

Flipchip Reliability Improvements for an Automotive Sensor Application

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Abstract:

During the launch and subsequent validation testing of a small diameter automotive pressure sensor that utilized a flipchip on flex electronics module, we experienced lower than expected reliability levels after extended thermal shock exposure. A subsequent failure analysis indicated cracked copper traces in the flipchip region of the flex circuit. FEA analysis confirmed that the copper trace stresses were in excess of the copper yield strength. Using the knowledge gleaned from the FEA, we were able to reduce the trace stresses by optimizing the trace layout. By changing the flipchip underfill, further trace stress reductions resulted in improved circuit reliability.

Analytical results were confirmed by running confirmation tests on actual hardware. Trace changes alone resulted in a 2-3x improvement in thermal shock reliability, while trace changes coupled with underfill changes made a 3-4x improvement in thermal shock reliability. The paper highlights the improvement process and the test to failure approach.

Keywords: Flipchip, Flex circuit, Underfill, Reliability, Test to Failure, FEA

Introduction:

The automotive sensor market continues to grow at a 6% compounded annual growth rate. Within this market, a large driver for the growth rate is the expanded emphasis on vehicle safety systems and in particular brake pressure sensors driven by expanded implementation of Electronic Stability Control (ESC) systems. National Highway Traffic and Safety

Administration (NHSTA) will mandate such systems in the US by 2011, and in Europe there is nearly 100% penetration pending. Pressure Sensors for these applications tend to be small in diameter (around 12mm +/-) so they can be housed in the hydraulic control unit of the braking system. This size constraint drives cutting edge electronic packaging technology. See Figure 1 for typical sensors for ESC systems.

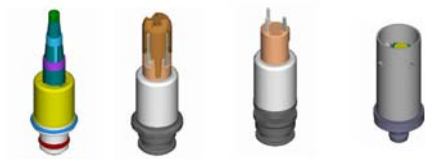


Figure 1 – Typical ESC Pressure Sensors

The original approach chosen by Sensata for packaging sensors of this product family was to employ a flip-chip on flex. A typical sensor of this type utilizes a strain gauge sensing element wirebonded to a flex circuit. The flex circuit serves as the interface between the sensing element and customer driven I/O/connector as well as the substrate for the signal conditioning ASIC and supporting components. The flex is bonded to a polymer support structure (support ring) that allows it to be attached to the sensing element (pressure port) that interfaces the brake system Hydraulic Control Unit (HCU). Figure 2 shows an HCU, and Figure 3 shows the internals of a typical sensor.



Figure 2 – Typical Hydraulic Control Unit (HCU) for an ESC system

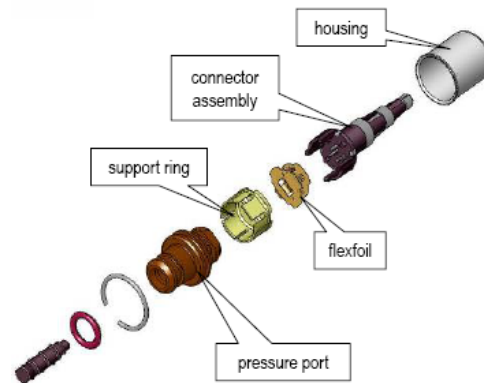


Figure 3 – “Exploded view” of typical Sensata Brake pressure sensor.

Drivers for this approach were smaller size and ease of manufacturing. The typical mounting location for the HCU is under the hood in the engine compartment. (See Figure 4 and 5)



