

University of Wales Trinity Saint David

School of Engineering

*Major Project Exhibition Report –
Effects of thermal cycling on surface flatness and electrical
performance of EPAS power modules.*

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Abstract

This major project report identifies the effects of induced thermal stress on EPAS power modules through thermal cycling.

Following thermal cycling of the power modules using thermal shock chambers, a complex methodology to collect data of the surface flatness and electrical performance was carried out on specialist automated equipment to gather data for analysis.

Analysis of the data has been carried out and it identified changes in the surface flatness and electrical performance with thermal cycles respectively.

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1. Introduction

This report investigates through research and testing, the concerns of a potential failure of an electrical power assisted steering system (EPAS) through extensive research into determining the implications thermal stress has on an EPAS power steering module.

1.1. Background

KSR International Ltd, in Swansea manufactures and supplies the EPAS power module to a customer. A defect was identified with the integrated direct bonded copper (DBC) circuit substrate which is supplied to KSR. Thermal stress relief dimples were found to be missing on the back of the DBC substrate. Through thermal cycling, the power module will be analysed on its performance and a comparison will be made between the power modules with defect DBC's and power modules with no defects.

Live testing will be carried out using testing equipment at KSR Swansea, thermal cycling carried out using a thermal shock chamber, surface flatness measured using an optical gaging product (OGP) coordinate measuring machine (CMM). A production line electrical tester will be used to carry out a continuity test to determine the voltage, current and resistance change of the internal metal-oxide-semiconductor-field-effect transistors (MOSFET) and ultrasound imaging will be used as a binary test, all data collected will be used to determine how thermal cycling has effected the working performance of the module, and provide a comparison between the power modules with missing dimples (defect) and power modules without missing dimples (controlled).

1.2. Aims

- Identify the effects of thermal induced stress on the surface flatness and electrical performance of electrical power assisted steering power modules.
- Carry out analytic processes through extensive research and live simulation testing techniques to assess the effects of thermal stress.

2. Research-Informed Literature Review

Steering systems are an extremely safety critical system within an automotive vehicle, they allow the vehicle to be accurately steered (turned) in a direction according to the drivers input.

Most modern automotive vehicles have power assist systems to aid steering. Power assist systems were introduced to vehicles to overcome the larger steering effort required as vehicles become larger and heavier (Horobin, 2003). The two main types of power assistive steering are Hydraulic assist (HPAS) and Electrical assist (EPAS)

2.1. Electrical Power Assisted Steering

EPAS is an alternative to hydraulic power assisted steering, which is entirely electrically powered by the use of an electric motor rather than a hydraulic pump (Jurgen, 1999), therefore as previously discussed EPAS systems can be subject to both mechanical and electrical failures. An electric motor replaces a hydraulic pump, therefore, fewer loads are placed on the engine, as a result EPAS only requires approximately 2% of the required power to power a belt driven hydraulic pump, therefore a significant reduction in energy usage and vehicle emissions (VanGelder, 2017).

2.2. Potential Failure Modes

Hydraulic and Electrical power assisted steering, much like many other mechanised/electrical systems; both have inherent concerns regarding potential failure modes.

Mechanical issues can occur such as parts ceasing, i.e. rack and pinion gears etc. usually result in a decrease in steering ability, however allowing the vehicle to be manoeuvred to a safe place (Thompson, 2013).

Although, a major concern for EPAS is the electrical components that control the assist, electrical components can be damaged by many contributing factors such as vibrations, electro-magnetic radiation/interference, water ingress and thermal stress/damage (Gilles, 2005).

In this project, the potential failure mode that will be critically analysed is the thermal stress factor of the electrical components within the EPAS system.

Electrical components can become subject to thermal fatigue due to thermomechanical and thermoelectric stresses caused during operation. Applied thermal stress, can cause electrical failures such as damaged MOSFET's, resulting in reduced performance or failure (Băzu & Băjenescu, 2011).

