Thermal Performance of Micro-springs in Electronic Systems

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July 31, 2009

Reviewed by NASA-USRP Mentor

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ES43

Nomenclature

A = cross-sectional area of conduction path
T = temperature
K = thermal conductivity
R = thermal resistance
l = length of conduction path

Abstract

Electronic components must be protected from physical damage caused by vibration and shear and from thermal extremes which may affect the functionality of the device. Currently, tin-lead solder balls are being used, however, beryllium copper micro-springs are showing potential to be more effective at preventing thermal and shear damage. Using the three dimensional modeling program Pro-Engineer and the thermal simulation programs IcePro and IcePak, a model of the solder ball and micro-spring was created and simulations were performed in vacuum conditions to characterize the thermal performance of micro-springs and compare them to the thermal performance of solder balls. From this data, a contact resistance interface to represent all interconnections was created to evaluate the performance of the element on a system level. By comparing the results of the micro-spring simulations with those of the solder ball, the micro-springs are less effective at transferring heat away from the component in vacuum conditions due to a longer conduction path. This was verified by hand calculations for the conduction through each element and will be further tested with a physical test. In an air flow situation, this may not be true since the open coils will allow for more heat to be carried away by convection.

I. Introduction

Transporting electronic components into space without causing damage to them poses a unique challenge. Integrated circuit chips and other electronic components must be attached to printed circuit boards in a way that will allow them to withstand flight conditions. In order to accomplish this, a chip is attached to the board with interconnections that serve not only to secure the component to the board, but to also allow charges to flow from the chip to the board. These interconnections are only on the order of 0.02 to 0.10 inches in height. Due to their small size and high importance, they must be well designed to ensure that there is a low probability of failure.

There are two major design considerations that must be addressed when designing interconnections: mechanical integrity and thermal integrity. Mechanically, the major causes of failure are shear and vibration. Thermally, the major cause of failure is overheating. The material can only withstand a certain amount of heat before it begins to overheat or melt; either situation would cause the interconnection to not function properly and potentially cause damage to the component it is connecting to the board. This issue is complicated by placing the component in a vacuum condition; the lack of air flow eliminates the possibility for heat to be removed by convection. Both mechanical and thermal issues must be considered when evaluating an interconnection and the advantages and disadvantages must be balanced.

Currently, tin-lead solder balls are being used as interconnections, which have a fairly good ability to withstand shear and conduct heat relatively well. There is much room for improvement on this technology as the surface area and conduction path can be changed to create a more thermally efficient interconnection; similarly, it can be improved mechanically to be able to withstand a greater amount of shear and vibration damage. A micro-spring has less surface area and a longer conduction path however, it creates the possibility for convection through the open coils. This could greatly reduce the amount of heat under the chip in air flow conditions. The thermal conductivity of the micro-springs is much higher than that of the solder balls which will decrease the thermal resistivity under the chip, allowing for more heat to be transferred away. Also, the micro-springs may be able to withstand damage from shear and vibration better than solder balls; research in that area is outside the scope of this paper. The objective of this project is to compare the thermal effectiveness of micro-springs to that of solder balls in vacuum conditions, create an interface that can be used in system level analysis and verify the results in a physical test.

II. Procedure

In order to characterize the thermal properties of micro-springs, two test methods were used: computer simulations and physical testing. Computer simulations allow for the testing of multiple situations and conditions without having to spend resources conducting the physical tests. This is done by building the geometry in a three dimensional drawing program and importing it into a simulation program. A mesh is generated around the geometry to allow the solver to evaluate equations at certain points around the geometry. It is very important to ensure that the mesh is of high quality and has enough nodes, or points to be solved at, in order to achieve accurate results. Once the mesh is of acceptable quality, the solver can be run. This allows for difficult problems to be solved with relative ease. After the solver has finished, the results can be easily read from either the output file or by creating a colored parameter object face. For this project, Pro-Engineer was used to construct the geometry. It was then imported to IcePro, converted to an IcePak file and the simulations were run in IcePak and ANSYS, thermal simulation programs.

Computer simulation programs make solving for parameters on complex geometries simple; however, there are many things that can cause the simulation to yield inaccurate results. In this simulation, vacuum conditions were being simulated. This made the calculations simple enough to do by hand to compare to the computer results. The results did not match perfectly however, as the simulation was not able to account for all possible sources of heat transfer. Hand calculations did, however, provide a relatively good comparison to determine the accuracy of simulation results. Once the computer simulations have been run, it is advantageous to run a physical test to compare the theoretical data from the simulation to the experimental data that is generated from testing.