Figure 4 & 5 – Typical location of ESC system HCU

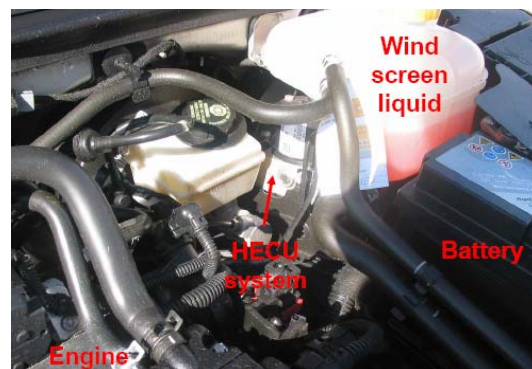


Figure 5

As might be expected the safety critical nature of the application as well as the automotive under hood reliability requirements for this type of sensor rival that of military electronics. A full gamut of environmental tests are performed which involve, full functional testing at three temperatures (-40C, 25C, 125C) followed by, heat soak (1000 hrs @ 125C), thermal shock/cycle (-40C to 125C air to air -1000 cycles minimum, then extended on to failure) , extended humidity exposure (85C/85%RH), and mechanical shock plus vibration. During thermal shock/cycle reliability testing, the full functional test is typically done every 250 cycles. For the other tests, it is usually done at the beginning and the end of the environmental exposure. In many cases, the tests are cascaded with multiple environmental stresses applied in series. In all cases, sensor output must perform within required specifications after environmental testing.

During testing of a new family of sensors, several failures were found at the high temperature functional test after exposure to 1250 thermal shock cycles. This exceeded specification requirements of 1000 thermal shocks, but did not offer sufficient head room. An investigation into the failure mode and improvement activity were initiated.

Investigation:

When the failure was first found, it was originally theorized that the ASIC solder bump connection had opened up or that the ASIC had

failed. This had long been an area of potential concern and captured in our FMEA's, as we had believed the Under Bump Metal (UBM) connection to the ASIC or the solder bump itself would be the most likely point of failure. A careful de-bonding of the ASIC and subsequent analysis indicated that the ASIC was still functional, and the bump connection and UBM appeared to be intact. With this information, a more detailed inspection of the flex circuit was performed and it was found that the Cu trace on the flex circuit leading to the power pin of the ASIC was cracked. This caused the circuit to open up at approximately 90C. A thorough inspection of several failed sensors indicated that the failures occurred (in the PWR or VDIG traces) at points coincident with the trace exiting the flipchip underfill region.

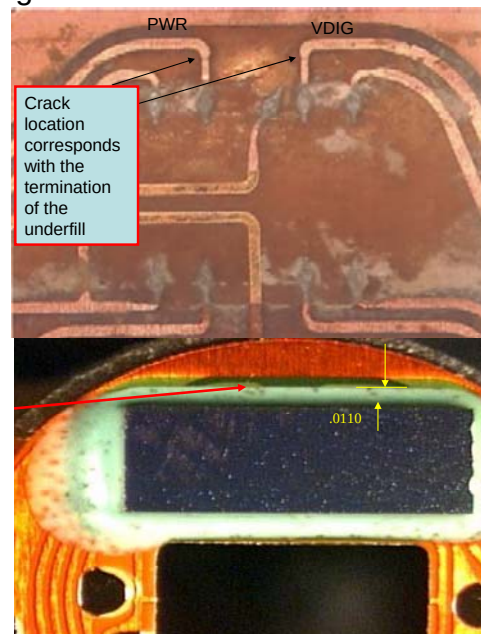


Figure 6 – Location of cracked flex trace

An FEA analysis keying in on this portion of the circuit was initiated. The results indicated that in the

region of failure Von Mises stresses slightly exceeded the yield strength of the Cu (Cu yield strength 10,000 – 11,000 psi).

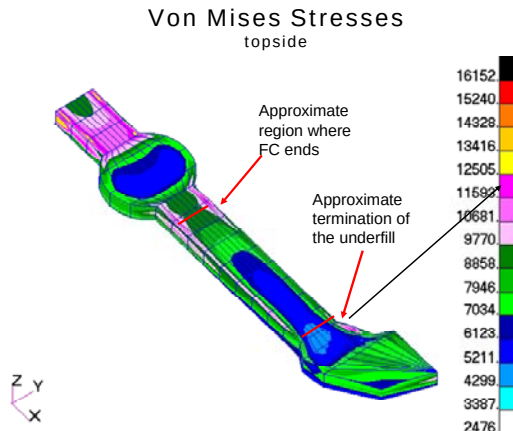


Figure 7 – FEA of original flex trace. Von Mises stresses.

