if initial resistance is >85 Ω, followed by 3 additional such events during 5 subsequent drops.</td></tr>
<tr><td>IPC/JEDEC-9702 (2004)</td><td>Bend test</td><td colspan="2">20% resistance increase. A lower or higher threshold may be more appropriate, depending upon test equipment capability and specific daisy-chain design scheme.</td></tr>
</table>

2. Methodology

In our view, if the resistance increase in a solder joint is significantly larger than natural variation by random causes, it indicates unusual things (mostly cracks) occurring in the solder joint. We need to establish the natural variation level of the resistance in a solder joint. In this paper, we propose to use X-bar and R charts as shown in Figure 1, similar to the method used in statistical process control [17, 18]. The resistance of solder joints or daisy-chains is measured *n* times. It is recommended that these measurements are done in the way to catch all possible variation or noise caused by the test setup, cables, the measurement system, and environments. Then the mean and the range of these *n* measurements for each solder joint or each component daisy-chain is plotted. If an analysis of the data shows no unusual large variations and/or no large resistance value, then all solder joints are good and the natural variation level of the resistance can be established. If an analysis of the data shows unusual large variations and/or large resistance values, these solder joints/daisy-chains need to be examined. We define *k* times the normal range as the failure criteria. During the reliability testing, if an increase in resistance of a solder joint is larger than *k* times the range, we say the solder joint fails.

It should be pointed out that the failure criterion developed from this study was for drop and random vibration reliability testing using a data logger. All measurements were done after each reliability test and at room temperature. The purpose of conducting post-measurement instead of using a high-speed data acquisition system or an event detector was to avoid the effect of cable weight during the drop and vibration testing.

An example is given below to demonstrate how the method works. In the test board described in our paper [19], there are 39 components in three different package platforms. The resistance of each daisy-chain was measured by an Agilent 34970A data logger with three 34901A 20-channel multiplexers and one 82357B USB/GPIB interface. The measurement unit has a specified accuracy of ± (0.0030% of reading + 0.0035% of range) in 24 hours, ± (0.008% of reading + 0.004% of range) in 90 days, and ± (0.010% of reading + 0.004% of range) in 1 year.

First, we did a gauge repeatability & reproducibility (GR&R) study for the Agilent measurement system. Gauge repeatability is defined as the measurement variation caused by a measurement system measuring the same dimension many times using the same measurement methodology. Gauge reproducibility is the measurement variation obtained by different operators measuring the same dimension. For a fully-automated measurement system requiring no operators, gauge reproducibility might be ignored though sometimes it may be used to characterize variation associated with different parts of the machine or different machines. It is interesting to note that none of the five IPC or JEDEC standards mentioned above required a measurement capability study.

We measured all daisy-chain resistances for 39 components on all 41 boards 8 times. These 8 measurements were done at different times and on different dates, all at room temperature since the drop testing and vibration testing were done at room temperature. The standard deviation of the gauge repeatability was calculated to be 0.004 Ω. The initial daisy chain resistances in this study are between 0.75 and 2.83 Ω at room temperature. Analysis shows that the variance component of the gauge repeatability is only 0.5% of total variation. Thus, the measurement system is capable of distinguishing the resistance difference among these components.

Then we plotted the mean and the range of resistance of solder joints in each component on each board. Figure 1 shows the mean and the range of resistances on board F01. It is clear that the range of 8 measurements for component 28 is over 1.0 Ω which seems high though the mean of the resistance looks normal. We found out that the resistance of this component on other boards had similar large variations as well. This may indicate that there are cracks in the solder joints for this component.

Figure 2 shows the mean and the range of resistance of solder joints on board T01. It is clear that two groups of components (components 10 ~ 15, and components 25 ~ 30) have unusual high resistance. SEM images of these two groups show all of them have cracks in solder joints of these components as documented in reference [19]. After excluding these data, the revised mean and range charts are shown in Figure 3. From examination of the mean and range of all solder joints on 5 randomly selected boards, we concluded that maximum natural variation of good solder joints with the Agilent measurement system is below 0.2 Ω. We propose to use 10 times the maximum variation, or 2 Ω as the failure criteria. Our principles for selecting the failure criteria are 1) to detect solder joint failure as early as possible, and 2) minimum fault detection due to measurement error/variation.

