Reliability of wire-bonded electronic devices in combined high temperature and vibrational environments

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ABSTRACT

High temperature electronic systems need to operate in extreme conditions that exceed the current levels specified by the military and aerospace standards. In high temperature and wide operating temperature applications, electronics can suffer from failure modes caused by a combination of environmental and operational loadings such as temperature, vibration, humidity, pressure, external stresses, etc. This work reports the findings and observations of the investigation of the combined effects of thermal and vibrational environments on wire-bonded interconnections used in high temperature electronic components. The work is focused on combined testing at temperatures up to 250°C and vibration loading with the sine frequency swept cycles ranging from 5Hz to 2000Hz and acceleration up to 20g rms. Analysis is focusing on the wire bond connections which has shown an increasing occurrence of wire deformation at a test temperature of 250°C whilst being subjected to vibration, particularly for wires with large loop shapes. Wire bonded samples have been evaluated through visual inspection, electrical characterization and ball shear tests to identify failure mechanisms.

Key words: wire bonding, high temperature applications, reliability, vibration testing

INTRODUCTION

1. Wire Bonding Reliability Issues in High Temperature Applications

Wire bonded electronic devices are often required to operate in extreme conditions that may affect their reliability and lifetime. The interest is mostly towards temperature induced failures. Intermetallic compound (IMC) growth and the associated voids are one of the main concerns. Au-Al systems are susceptible to fast growth of IMCs within a few hours of testing [1]. Murali et al. [2] investigated the interface morphology and metallurgical behaviour of Au and Cu ball bonds for different wire diameters and thermal ageing periods. They found that Au wires on Al metallization are more susceptible to void formation; the phenomenon was mostly observed in finer wires. Murali et al [3] also reported that on thermal aging, gold aluminide easily forms in gold ball bonds while no IMCs formation is observed in copper ball bonds. Ratchev et al [4] reported that Au ball bonds on Al surface show Kirkendall voiding after 60 days of thermal aging at 150˚C, while Cu wire bonds on Al bond pads show much slower IMC formation and no Kirkendall voiding. Mustain et al. [5] investigated the Al and Au wire bonding processes for high temperature electronics. It was suggested that the bonding pad and the wire should be of the same material due to the degradation of the bond strength caused by interdiffusion and interface corrosion between dissimilar metals at high temperatures. Indeed, the work conducted by Shepherd et al [6] reports that Au-Au wire bonds are a better solution due to their mechanical robustness and microstructural stability.

In addition to stresses caused by thermal exposure, electronic systems often experience vibration environments as well. In order to assure the long term reliability of components, the effects of the aforementioned vibration in combination with high temperature exposure conditions need to be investigated. However, separate environmental tests are commonly used in qualification testing by the electronics industry and are not able to reveal the effects of the combined conditions on the failure modes and reliability. Therefore, the development of guidelines and testing standards is necessary to qualify electronic components that need to operate in combined high temperature and vibration conditions.

2. Preliminary Work

Previous work by the authors on the combined effects of thermal and vibration loadings on wire-bonded devices has shown that when such environmental factors are combined, there is an increased susceptibility of the interconnections to failure compared to single environmental tests [7]. The electrical and mechanical performance of wire bonded devices was evaluated under various combinations of temperature, fixed frequency and acceleration levels to determine the effect of each parameter on the system. The effect of different wire loop geometries on the mechanical deformation of the wires was also investigated. The work focused on Au ball/wedge bonding on substrates with Au thick film metallized pads and alumina ceramic bases.

Shear load to failure measurements revealed a considerable decrease of the shear strength of the ball bonds after only few hours of testing. Table I shows the shear force mean values and standard deviations of the devices tested under different combinations of testing conditions at each of the equipment's three orthogonal axes. As seen in the table, the lowest shear force values observed at the low frequency domain where the highest displacements are applied. Weakening of the ball bond/thick film metallization interface at that frequency level (500Hz) and, especially at the higher temperature level (250˚C), led to several wire lift-offs on testing.

A general decrease in the electrical resistance for both the wire loop geometries has been observed. The resistance decrease in the wires after testing could be attributed to annealing of the wire at temperature, rather than any specific failure mechanism caused by the vibration/temperature conditions. As seen in Table II, the highest decrease in resistance was observed at the high temperature level for both wire loop geometries.