By resolving the stress into directional components and looking at the axial load it revealed a relatively high stress area that matched the failure point. While not in excess of the yield stress of the Cu, the correlation of high stress region to the failure point could not be ignored. It was theorized that the transition out of the underfill and width change concentrated the stress at the failure point.

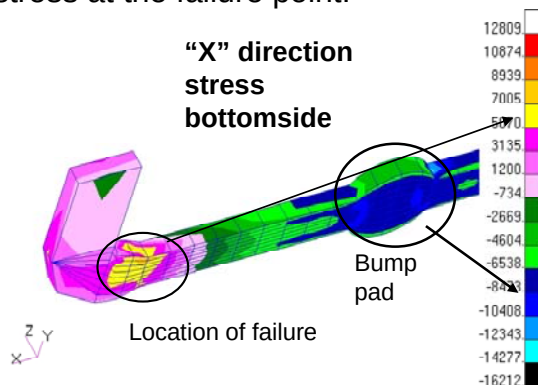


Figure 8 - FEA of original flex trace with stress direction resolved

Further, it can be seen that the stress rises as the trace transitions from regions under the chip /

underfill region. Please note, due to design guidelines for proper reflow of the flipchip, the trace directly exiting the bump pad was kept as narrow as possible, and thus prone to higher stress levels, particularly where it widened out. This observation led to the belief that improvement in the stress levels could be made by keeping the trace under the ASIC or at a minimum under the underfill until it could be widened, and thus exit the flip chip region with a much wider width, so as to lower the stress. The revised trace layout is shown in Figure 9. Resulting FEA analysis of this revised layout is shown in Figure 10.

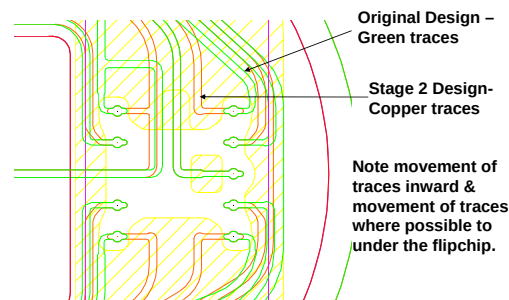


Figure 9 – Comparison of original and revised flex traces.

A first pass analysis of the stresses showed no improvement in trace stress when looking at Von Mises stresses. This was a little surprising. Resolving the Von Mises stresses into their X and Y components told a different story. When observing the situation in this manner, one can see that the stress level was dramatically reduced in the potentially damaging tensile direction, and converted primarily to more benign compressive stresses. Conversely as seen in Figure 8 stress levels in the original trace layout showed mostly tensile components when

resolved into their directional components.