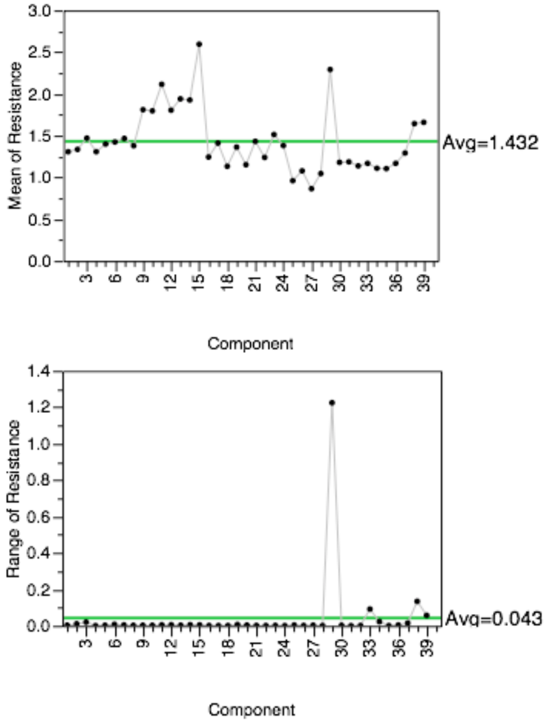

Figure 1. Mean and Range charts for resistances of 39 components in Board F01 measured 8 times.

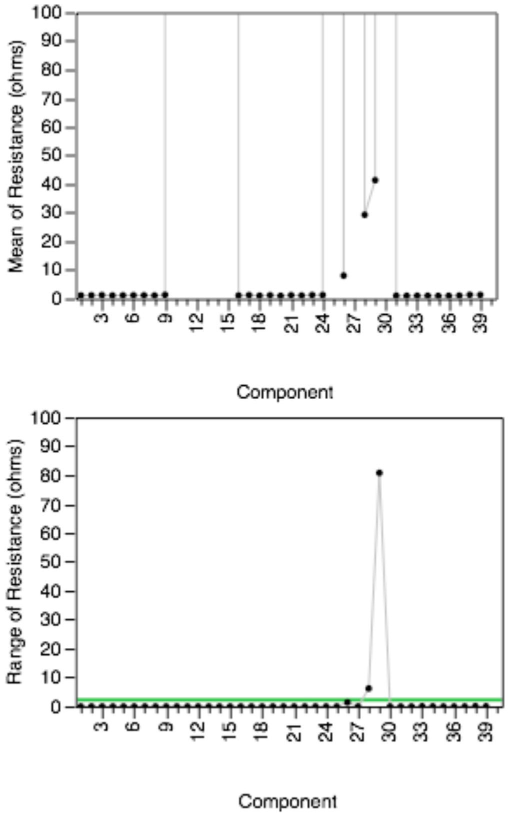

Figure 2. Mean and Range of Resistance for 39 solder joints on Board T01 measured 8 times.