Mechanical deformation occurred on the wires following particular patterns based on the orientation of the wires on the vibration system. Wires that were vertically oriented towards the axis of the vibration collapsed following one direction (see Fig. 1a), while a number of wires that were parallel to the axis of the vibration appeared sharply curved at the highest point of the wire loop – phenomenon that mostly observed on the large loop wires (see Fig 1b). Finally, wires in close proximity caused short circuits in several cases (see Fig. 1c).

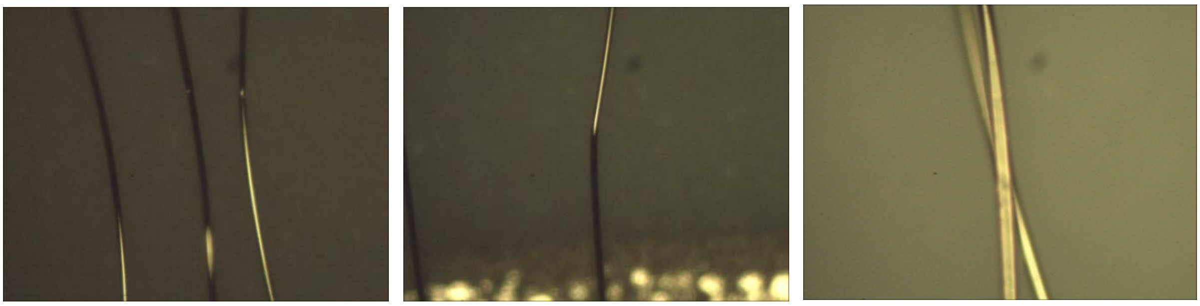
The next step in the investigation of the performance of wire bonded devices under combined conditions of thermal and vibration loadings is presented in this paper. The work is an attempt to cover the different aspects of the vibration conditions combined with thermal loadings that electronic devices are subjected to. In the work described above, the electronic components were subjected under fixed loading conditions at specific levels. In this work described below, the behaviour of wire bonded devices in sine swept frequency vibration environments combined with thermal loading is investigated.

Table I
Shear load mean values and standard deviation for bonds after the combined testing

		Testing Conditions							
Wire Orientation on the Vibration System	**Ball Bond Shear Failure Load, g(f)**	**120°C, 500Hz, 10grms**	**250°C, 500Hz, 10grms**	**120°C, 2000Hz, 10grms**	**250°C, 2000Hz, 10grms**	**120°C, 500Hz, 20grms**	**250°C, 500Hz, 20grms**	**120°C, 2000Hz, 20grms**	**250°C, 2000Hz, 20grms**
Y	Mean	48.73	***32.03***	49.61	42.50	49.25	***37.28***	50.46	50.85
	SD	8.63	3.00	10.92	9.87	12.50	15.82	8.32	16.78
X	Mean	50.26	***30.13***	56.92	44.29	47.07	***28.72***	51.06	44.48
	SD	8.08	3.07	2.54	13.74	12.45	6.13	8.78	15.78
Z	Mean	43.61	41.92	54.55	40.49	58.16	***32.97***	53.39	44.53
	SD	11.35	9.36	4.66	10.80	2.34	9.38	4.06	14.36
All bonds	Mean	47.38	***34.98***	53.73	42.35	51.76	***32.99***	51.70	46.54
	SD	9.62	7.96	7.30	11.17	10.84	11.20	7.06	15.25

Table II
Percentage of resistance change for wires after the combined testing

	Testing Conditions							
% Average Resistance Change	120°C, 500Hz, 10grms	250°C, 500Hz, 10grms	120°C, 2000Hz, 10grms	250°C, 2000Hz, 10grms	120°C, 500Hz, 20grms	250°C, 500Hz, 20grms	120°C, 2000Hz, 20grms	250°C, 2000Hz, 20grms
Small Loop	-4.1%	-11.7%	-3.4%	-5.8%	-2.9%	-13.7%	-4.9%	-7.3%
Large Loop	-6.7%	-14.3%	-7.1%	-11.5%	-4.2%	-14.3%	-7%	-12.4%