Thermal stress can cause cracking and shape changes (warping) to the integrated circuits/DBC's which can damage solder joints and wire bonds causing the power module to fail (Frear et al., 1988). The encapsulate material i.e. the plastic moulding enclosure, which acts as a protective barrier to the components and wire bonds, could possibly delaminate as a result of thermal stress, compromising its structural integrity (Yao et al., 2011).

However, in the result, there is any assist system failure, there is a fail-safe and the system reverts to manual steering without assist (Hillier et al., 2004), even in fully electrical steering (steer-by-wire), the system has a backup source of power which provides a minimum of 50% of the required power (Els, 2017).

A sample of 6 defect parts as seen in figure 1 (left) have been selected for testing and analysis along with a sample of 6 controlled parts as seen in figure 1 (right) as a comparison. Using 12 parts in total provides extensive data on the effects of thermal stress on the power modules with a comparison to determine if the thermal relief dimples missing on the defect modules has any possible accelerated effects of thermal stress.



Figure 1: KSR power modules with defect DBC (left) and controlled DBC (right)

2.3. DBC Substrates

The DBC substrates (figure 2) are made up of copper and ceramic (a ceramic tile coated with a sheet of copper each side to produce a top and bottom layer of oxidised copper). The ceramic material is made up of Aluminium Oxide (Al_2O_3).

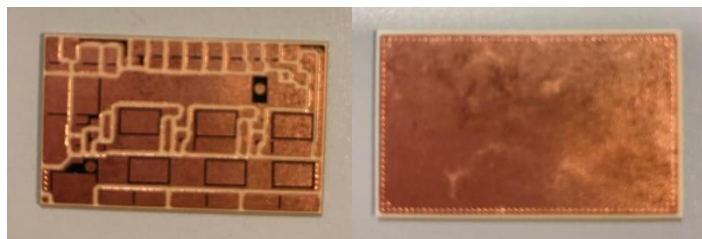


Figure 2: DBC substrate (Source: KSR and Thomas, 2017)

Al_2O_3 is widely used for this purpose due to its low cost and very low coefficient of thermal expansion which is significantly lower than copper alone - as a result provides excellent electrical insulation (Dong et al., 2010).

Copper and Aluminium Oxide however have different thermal expansion properties, therefore excessive thermal cycling can cause delamination and cracks can form between the copper and aluminium oxide causing warpage and performance reduction (Lei et al, 2009).

The thermal relief dimples work by reducing the mass and overall volume of the copper, copper has an extremely high electrical and thermal conductivity, and when current passes through it, it can heat up largely (Laughton & Warne, 2003).

It can be seen from figure 3 that virgin DBC's (not power module) without dimples appear to endure less than 100 thermal cycles, however, DBC's with dimples endure approximately 600 thermal cycles, therefore the advantages of thermal relief dimples can be seen (Curamik, 2014).

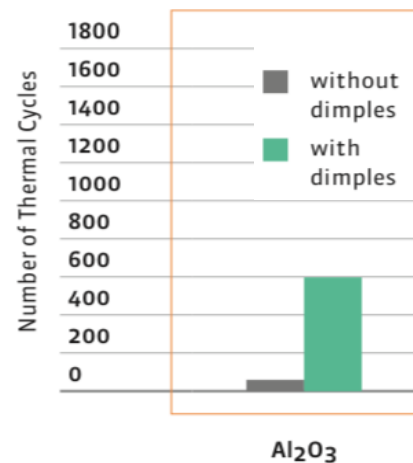


Figure 3: Comparison with/without thermal relief dimples (Source: Curamik, 2014)

2.4. What is the purpose and significance of the flatness measurements?

The flatness is significant to the customer, due to the connection of the power module to the customer's assembly – the power module is attached to a heatsink via thermal adhesive and bolt connections as shown in figure 4.