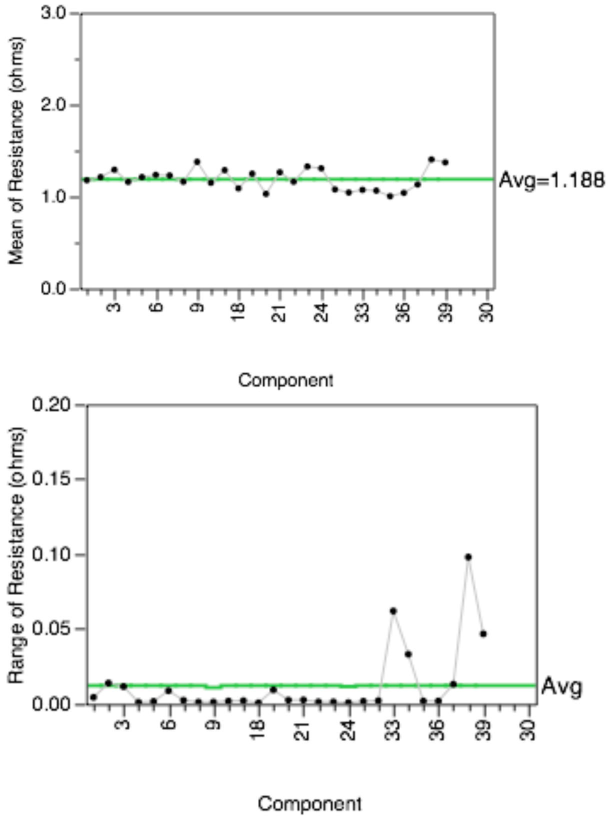

Figure 3. Revised Mean and Range charts of Resistance for 39 daisy-chained solder joints on Board T01 measured 8 times after data of components 10~15 and 25~30 are removed.

3. Relationship between the resistance change and the crack in solder joints

To confirm whether there are cracks in solder joints when more than 2 Ω increase in resistance occurred, cross-sectioning and SEM is used. Figure 4 shows the resistance value of component AT30 on Board F08 after each reliability test. V0D0 in the x-axis represents no random vibration and no mechanical drop, V1D10 represents 1 cycle (or 50 minutes) of random vibration and 10 drops, and so forth. The critical value line represents 2 Ω above the initial resistance. As shown in Figure 4, the resistance value of the solder joint daisy-chain was about 35 Ω, after 10 cycles of random vibration tests and 100 drop tests, which exceeded the critical value. A SEM image of one of the solder joints in this component shown in Figure 5 clearly indicates that a full crack occurred. Note that a set level such as the JESD22-B111's 100 Ω would have not detected failure as early.

Figures 6 and 8 show that the resistance increase was slightly over 2 Ω during the reliability testing and below 2 Ω at the end of the reliability testing.

Figures 7 and 9 show that a full crack occurred on at least one of the solder joints at the end of the reliability testing. Thus, our definition of failure criterion of 2 Ω increase in resistance proved to be able to detect solder joint failure, or a full crack. More examples on the relationship between the resistance change and the crack in solder joints are shown in Figures 10 to 18.

The next question is whether the failure criteria of 2 Ω increase in resistance can detect partial cracks in solder joints. Figure 19 shows the resistance value after each reliability test for Component AT30 on Board F07. It indicates that no resistance values exceed the critical value. However, a SEM image of one of the solder joints in the daisy-chain shown in Figure 20 indicates that partial cracks occurred in the solder joint. Thus, partial cracks cannot be detected using the method described in this paper. We believe that none of the failure criteria defined in five industry guidelines summarized in Table 1 are able to detect partial cracks in solder joints because they all rely on an electrical discontinuity while there is electrical continuity in partially cracked solder joints. Time-domain reflectometry (TDR) or a new approach based on acoustic emission [20] may be the solutions to detect partial cracks. Note that the method using acoustic emission was developed for early detection of pad cratering [20]. It is unclear yet whether the method could be used for detecting partial cracks in solder joints.