A. Simulation Process

To begin the process of performing a computer simulation, the geometry must first be built; this was done using Pro-Engineer. The open spring coils were the only part of the geometry created using this software. This was done to minimize the complexity of the geometry for the meshing process and to allow for the solder filled ends to have a different thermal conductivity than the coils. If the entire spring had been created in Pro-Engineer, every section would have the same thermal conductivity and the mesh would have been very coarse. Another simplification was made to the wire; though the spring wire is round, the cross-sectional area was evaluated and an equivalent area square was used. Once the geometry was created, it was imported to IcePro. This program converts Pro-Engineer files to IcePak files. The quality of the conversion depends on the complexity desired: it can be modeled by something as simple as a block to something as complex as the actual geometry. The more complex the geometry is, the less advanced the conversion can be. Otherwise, the resulting file may be severely distorted. For example, the round wire was significantly distorted and appeared to be square while the square wire converted well and did not lose much definition. Figure 1 shows the geometry in IcePak before and after the simulation was run.

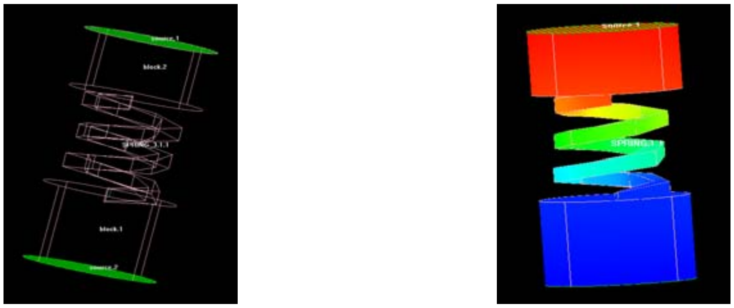

Figure 1. Thermal Simulation and Geometry of Micro-spring. *Left: The wireframe of the completed geometry before the simulation begins is shown. Right: Using IcePak, it is possible to see the temperature gradient through the micro-spring.*

From here, the geometry was ready to be imported to IcePak. The closed coils of the spring were simulated as solder filled cylinders and created in IcePak. A heat source was placed on the top of the upper solder block and set to generate 1 watt of power. A second heat source was placed on the bottom of the lower solder block and changed to represent a zero degree Celsius cold plate. The component was placed on a cold plate to instruct the simulation program to allow heat to be conducted through the component along the conduction path. Once the geometry had been created and prepared for the simulation, the air flow conditions were modified to represent a vacuum. This was done by setting the density and molecular weight to near zero values. IcePak does not have a built in vacuum condition nor can it accommodate for density and molecular weight to equal zero; therefore, air was still present in the simulation.

The same process was used for the solder ball. For this geometry, the volume of the sphere was evaluated and a height that would yield an equivalent volume was used to create a cylinder. ANSYS was also used to compare results from IcePak, as ANSYS simulates vacuum conditions more closely. IcePak yielded results that were inconsistent with calculations and the results from the physical test but ANSYS yielded results that were not very different.

B. Physical Test Process

Simulation results will yield theoretical data, but in order to verify the results, a physical test should be conducted. This is done by building a printed circuit board that has 4 chips connected with various interconnections. In this experiment, micro-springs, high lead columns, high lead solder balls and solder balls were tested. Thermocouples were attached to the top of the printed circuit board and to the underside of the chip. Tape heaters capable of producing 2.5 watts of heat were placed on top of the chips to simulate functioning, powered chips. Silver epoxy was used to adhere the heater to the top of the chip. The experimental configuration can be seen in Figure 2.