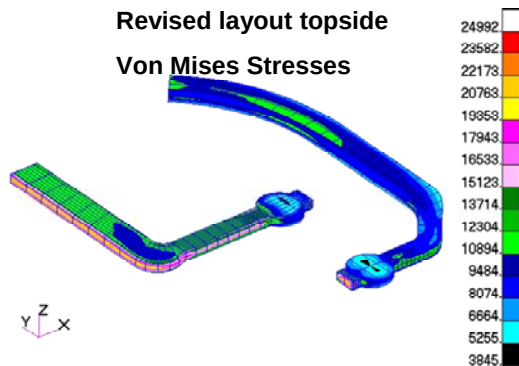


Figure 10 – FEA of revised trace layout – Von Mises stresses

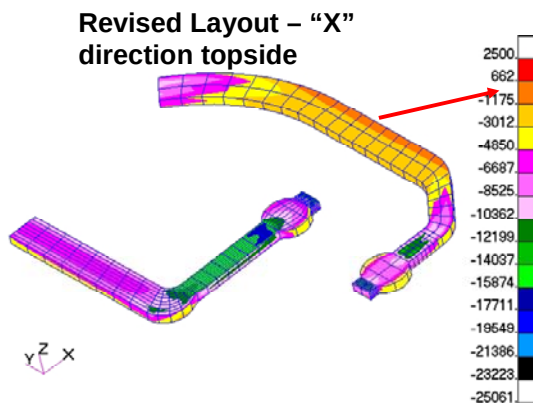


Figure 11 – FEA of revised trace layout – X direction stresses + = tensile

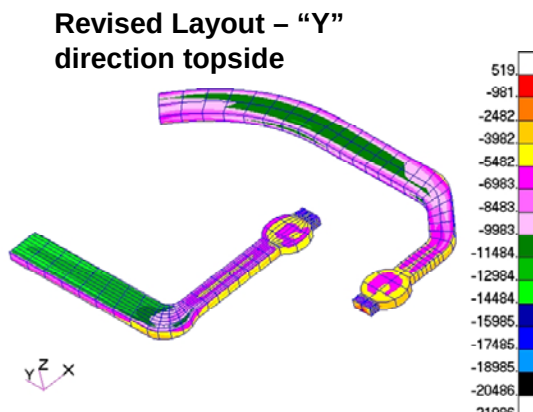


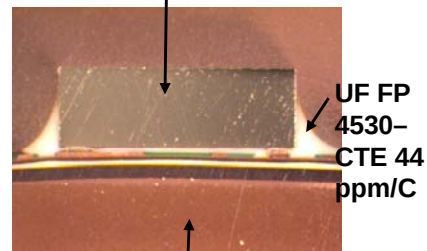
Figure 12 – FEA of revised trace layout – Y direction stresses + = tensile

Further Improvements:

Another area that was investigated for further improvement was the

influence of the material properties on the stress situation. It was brought to the authors attention that other underfills besides the one selected may be more appropriate for flipchip on flex circuit applications. Figure 13 highlights the materials used and their Coefficient of Thermal Expansion's (CTE's)

Si die – CTE 3 ppm/C



Ultem 2310 – CTE 20 ppm/C

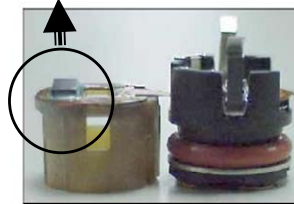


Figure 13 – View of the flipchip and surrounding materials.

In general underfill property selection tends to be a balance between imparting stress to the die vs imparting stress to the bump. The primary driver for imparting stress to the die in this application is the underfill modulus of elasticity. As elastic modulus increases, more stress is transmitted to the die. Due to some early die related failures in our process development, our bias was to minimize stress to the die and

let other properties fallout. This drove our selection of Henkel Loctite FP 4530 for the underfill, which was a relatively new material when this product was originally released. Figure 14 highlights the situation graphically with the underfill property normalized to 25ppm as at that point in time, underfill selection was not firm. This graph compares a traditional flipchip vs. a Chip Scale Package (CSP).

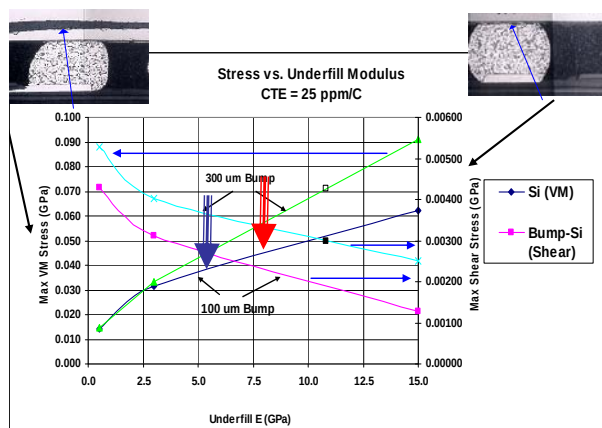


Figure 14 – Bump & Si stress level vs modulus of elasticity, with CTE held @ 25ppm/C. Note – Red arrow shows where FP 4531 would be, and Blue arrow shows where FP 4530 would be different CTE levels not withstanding. Pictures correspond to Si fracture from increasing Si stress on the left axis, and bump fracture from increasing bump shear stress on the right axis.