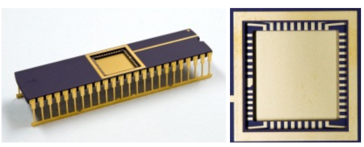


a) b) c)
Fig. 1. Deformation of wires oriented a) vertically and, b) parallel to the axis of vibration and, c) overlapping wires

EXPERIMENTAL

1. Wire bonding

Au ball/wedge wire bonding was performed on 48-pin Dual-in-Line (DIL) High Temperature Co-fired Ceramic (HTCC) packages (Fig. 2a). Au wires of 25 μm diameter were bonded on the Au bond pad metallization (Fig. 2b). The packages were thermosonically bonded using a semi-automatic Kulicke & Soffa wire bonder. Two different bonding profiles applied; one where the wire is forming a small loop and one larger. The maximum height for the large loop is h_1= 1.2mm and for the small loop h_2= 1.05mm. The distance between the ball and the wedge bonds for the large loop wires is L_1≈2.35mm and for the small loop wires is L_2≈1.94mm. The wire bonding structure can be seen in Fig. 3. Optimised bonding parameters applied for the two bonding profiles.



a) b)
Fig. 2. Au/Ni 48-pin DIL HTCC test package, a) side view and, b) bonding area

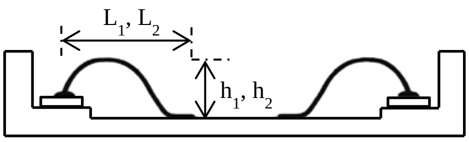


Fig. 3. Schematic representation of the wire bonding structure

2. High Temperature/Vibration Testing

Based on testing guidelines specified in the RTCA Aviation Standard DO-160E [8] for qualification of electronics, the packages have been subjected to sinusoidal frequency vibration at room temperature, 180˚C and, 250˚C. The tests were performed in each of the equipment's three orthogonal axes for one hour per axis. Sine frequency sweep cycles were performed varying the vibration frequency from the lowest (5 Hz) to the highest (2000 Hz) (up-sweep) to the lowest (down-sweep) with a logarithmic rate not exceeding 1.0 oct/min. The acceleration was varying from 1 g-PK to 20 g-PK with the amplitude between 0.0001 to 0.1 inches (peak-to-peak).
The LDS V650 electrodynamic shaker has been employed for the vibration testing. A hot plate was fixed on the shaker head for the temperature application; the hot plate served as a sample fixture as well. Thermocouples, attached on the hot plate and sample, were controlling the temperature. The RLV-5500 laser vibrometer was used to measure

the vibration response on the test packages. Accelerometers were fixed on the shaker head to measure the input signal. Shear testing was performed on the ball bonds to measure their strength before and after the high temperature/vibration testing. The electrical performance of the packages was evaluated using a specially designed 4-point resistance probe system. An optical microscope has been employed to observe any possible wire deformation.

RESULTS & DISCUSSION

1. *Electrical Performance*

The resistance on the packages was measured between two adjacent pins; this includes the resistances of two wires and the associated tracking. An X-ray image that shows the tracks inside the package can be found in Fig. 4. The two tracks of each pair are of equal length. From pairs 1 to 10 the total length of the pair of tracks gradually decreases and starts to increase again after pair 11. The first 10 pairs include the wires that form small loop and the last 10 pairs include the large loop wires. This explains the “V” shape of the graph for the resistance levels in Fig. 5.

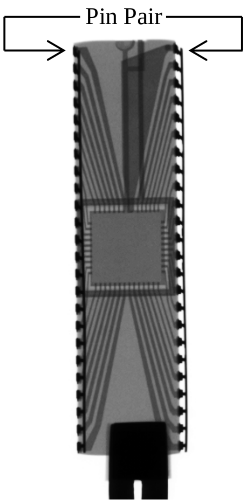
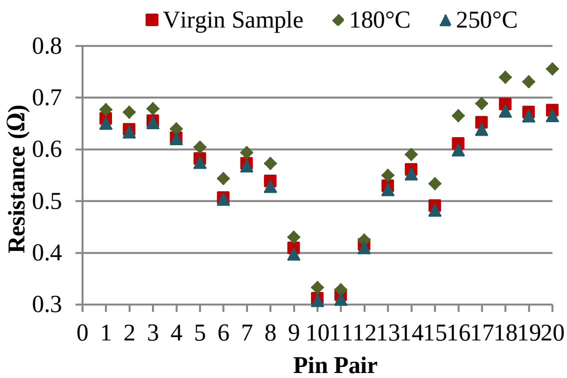