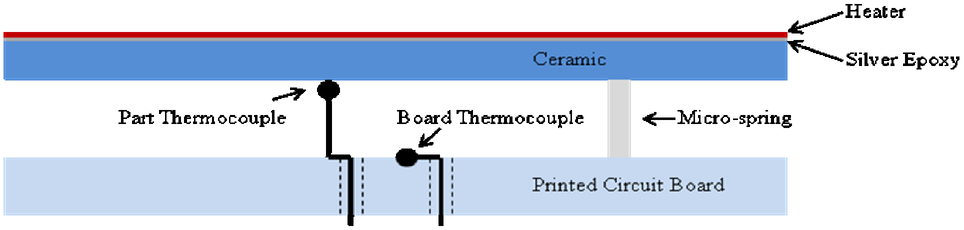

Figure 2. Experimental Set-up of Physical Test of Micro-springs. *The thermocouple was attached to the top of the printed circuit board and to the bottom of the ceramic part. One micro-spring was left out of the configuration in order to allow the thermocouple to be attached. The absence of one interconnection did not significantly affect the results.*

The data from the thermocouples was read by the data acquisition program, Omnilog. Small foam strips were used to insulate the chip from as much air flow as possible. This could only be done on three sides due to the wires from the heaters and the thermocouples on the last side. The heaters were connected to a 28 volt dc power source and the thermocouples were connected to channels on the data acquisition box. By starting the data acquisition program before turning on the power source, the entire temperature range could be recorded. Two tests were run and two sets of data were obtained for each interconnect technology.

C. Calculations

The calculations for this simulation were greatly simplified by assuming vacuum conditions. This assumption reduced the problem to a pure conduction. The only parameter desired was the thermal resistance through the interconnection.

$$R = \sum \frac{l}{kA} \tag{1}$$

Using Eq. (1), the overall thermal resistance of the object can be calculated[1]. The length in this equation is the length of the conduction path; for the solder ball, it is simply the diameter; however for the spring, it will be the length of the uncoiled wire.

III. Results and Analysis

Based on the computer simulation and physical test, the solder balls are more efficient at transferring heat than the micro-spring in a vacuum. This was expected as the conduction path of the solder ball is significantly less than that of the micro-spring. The initial results from the IcePak did not correspond with the hand calculations or the physical test results. ANSYS was used to run another simulation to compare to the results of IcePak. These results were more consistent with the data obtained in the physical test and with the results of the hand calculations.

A. Simulation Results

Analyzing each component individually showed that the relationship between the thermal resistance and the wattage of the power source is linear. The value for one watt was used to find the temperature differential per watt of heat applied. Though both components produced linear results, the values of the micro-spring results were not in a range that would be physically possible without melting the component. Therefore, the linearity of this relationship is demonstrated using the solder ball data. Figure 3 shows the results of running the simulations at each of the various power values graphed against the resulting values from using Eq. (1). Using the value at one watt, an interface was created and simulated using a contact resistance. This created problems and yielded results that were inconsistent with those of the physical test and the hand calculations. These inconsistencies could be caused by the simulation program, IcePak.

Based on the results of the simulation run in ANSYS, a value of 0.0788°C/Watt was obtained for the contact resistance of the micro-springs. For the solder balls, the interface value was calculated to be 0.0839°C/Watt, which was obtained using IcePak. These values were obtained by placing four hundred interconnections in parallel. For the micro-spring, IcePak yielded a thermal resistance of 12°C/Watt while ANSYS yielded a result of 31.5°C/Watt. The large difference can be attributed to the presence of air in the vacuum. Also, the file may have contained underlying errors that were providing such inaccurate results. This error was mostly prevalent in the micro-spring simulation; the solder ball was not affected greatly.

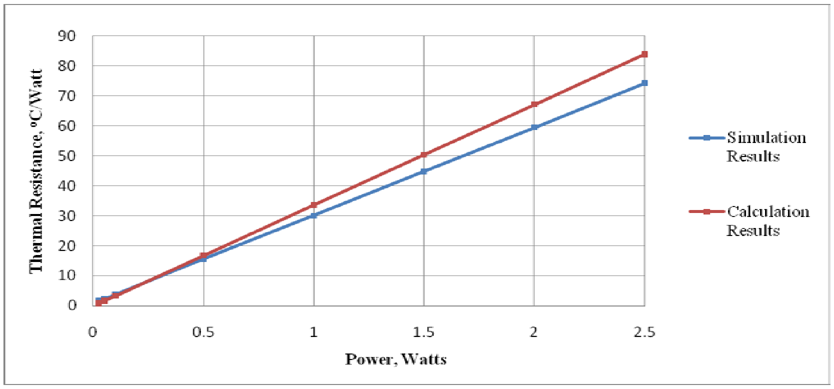

Figure 3. Variation of Thermal Resistance with Power of a Solder Ball in Vacuum Conditions. *The simulation results and calculations both yielded a linear relationship between the thermal resistance and power applied to a solder ball in vacuum conditions.*