Figure 4: Power Module attached to customer's heatsink (Source: Thomas and KSR, 2018)

Flatness is extremely important as it ensures all sections of the power modules relationship face with the customer's heatsink component are in contact, if it wasn't micro pockets of air would form and would increase the thermal resistance between the heatsink and the module (Lutz et al, 2018).

2.5. Electrical Performance Parameters

During the manufacturing process of the power module each DBC substrate is populated with 6 MOSFET's, used to control the voltage and current flow by switching and amplifying the source signal (Baliga, 2014).

Resistance in particular is thermal sensitive, its reduced when temperature increases and increases when temperature falls (Vassighi & Sachdev, 2011). Considering ohm's law, $\text{Voltage} = \text{Current} \times \text{Resistance}$, it would be expected to see changes to the current and voltage also (Luryi & Xu, 2010).

2.6. Further Research

A question was asked in the initial viva presentation if the concerns of the effects of thermal stress on electrical integrated circuits are a concern in other applications as well as this power module, this was a question which required research to provide an answer.

Thermal stress is a concern in all electrical components and circuitry, electrical resistance is sensitive to thermal changes, and therefore, applied thermal stress could affect the electrical performance as discussed above (Cook, 2010).

Distortion/warpage is a concern in all applications where a material is thermal sensitive; material will expand and contract, contributing to distortion/warpage of the material and/or cracks (Fischer, 2013)

3. Methodology

Thermal stress was induced using a thermal shock chamber (figure 5) for a total of 1000 cycles, completed in 250 cycle increments.

One cycle consisted of $-40^{\circ}\text{C} \pm 5\%$ for 30 minutes with a maximum of 30 second transition to $115^{\circ}\text{C} \pm 5\%$ for 30 minutes and maximum 30 second transition back to $-40^{\circ}\text{C} \pm 5\%$.

3.1. Visual Inspection and Electrical Continuity Test

Following each 250 thermal cycles, the power modules were inspected by the failure analysis engineer, with the use of Scanning Acoustic Microscopy (CSAM), which uses ultra-high frequency ultrasound to identify any physical failures within the power modules. Other methods such as X-Ray could be used; however CSAM imaging provides clearer and more accurate analysis (Kessler, 2013).

The electrical continuity test was carried out by the validation engineer, which can be carried out with simple electrical test

equipment such as a multi-meter, however as

the power module is a

bespoke product with specific power terminals, a specific and custom-made electrical testing machine (figure 7) has been specially made. It has specific contact points which line up to each terminal on the power module keys, each key corresponds to specific MOSFET's, it is also automated, and therefore reducing human contact and subsequently reducing human error and increasing accuracy and validity of results (Cresswell, 2002).



Figure 5: Thermal Shock Chamber (Source: KSR and Thomas, 2017)



Figure 6: CSAM ultrasound (Source: KSR and Thomas, 2017)



Figure 7: Electrical Test Machine (top) and Internal contact points (bottom) (Source: KSR & Thomas, 2017)

3.2. Flatness Measurements

The flatness measurements were completed using a specialist coordinate measuring machine(CMM), produced by a company called Optical Gaging Products (OGP), this OGP machine (figure 8) uses specialist software which is programmed and calibrated every 6 months to ensure it is extremely accurate, the software is programmed with customers specified dimensions and tolerances and can therefore accurately measure the distance the surface differs from the specified plane – providing an accurate flatness measurement.

The OGP machine uses specially written programme software, relating to the drawing design and dimensions, with it being a bespoke automated programme, it reduces the possibility of human error, and there is increased accuracy due to laser measurement technology (Dhillon, 2013).