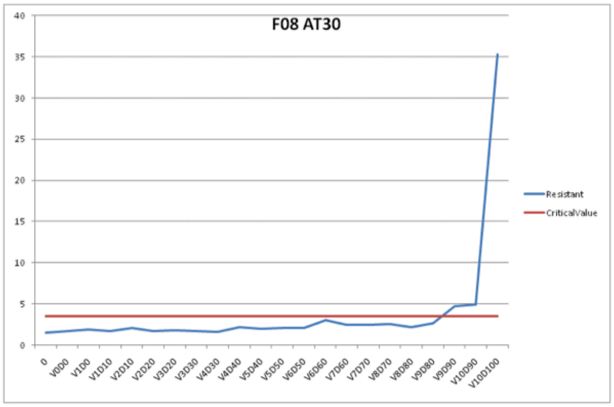

Figure 4. Resistance value of each reliability test for Component AT 30 on Board F08

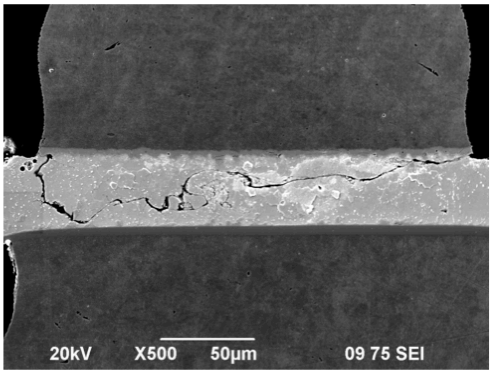

Figure 5. SEM image of one of the solder joints in the daisy-chain of Component AT30 on Board F08

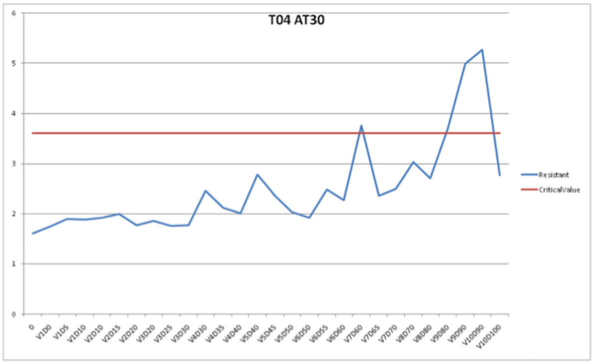

Figure 6. Resistance value of each reliability test for Component AT 30 on Board T04

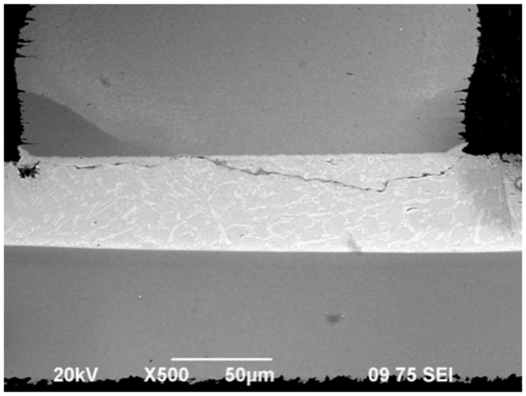

Figure 7. SEM image of solder joint Pin32 in the daisy-chain of Component AT30 on Board T04

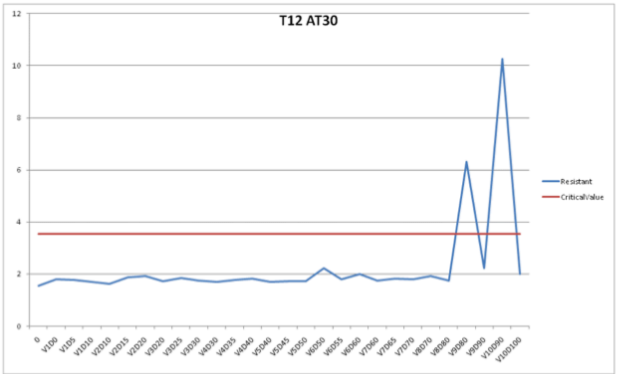

Figure 8. Resistance value of each reliability test for Component AT 30 on Board T12