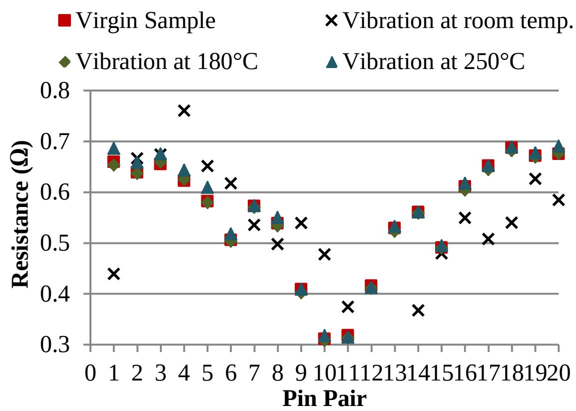
Fig. 4. X-ray image of 48-pin DIL-HTCC package. The tracks inside the package provide connection between the pins and the bond pad

Vibration related effects on the electrical performance have been identified. In general, the changes in the resistance from the thermal aging at 180˚C and 250˚ and the vibration testing at those levels follow the same patterns but the change rates are different. A lower increase rate in the electrical resistance was observed from the thermal aging at 180˚C combined with vibration compared to the thermal aging at 180˚C. Also, a lower decrease rate in the resistance after the vibration testing at 250˚C compared to the decrease after only thermal aging at 250˚C was observed. The change in the resistance for the thermal storage tests can be found in Fig. 5a. A slight average increase of 5.7% in the resistance has been observed after only 3 hours of temperature storage at 180˚C. The largest increase occurred on the pin pair that included the large loop wires. On the contrary, temperature storage for 3 hours at 250°C caused the resistance of the tracks to decrease by an average of 1.5%. After the vibration testing at 180°C a small increase of 0.6% has been observed and a decrease of 1.5% in the resistance after the vibration testing at 250°C. After the vibration testing at room temperature the resistance change follows two different patterns related to the wire length and loop size (see Fig. 5b). For the low loop wire pairs the resistance increased by 10.1% while for the large loop wire pairs a decrease of 17.5% has been observed.

The findings from the vibration testing at room temperature are being examined again and further tests are being performed to verify the results. Also, in order to evaluate the contribution of the tracks on the resistance changes, non-bonded packages are being tested and the change in resistance of the tracks is being measured.



a)



b)

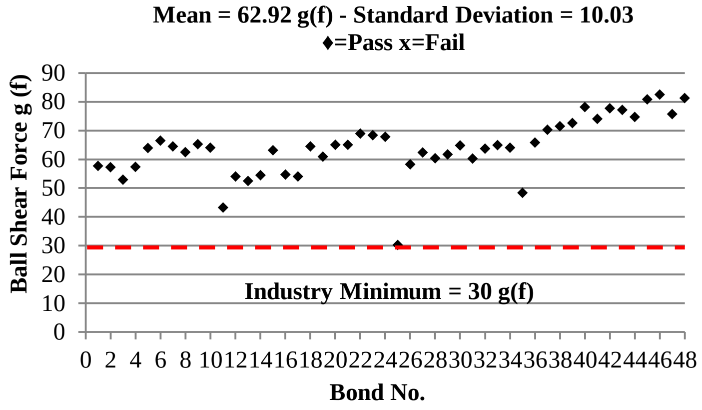
Fig. 5. Resistance levels of pin pairs after a) temperature storage and, b) combined high temperature/vibration testing