Figure 8: OGP machine (Source: Thomas, 2017)

4. Results & Analysis

DBC Flatness (microns)	Benchmark	Post 250 Cycles	Post 500 Cycles	Post 750 Cycles	Post 1000 Cycles
Controlled Average	34.9	37.78	39.17	40.02	40.28
Controlled Standard Deviation	2.47	2.37	0.88	2.35	2.11
Defect Average	35.53	38.83	40.63	41.53	41.85
Defect Standard Deviation	2.42	0.78	1.87	1.6	1.11

Figure 9: DBC Flatness measurements post 1000 cycles (Thomas & KSR, 2017)

From figure 9 it can be seen on average the surface flatness measurement increases with thermal cycles respectively, increasing from 34.9 microns to 40.28 microns for controlled, increasing 5.38 microns. The defect increase

is 6.32 microns; this is a larger increase than the controlled, increasing from 35.53 microns to 41.85 microns after 1000 thermal cycles.

The flatness change of the DBC is far more drastic, between benchmark and post 500 cycles; this can be seen also in figure 10.

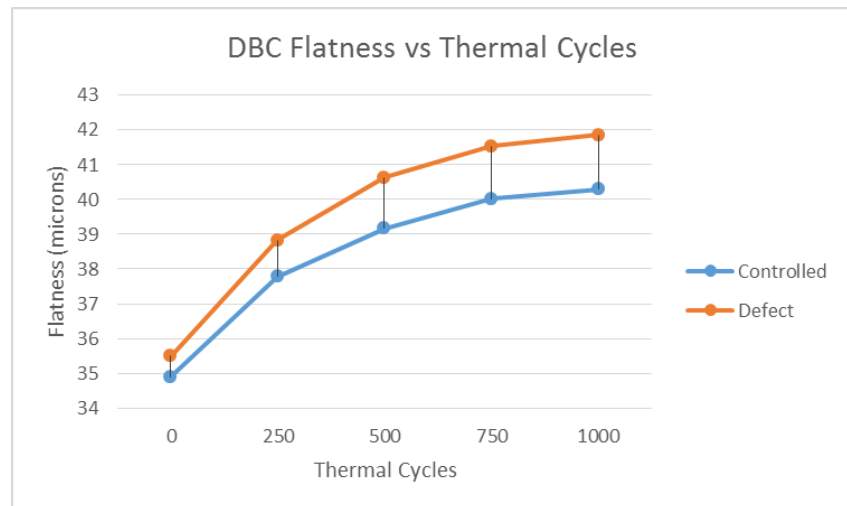


Figure 10: DBC Flatness vs Thermal Cycles

It can be seen from both figures 9 and 10 that DBC flatness increases respectively with thermal cycles, therefore thermal cycling causes flatness capability to decline, this suggests that initial distortion of the DBC could well be occurring (Dunn, 2017).

However, overall the defect samples increase was 0.94 microns more than the controlled samples. Therefore, it can be suggested that due to the defect samples having a number of missing thermal relief dimples on the DBC, the thermal dissipation isn't as effective as the controlled samples and therefore on average the DBC on the defect samples have an increased sensitivity to the applied thermal stress (Spencer & Lorenz, 2008).

Plastic Flatness (microns)	Benchmark	Post 250 Cycles	Post 500 Cycles	Post 750 Cycles	Post 1000 Cycles
Controlled Average	67.5	74.4	76.22	79.32	80.12
Controlled Standard Deviation	2.79	1.76	1.65	2.06	1.54
Defect Average	66.2	74.23	75.97	78.4	79.27
Defect Standard Deviation	1.85	1.72	1.18	1.81	1.67
Overall Flatness (microns)					
Controlled Average	71.6	80.25	82.53	84.47	86.25
Controlled Standard Deviation	3.85	1.63	2.44	1.4	2.14
Defect Average	68.17	81.05	83.8	85.67	85.77
Defect Standard Deviation	4.66	1.41	1.68	2.39	1.43

Figure 11: Plastic and Overall Flatness measurements post 1000 cycles (Thomas & KSR, 2017)

The controlled plastic flatness rises from 67.5 microns to 80.12 microns, a total of 12.62 microns and the average defect plastic flatness increases by 13.07 microns, from 66.2 microns to 79.27 microns. However, defect samples have increased by 0.45 microns more than the controlled samples over the 1000 cycles. Although, the controlled samples have a larger flatness measurement, 0.85 microns larger, therefore 0.85 microns lesser flatness capability as shown in figure 12.