B. Physical Test Results

Each interconnection was tested twice and the data from the thermocouples is graphed in Figure 4 and Figure 5. The flat region at the beginning of the graph in both figures was caused by the delay between starting the data acquisition program and turning on the power supply. Figure 4 shows the temperature difference increased until it reached a maximum of approximately 13°C. After this point the power supply was turned off, which is why the temperature falls slightly toward the end. The curve for the solder ball is not as smooth as the curve for the micro-spring. This could be caused by small amounts of air flowing through the experiment. Both curves have the same general shape so this could be attributed to the nature of heat flowing through the solder balls. Figure 5 shows the results from the micro-spring test. This curve has similar traits as the solder ball, however it is smoother. The maximum temperature reached is approximately 25°C.

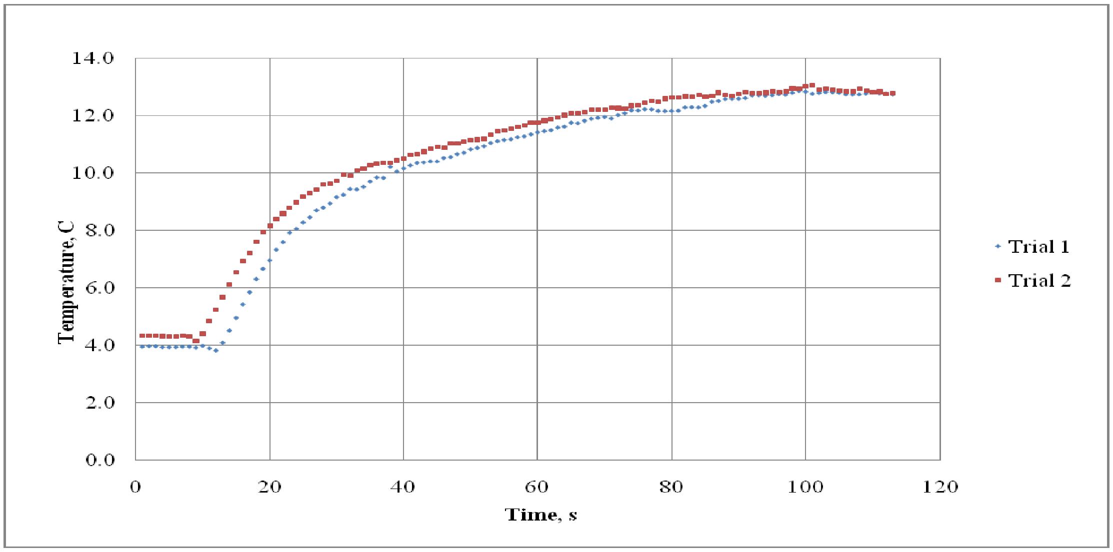

Figure 4. Results from Physical Test of the Solder Ball. *The temperature plotted is the difference between the thermocouple on the board and on the part. This is the temperature differential through the solder ball.*