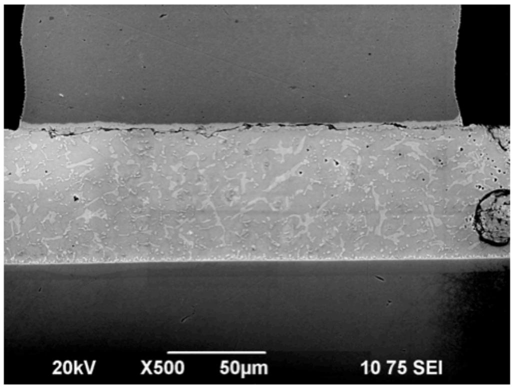

Figure 9. SEM image of solder joint Pin1 in the daisy-chain of Component AT30 on Board T12 AT30

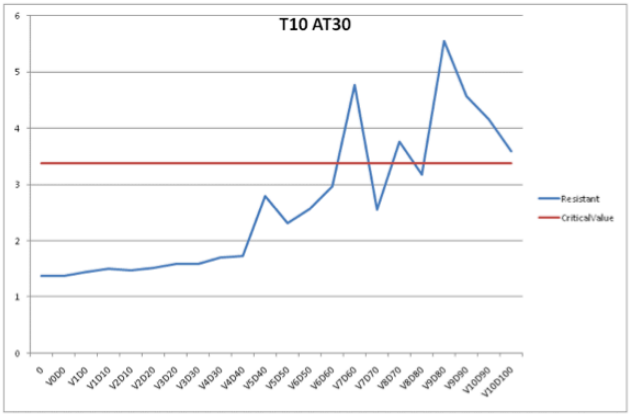

Figure 10. Resistance value of each reliability test for Component AT 30 on Board T10

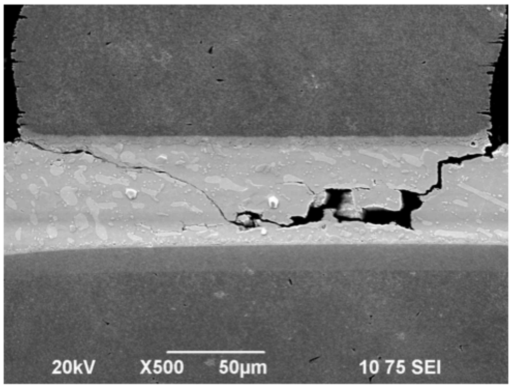

Figure 11. SEM image of solder joint Pin32 in Component AT30 on Board T10

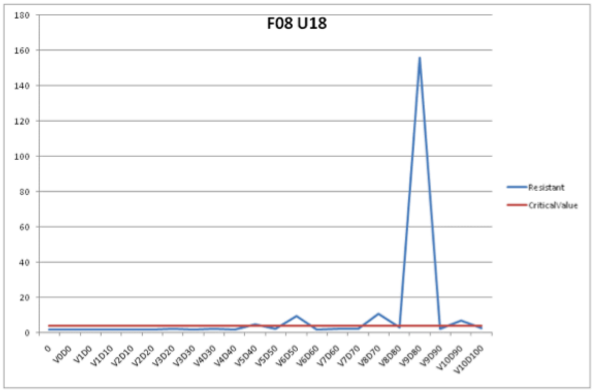

Figure 12. Resistance value of each reliability test for Component U18 on Board F08