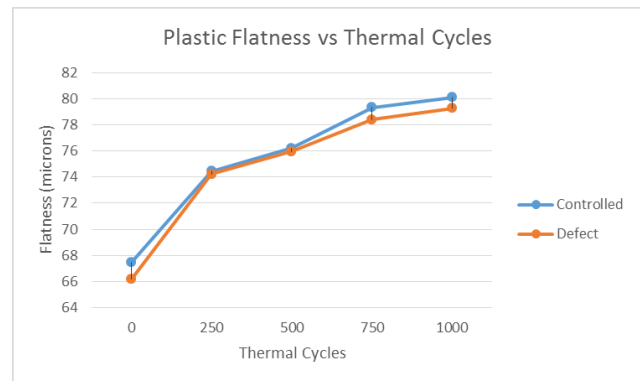


Figure 12: Plastic Flatness vs Thermal Cycles

The plastic increase is far more significant than the DBC flatness increase, 6.32 microns was the largest increase for DBC, and 13.07 microns for plastic, this could be due to the polyethylene resin pellets having a larger thermal expansion coefficient than DBC substrates (Ho, & Taylor, 1998).

The overall flatness increases 14.68 microns for controlled and 17.6 microns for defect as shown in figure 13. Again it can be seen that the defect samples overall have the largest increase in flatness

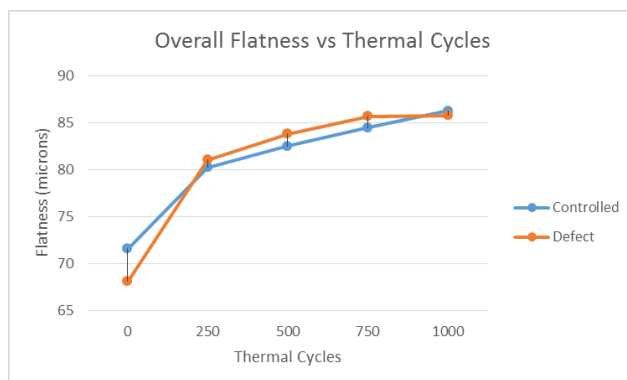


Figure 13: Overall Flatness vs Thermal Cycles

measurement and therefore the largest decline in flatness capability.

Comparing all three parameters of flatness, the defect samples appear to have the greatest change from benchmark to post 1000 cycles, 0.83 microns more on DBC flatness, 0.45 microns more on plastic flatness and 2.92 microns more overall, therefore suggesting that

the defect DBC substrate causes the thermomechanical effects to possibly be accelerated (Lau, 2012). However, surface flatness measurements for all three parameters increase with thermal cycles respectively. Therefore, with the surface flatness capability declining, it can be suggested that an effect of applied thermal stress and the reaction from the power module as a result of the thermomechanical stress is that surface flatness capability declines with thermal cycling respectively.

CSAM imaging confirmed no cracks were found in any of the material, wire bonds and all solder joints remained intact, and there appeared to be no cosmetic defects as a result of thermal shock cycling as shown in figure 14 (Dunn, 2017).

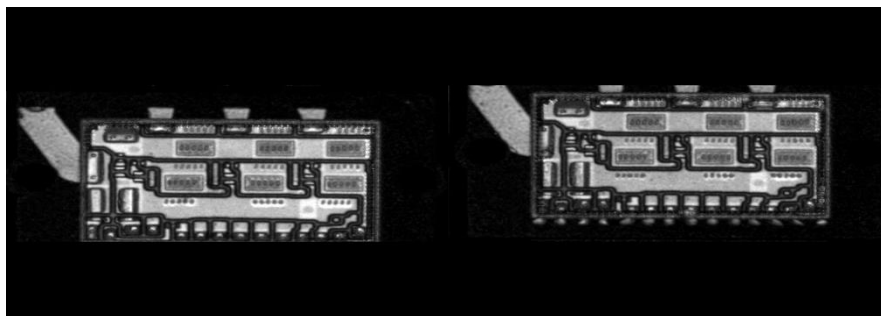


Figure 14: CSAM imaging of defect (left) and controlled (right) parts post 1000 cycles (Source: Dunn & KSR, 2017)