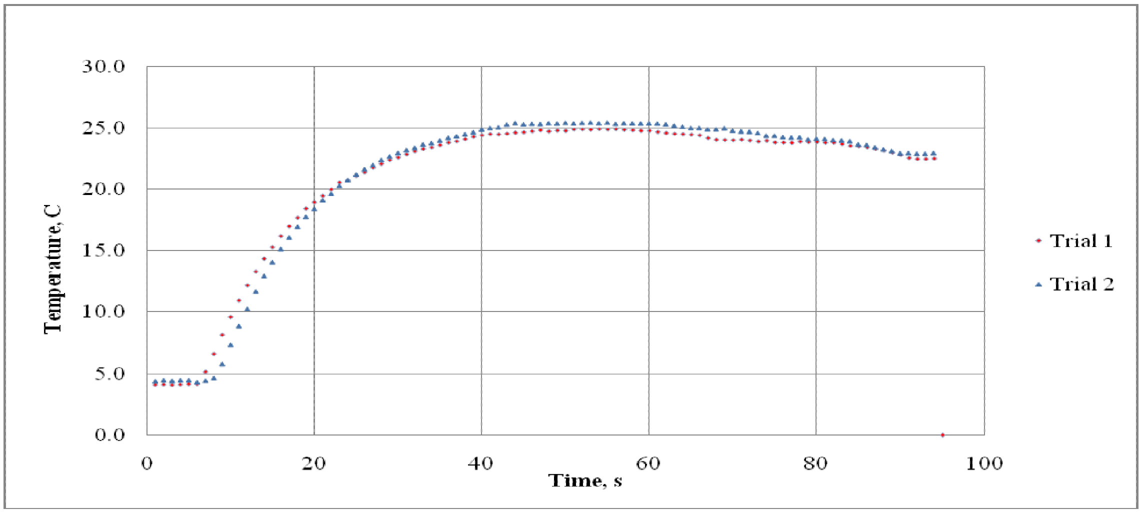

Figure 5. Results from Physical Test of the Micro-spring. *The temperature plotted is the difference between the thermocouple on the board and on the part. This is the temperature differential through the micro-spring.*

One issue that did arise in the test was bubbling in the heater. This is shown in Figure 6. The temperature in this region is lower than the surrounding area because it is not in direct contact with the chip and is experiencing air flow under it. Despite the uneven heat distribution caused by the bubble, it did not significantly alter the results of the test. It could explain the differences in Figure 3 and Figure 4; the bubble did not appear until the solder ball was being tested.

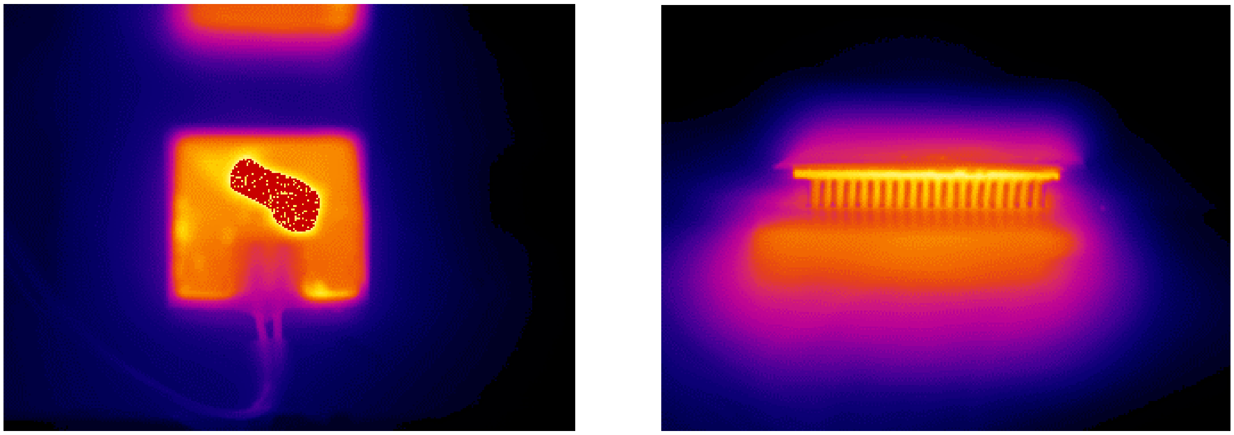

Figure 6. Thermal Pictures of an Air Bubble Developing in Heater and Side View of Temperature Differential. *Left: During the test, an air bubble developed between the heater and surface of the chip. This area is cooler than the surrounding area and created an uneven distribution of heat during the test. Right: Due to the small size of the solder balls and micro-springs, a side view of the high lead columns is used to show the temperature differential across the interconnection.*

C. Further Research

Future work will need to be done to refine the simulation. The open coils in the spring create a longer conduction path but also provide the opportunity for convection to take place. Research on how much benefit can be gained by this convection is on-going. Once this method is producing consistent results, it can be applied to other types of interconnect technologies.

IV. Conclusion

Based on the data gathered in the physical test and confirmed by the simulations, the solder balls are about twice as effective at conducting heat as the micro-springs. This was expected in vacuum conditions, however, this test was not performed in a vacuum. Steps were taken to reduce the amount of air flow as much as possible but air was still presence in the test. Due to this, the temperatures are slightly lower than they would be in a true vacuum. The conditions for each test were identical so the results can still be compared to one another.

Acknowledgments

Allison M. Copus would like to thank Marshall Space Flight Center Branch ES43, Electronic Packaging, for support in this project.

References

[1] De Witt, D. P., Incropera, F. P., *Fundamentals of Heat and Mass Transfer*, 3rd ed., John Wiley and Sons, New York, 1985, Chap. 3.