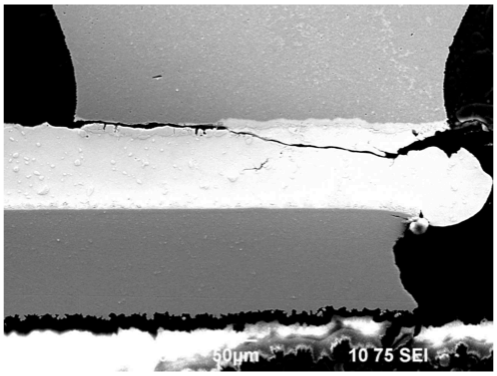

Figure 13. SEM image of solder joint Pin30 in Component U18 on Board F08

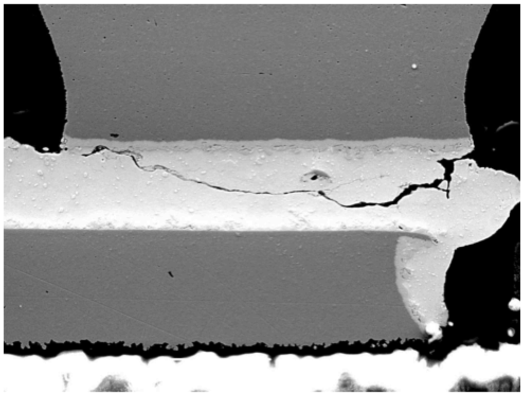

Figure 14. SEM image of solder joint Pin29 in Component U18 on Board F08

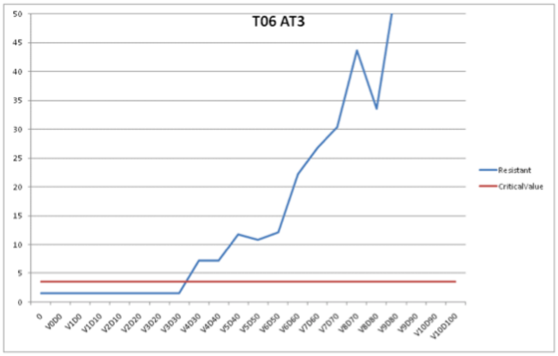

Figure 15. Resistance value of each reliability test for Component AT3 on Board T06

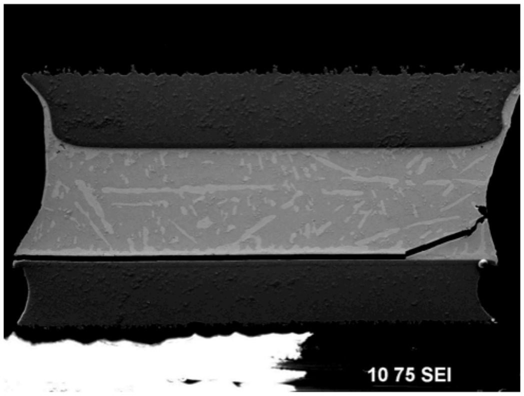

Figure 16. SEM image of solder joint Pin2 in Component AT3 on Board T06 (full cracks were founded in 7 solder joints in this component)

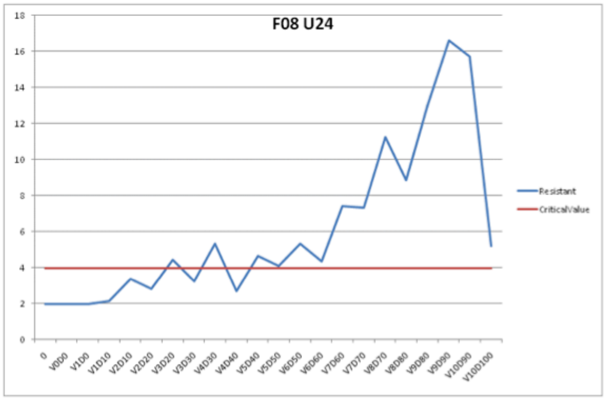

Figure 17. Resistance value of each reliability test for Component U24 on Board F08

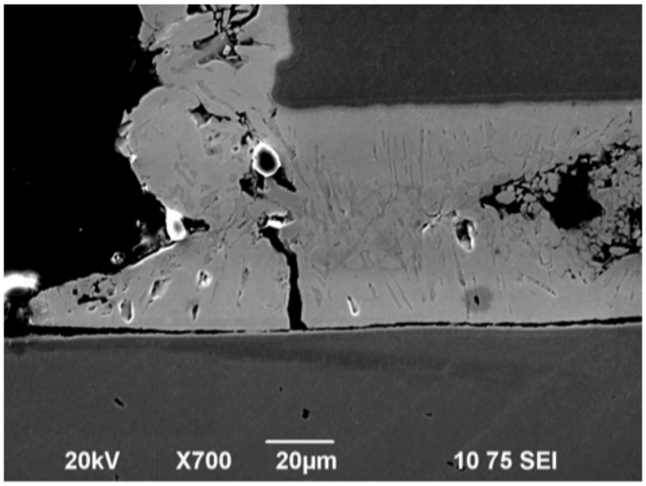

Figure 18. SEM image of solder joint Pin1 in Component U24 on Board F08, IMC Cracks