Drain Current (amps)	Benchmark	Post 250 Cycles	Post 500 Cycles	Post 750 Cycles	Post 1000 Cycles
Controlled Average	8.76×10^{-8}	8.26×10^{-8}	7.99×10^{-8}	7.45×10^{-8}	7.25×10^{-8}
Controlled Standard Deviation	4.19×10^{-9}	5.65×10^{-9}	3.91×10^{-8}	3.53×10^{-8}	3.57×10^{-8}
Defect Average	8.97×10^{-8}	8.51×10^{-8}	7.66×10^{-8}	7.15×10^{-8}	6.89×10^{-8}
Defect Standard Deviation	4.26×10^{-8}	3.70×10^{-8}	4.59×10^{-9}	4.47×10^{-9}	4.37×10^{-9}
Drain Voltage (V)					
Controlled Average	43.63	43.64	43.70	43.75	43.77
Controlled Standard Deviation	0.2	0.24	0.38	0.41	0.43
Defect Average	43.44	43.53	43.75	43.83	43.86
Defect Standard Deviation	0.25	0.36	0.27	0.30	0.31
Drain Resistance (Ω)					
Controlled Average	1.8847×10^{-3}	1.8864×10^{-3}	1.8915×10^{-3}	1.8982×10^{-3}	1.9012×10^{-3}
Controlled Standard Deviation	5.46×10^{-6}	7.85×10^{-6}	1.52×10^{-5}	1.48×10^{-5}	2.05×10^{-5}
Defect Average	1.8883×10^{-3}	1.8894×10^{-3}	1.8976×10^{-3}	1.9036×10^{-3}	1.9061×10^{-3}
Defect Standard Deviation	1.47×10^{-5}	1.79×10^{-5}	6.41×10^{-6}	6.78×10^{-6}	8.1×10^{-6}

Figure 15: Electrical test data post 1000 cycles (Source: KSR, 2017)

It can be seen from figure 15 that voltage and resistance appears to increase and current decreases in value with thermal cycles respectively. It can be seen that the voltage and resistance increases respectively, the change increase is very small in relation to the scale and in both samples increasing

from a lowest of 43.44 volts to a highest of 43.86 volts. However, the controlled sample average resistance increases from 1.8847milliohms to 1.9012milliohms, an increase of 0.0165milliohms. The defect sample average increases by 0.0178milliohms, from 1.8883milliohms to 1.9061milliohms, again the defect samples have a larger increase and higher resistance post 1000 cycles as shown below in figure 16.