Given that our current reliability situation had highlighted a high stress condition on the Cu traces and no die failures, the take away was that we had room to move towards a more rigid material that would enable a CTE reduction. In relative terms, our die size was on the small size of the spectrum of FC devices. This also led us to believe that we had some latitude with respect to the elastic modulus

property of the underfill. Given this background we chose to evaluate a lower CTE, higher elastic modulus material as part of our improvement activity. In the end Henkel Loctite FP 4531 material was selected as this material was chemically similar to our original FP 4530 material and processed in a similar manner. The properties of the materials on compared in Table 1.

Table 1 - Underfill Properties

Underfill -Key Property Comparison			
	CTE (ppm/C)	Flexural Modulus (Gpa)	Filler Content (%)
FP4530	44	5.6	50
FP4531	28	7.6	62
Both materials Henkel- Loctite			

The only changes were its lower CTE and higher elastic modulus driven by higher filler loading (see Figure 15 reprinted from the Henkel Loctite application guide for the trade off's). Gap size capability was slightly reduced, however this was not an issue with our relatively conservative bump size and relatively robust gap size.

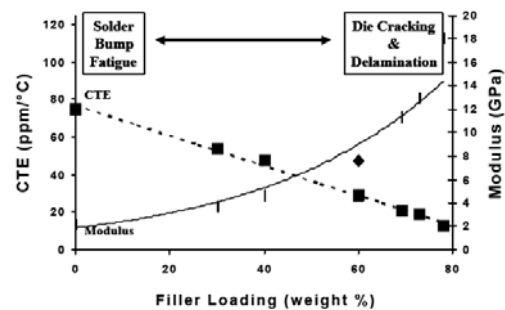


Figure 15 – Relation between underfill filler loading, and CTE and Elastic Modulus - Reprinted from "Application Guidelines for Loctite underfill encapsulants"

Reliability Testing:

Flex circuit assemblies were procured with the trace layout improvement noted in the first section. Two groups were ordered.

One with FP 4530 and one with FP 4531. Circuits were subjected to thermal shocks and die continuity from each bump was checked every 250 thermal shocks. The results are summarized in Table 2. As can be seen, the trace layout change alone yielded a roughly 2-3x improvement in reliability. Underfill change combined with the trace change yielded a module that made it to 4000 thermal shock cycles without failing, resulting in a 3-4x improvement in reliability. Testing was suspended at this point as the passive devices and connector I/O's were beginning to fail completely.

Table 2 – T-shock Performance

Thermal shock performance comparison		
	Cycles to first failure	Cycles to 50% Failure
Control	1250	1750
New Trace FP 4530	3000	4000
New Trace FP 4531	Exceed 4000	N/A

Conditions - -40C to 125C Air to Air

Conclusion:

Results indicate that it is possible to develop an extremely robust “flipchip on flex” electronics module for harsh automotive applications. By understanding the stress at work on the FC and surrounding traces the design can be optimized to obtain high reliability levels. This work also highlights the benefit of testing to failure, and analyzing the failure mode for product improvement.

Acknowledgements:

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selection, as well as the Henkel Loctite technical support team – in particular Michael Todd for his support and consultation relative to underfill materials.

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- 2.) “Application Guidelines for Loctite Underfill Encapsulants” – A Henkel Loctite Publication
- 3.) Henkel Loctite Technical Data Sheets for FP 4530 and FP 4531
- 4.) Tom Maher, - Sensata Internal Document – “Flip Chip on Flex Finite Element Analysis”, May 19, 1999.