2. *Evaluation of Wire Bond Quality*

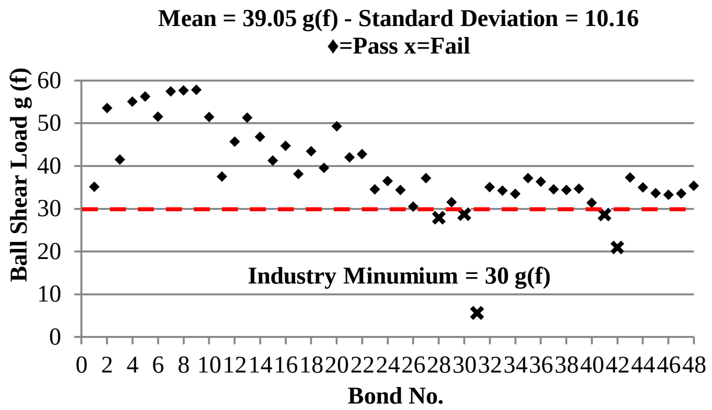
Figure 6 shows the mechanical test results for the wires tested under the three different conditions – vibration test at a) room temperature, b) 180°C and c) 250°C. The strength of the wire bonds has been evaluated by means of bond shear tests. The plots include the mean values and the standard deviation of the wires tested.

Figures 6a, 6b, and, 6c are the ball shear test results for the three conditions. A clear trend can be identified with respect to the level of temperature applied along with the vibration load. After the vibration test at room temperature all the ball shear test results exceeded the industry minimum of 30 g(f) while at 180°C and 250°C, 10.4% and 43.8% failed this level, respectively. The high shear load values after the vibration test at room temperature could be attributed to the strong adhesion between the bond and the bond pad. At higher temperatures the average shear loads to failure are lower compared to those at room temperature.

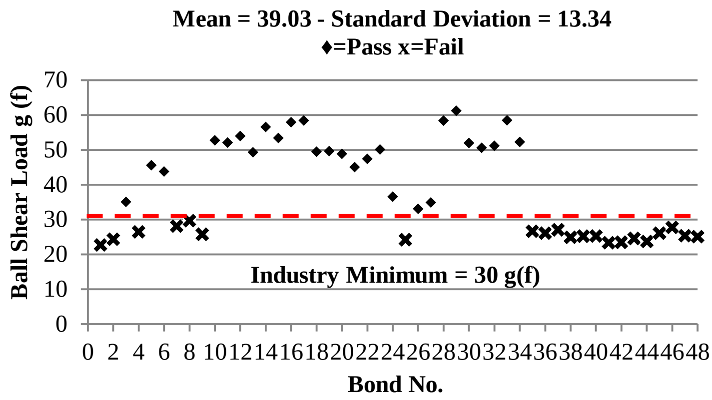
The work is being extended by investigating the wire pull strength and the results will be presented in the near future.



a)



b)



c)

Fig. 6. Shear force values of bonds subjected to vibration test at a) room temperature, b) 180°C and, c) 250°C

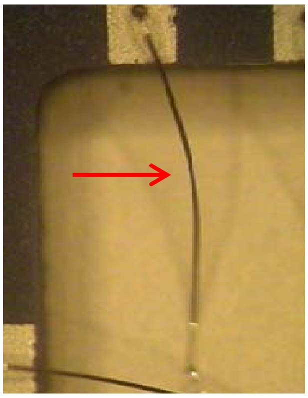
3. Mechanical Deformation

As reported previously [7], [9], [10], the orientation of the wires in respect to the axis of the vibration, results in different failure modes. Applying sine frequency vibration as a single loading condition caused deformation of the wires in particular patterns. Two failure modes have been identified after the sine swept vibration test:

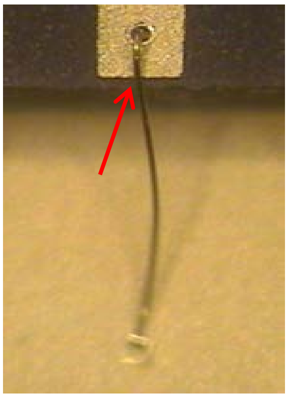
1. The wire collapsed sideways and the loop height reduced. Wires vertically oriented towards the axis of the vibration deformed following one direction (Fig. 7a). Testing on the other two axes had the same effect on some of the wires but no particular pattern of deformation was observed.
2. The wire loop collapsed downwards (towards the Au pad). As a result, several wires touched the edge of the Au bond pad and caused short circuits (Fig. 7b). The phenomenon mostly observed at the large loop wires.