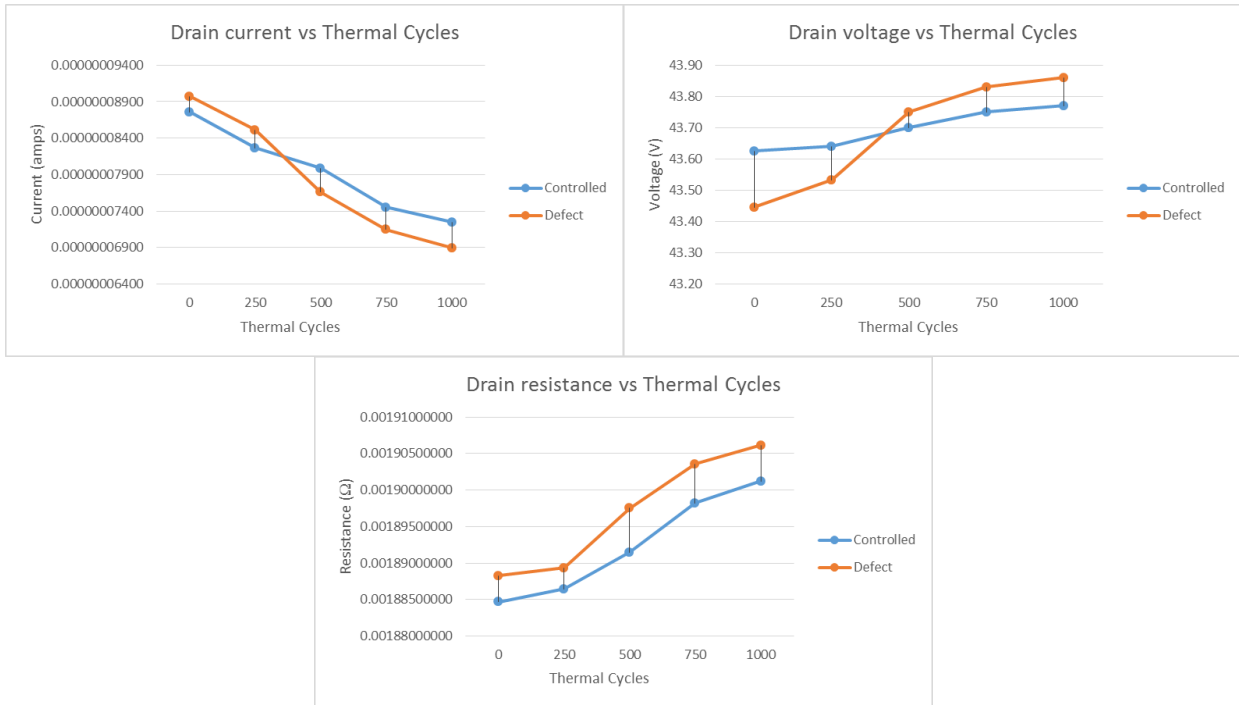


Figure 16: Current, Voltage and Resistance vs Thermal cycles (post 1000)

As a result of the resistance increase and compliance with Ohm's law, current of both controlled and defect samples decrease.

The current of the controlled samples average decreases from 8.76×10^{-8} amps to 7.25×10^{-8} amps, a reduction of 1.51×10^{-8} amps, however the defect samples average reduces by 2.08×10^{-8} amps, again a larger reduction than the controlled sample average, decreasing from 8.97×10^{-8} amps to 6.89×10^{-8} amps.

As illustrated, all power modules have experienced a current reduction as a result of an increase in resistance. Due to the data gathered it could be suggested that the increase in thermal cycles is directly proportional to the resistance, due to electrical resistance being sensitive to thermal changes (Warren, Adams & Molle, 2011).

The data gathered suggests that the defect samples performed worse than the controlled samples and experienced an accelerated decline in flatness capability, and larger decline in electrical performance in comparison to the control samples.

An attempt to validate the data collected was endeavoured, through CAD (computer aided design) modelling of the power module and simulating thermal shock testing to determine the overall stress applied on the power module. However, due to limitations of the software used (solid works); the simulation wasn't able to be completed as desired.

The design engineer at KSR advised that solid works isn't the best software for thermal analysis as it is very limited to its abilities of applying thermal loads (Dias, 2018).

5. Conclusion

Based on the results and analysis it was concluded that the power modules were both mechanically and electrically negatively affected by the applied thermal stress through thermal cycling. The conclusion made is that defect samples with a number of missing thermal relief dimples experienced increased and accelerated stress compared to control samples with no missing thermal relief dimples, and therefore the hypothesis that it would be expected that the control sample would perform better was confirmed.

The results and data found is similar to the data and report written by Lei et al in 2009, where it was found that thermal cycling would lead to surface changes to DBC's, in the report it summarized how extensive thermal cycling caused thermal fatigue of the material and result in shape changes, this was suggested by the changes in flatness measurements in this project.