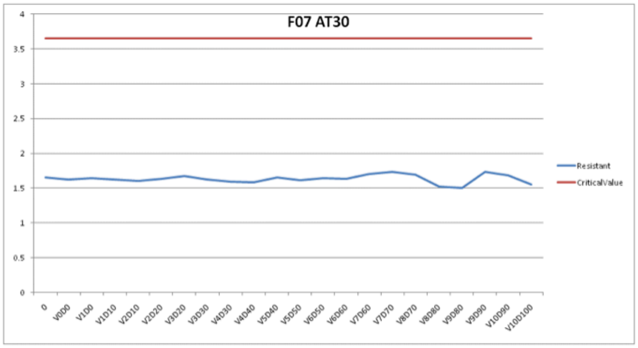

Figure 19. Resistance value of each reliability test for Component AT30 on Board F07

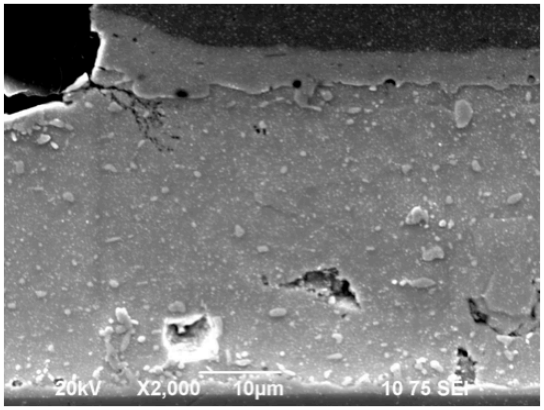

Figure 20. SEM image of one of the solder joints in Component AT30 on Board F07

4. Conclusions and Discussions

A study of solder joint failure criteria was conducted. After reviewing various failure criteria definitions, a new method for defining solder joint failure is proposed. This method is based on X-bar and R charts, similar to the charts used in statistical process control, to calculate the range of the natural variation. First, a GR&R study or a measurement capability study is needed to make sure that the measurement system used is capable of distinguishing the resistance difference among components. Then, the range over which the natural variation of resistance in a solder joint as determined by a measurement system in a real reliability testing setup is established. The natural variation can be caused by the measurement instrument, test setup, cables, and temperature. If an unusual large resistance value and/or range occur, an analysis should be done to investigate the cause of the large variation or large resistance value. The failure criterion is then established as the resistance increase in a solder joint exceeding a threshold, which is determined by *k* times the natural variation. We recommend using 10 times the natural variation as a failure criterion to minimize the false detection error.

An experimental study confirmed that a full crack of an interconnection occurs when the increase of resistance in the interconnection by 10 times the range of natural variation in resistance. This relationship proves that the new method for defining failure criteria is valid.

We argue that the criterion of 20% increase in resistance may lead to large Type I error or false detection error if the initial resistance value is small, say less than 1 Ω. Our method does not depend on the initial resistance value of solder joints. Our method is based on natural variation in resistance caused by the measurement system, the test setup, and other variables.

The methods using 100 Ω or 1000 Ω resistance threshold, 20% resistance increase, or our method are unable to detect partial cracks in solder joints because a solder joint with partial cracks does not exhibit an electrical discontinuity.

The methodology developed from this study might be useful to narrow the failure definition in IPC 9701A, JESD22-B111, and IPC/JEDEC-9702. In a temperature cycling test, it is advised to measure variations in resistance change during the hot dwell temperature and cold dwell temperature. It is also recommended to include a requirement of a GR&R study or a measurement capability study in a future revision of these standards.

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