A different failure mode observed after the vibration testing at 180°C. One of the wires collapsed sideways and the loop appeared sharply curved at its highest point (see Fig. 8). Again, the phenomenon occurred on a wire that was vertically oriented to the axis of the vibration.

Fig. 9 shows the deformation of the wires after vibration testing at 250°C. For the large loop wires, parallel to the axis of the vibration, no particular deformation patterns have been observed. The wire deformation was random and the loop collapsed sideways either left or right from the initial wire position (see Fig. 9a). Deformation following one particular direction occurred for the wires that were vertically oriented to the axis of the vibration. An example can be seen in Fig. 9b. Also in this case, wire kinks occurred near the wedge bond as well, as indicated in Fig. 9c.



a)



b)

Fig. 7. Wire deformation, loop collapsed a) sideways following one direction and, loop collapsed downwards where b) the wire touched the Au bonding area and c) the wire was sharply curved after testing

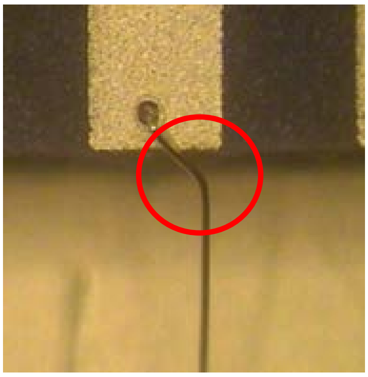
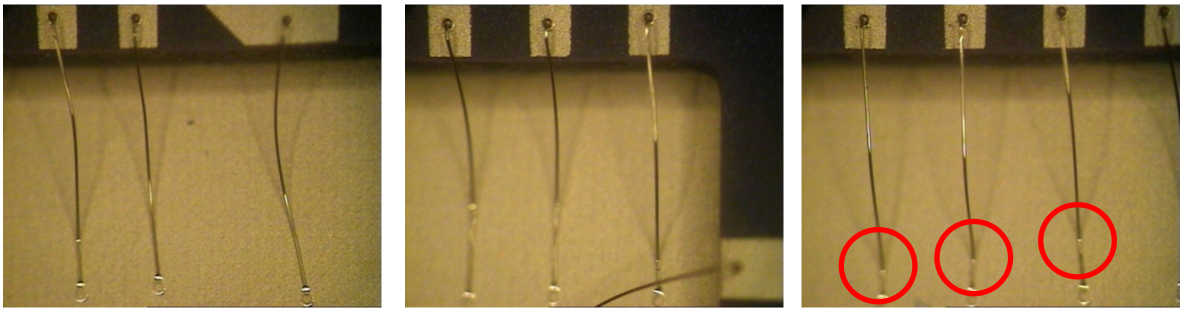


Fig. 8. Sharply curved and deformed wire after combined testing



a) b) c)

Fig. 9. Wire deformation from testing a) on vibration axis, b) on axis vertical to direction of vibration and, c) sharply curved wires close to wedge bond

CONCLUSIONS

The combined effects of temperature and vibration on wire bonded electronic packages have been investigated. Sine frequency sweep cycles were performed with the vibration frequency varying from 5Hz to 2000Hz, along with thermal loading at three different levels (25˚C, 180˚C, 250˚C). The results can be summarised as follows:

1. A reduction in ball shear load to failure has been observed after vibration at 180˚C and 250˚C. 43.8% of the bonds failed to exceed the industry's minimum of 30 g(f) after the vibration test at 250˚C compared to 0% at room temperature.
2. Vibration and temperature related effects on the electrical resistance of tracks and wire at high temperatures have been observed. The resistance of the tracks and wires increased after the vibration test at 180˚C and, decreased after the vibration test at 250˚C. Further investigation is being conducted to understand and verify the results.
3. Different wire deformation patterns have been identified in each combination of loading conditions and orientations on the vibration system. Vibration testing as a single loading condition caused the wires to collapse and touch part of the bonding pad causing short circuiting. Also, the wires oriented vertically to axis of the vibration deformed following one direction. Vibration testing at either 180˚C or 250˚C caused mechanical softening and consequently severe deformation of the wires especially for the large loop ones.

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