A suggestion for further live simulation testing, particularly in this major project would have been to complete a durability test of the power modules ,this would help determine the performance of the power modules while switched on during application of thermal loads.

Testing the power modules to failure would have allowed for the hypothesis of warping of the material due to thermal fatigue to be fully confirmed or not. Extensive thermal cycling until failure, along with CAD simulation could prove beneficial to the analysis of the overall products thermal capabilities.

6. References

- Baliga, B.J., 2014. Advanced power mosfet concepts, Springer.
- Bâzu, M.I. & Băjenescu, T.-M.I., 2011. Failure analysis: a practical guide for manufacturers of electronic components and systems, Chichester: Wiley.
- Cook, D., 2010. Intermediate Robot Building, Berkeley, CA: Apress.
- Cresswell, L., 2002. Product design graphics with materials technology, Oxford: Heinemann.
- Curamik, 2014. Design Rules DBC. Curamik Ceramic Substrates.
- Dhillon, B.S., 2013. Safety and human error in engineering systems, Boca Raton, FL, USA: CRC Press, Taylor & Francis Group.
- Dong, G. et al., 2010. Thermal fatigue behaviour of Al₂O₃-DBC substrates under high temperature cyclic loading, Soldering & Surface Mount Technology.
- Els, P., 2017. Electric power steering systems (EPS) have never been safer. Automotive IQ. Available at: <https://www.automotive-iq.com/chassis-systems/articles/electric-power-steering-systems-eps-have-never-been-safer> [Accessed November 9, 2017].
- Fischer, J.M., 2013. Handbook of moulded part shrinkage and warpage, Norwich, NY: William Andrew.
- Frear, D., Grivas, D. & Morris, J., 1988. A microstructural study of the thermal fatigue failures of 60Sn-40Pb solder joints, Sandia National Laboratory.
- Gilles, T., 2005. Automotive chassis: brakes, suspension, and steering, Clifton Park, NY: Thomson Delmar Learning.
- Hillier, V.A.W. et al., 2004. Hilliers fundamentals of motor vehicle technology, Cheltenham: Nelson Thornes
- Ho, C.Y. & Taylor, R.E., 1998. Thermal expansion of solids, Materials Park, OH: ASM International.
- Horobin, 2003. How it works: science and technology, New York: Marshall Cavendish.
- Kessler, L., 2013. Acoustical Imaging, Springer Verlag.
- Lau, 2012. Thermal Stress and Strain in Microelectronics Packaging, Springer Verlag.
- Laughton, M.A. & Warne, D.F., 2003. Electrical engineers reference book, Burlington, MA: Newnes.
- Lei, T.G. et al., 2009. Effects of Large-Temperature Cycling Range on Direct Bond Aluminium Substrate. IEEE Transactions on Device and Materials Reliability, 9(4), pp.563–568.
- Luryi, S. & Xu, J., 2010. Future Trends in Microelectronics: From Nano photonics to Sensors to Energy, John Wiley & Sons.
- Lutz et al., 2018. SEMICONDUCTOR POWER DEVICES: physics, characteristics, reliability, S.l.: SPRINGER INTERNATIONAL PU.

Spencer, M.L. & Lorenz, R.D., 2008. Analysis and In-Situ Measurement of Thermal-Mechanical Strain in Active Silicon Power Semiconductors. 2008 IEEE Industry Applications Society Annual Meeting.

VanGelder, K. (2017). Fundamentals of automotive technology. Jones & Bartlett Learning.

Vassighi, A. & Sachdev, M., 2011. Thermal and power management of integrated circuits, New York: Springer.

Warren, J.-D., Adams, J. & Molle, H., 2011. Arduino robotics, New York: APress.

Yao, B. et al., 2011. The effect of thermal stress on high density packaging integrated circuits. 2011 International Symposium on Advanced Packaging Materials (APM).