

University of Wales Trinity Saint David

School of Engineering

*Major Project 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. Extensive research has been carried out to determine the importance of steering systems to control automotive vehicles and how assistive control has evolved from conventional, to electronic control.

Research and analysis has been completed to establish the inherent potential failure modes and effects of EPAS systems, in this instance potential failures as a result of applied thermal stress and fatigue. 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 identified the effects of thermal cycling, where it was found that as a result of thermal fatigue, there are changes in the surface flatness and electrical performance with thermal cycles respectively.

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1. Introduction

This major project report is an investigation in to the performance of a manufactured product following extensive applied thermal cycling.

The manufactured product is a power control module for an automotive electrical power assisted steering system (EPAS). This major project investigates through research and testing, the concerns of a potential failure of an EPAS system through extensive research into determining the implications, thermal stress has on its capability.

Steering systems are extremely critical within an automotive vehicle; they allow the driver to control the vehicle accordingly in every instance, for example during cornering. Therefore, it is a safety critical feature of a vehicle and it is extremely important to identify and reduce any inherent issues with the systems.

Issues such as a defect concern with a manufactured EPAS power control module could possibly result in EPAS failure, where worst case scenario is loss of steering.

Prior to the introduction of EPAS, steering assist systems were predominantly hydraulic assist, therefore mechanical issues would have been the more prevalent concern, such as loss of fluid or issues with the drive to rotary pump etc. Mechanical issues can also occur in EPAS systems, such as failure with the rack and pinion or steering column.

However, EPAS can also experience electrical failures, electrical items could experience inherent issues, such as the ECU or the power control module, issues can lead to failure within the electrics and have consequences on the overall system, issues can occur from noise and vibration damage, water ingress, electrical radiation interference and thermal stress etc.

The main objective of this major project is to determine the effects of thermal stress on the manufactured EPAS power control module.

1.1. Background

The EPAS power control module that will be critically analysed is manufactured at KSR International Swansea. KSR manufacture and supply to a customer which uses the power control module within its EPAS system. During manufacturing of the module a defect was identified with the integrated direct bonded copper (DBC) circuit substrate which is supplied to KSR from an external supplier. The defect was identified at end of the production line by quality inspection staff, and it was found that several power modules had missing thermal stress dimples on the back of the DBC substrate. To determine the effects of the missing dimples the power module will be thermal stress tested and critically analysed. 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, a thermal shock chamber will be used to apply thermal stress to the power modules through cycling of a top and bottom temperature, and surface flatness will be measured using an optical gaging product (OGP) coordinate measuring machine (CMM), where a surface flatness measurement will be taken of the modules surface plane.

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

As discussed, 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. Steering systems consist of a steering column and wheel, and steering gears and linkage (Jain and Asthana, 2002). The drivers input through the steering wheel, rotates the steering column shaft – the steering gears transfer the rotational motion of the shaft to linear motion of the steering linkage which moves the vehicles front wheels in the desired direction and the steering gears increase the steering output allowing the drivers input effort to be reduced (Erjavec and Thompson, 2014).

There are two types of steering gear systems most commonly used in automotive vehicles; these are the “rack and pinion” and “recirculating ball” mechanisms.

Rack and pinion systems use a pinion gear at the end of the steering column shaft, which transfers rotational motion to a geared rack which transfers linear motion to the wheels via tie rods (Noorulla et al., 2010) as shown in figure 1.

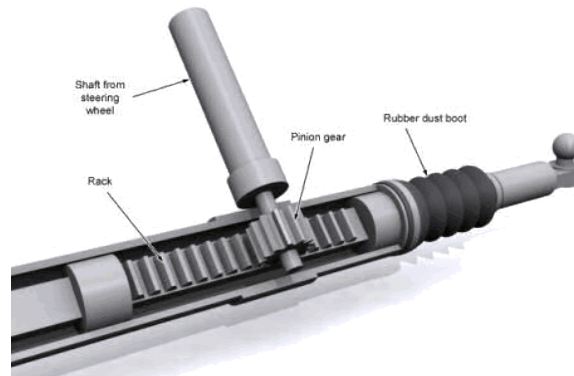


Figure 1: Rack and Pinion (Source: Sharma, 2017)

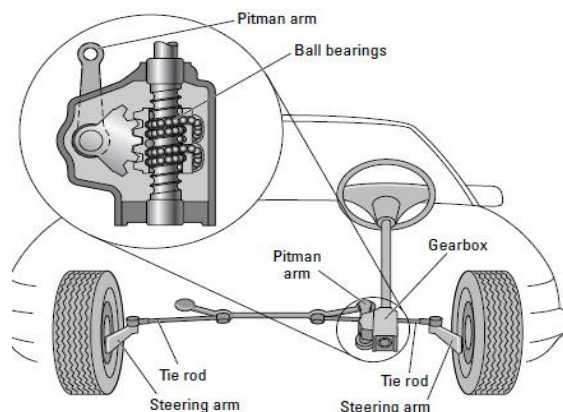


Figure 2: Recirculating ball system (Source: Bajza, 2009)

and down), which transfers the motion across the steering linkage to the tie rod ends (Bennett, 2007).

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 – also as tyres became wider the tyres resistance to motion became larger, therefore a greater effort was required (Horobin, 2003).

An advantage of power assisted steering is it provides increased accuracy and reacts quicker to allow for sudden wheel movements while allowing for heavier steering loads (Nunney, 2015).

There are two main types of power assisted steering, Hydraulic assist and Electrical assist. Both assist systems are used within the automotive industry, however prior to the introduction of Electrical assist, hydraulic was more prevalent (Automotive Training Centre, 2014).

Hydraulic power assist systems (HPAS) work with the use of a hydraulic pump which is driven by the engine, predominantly driven by the engines crank via a belt. The hydraulic pump, delivers hydraulic fluid to a ram cylinder, which using pistons, manoeuvres the pressurized fluid through a rotary valve which transfers torque to a torsion bar connected to the pinion/worm gear (Denton, 2011).

However, although this system was widely used, there are many disadvantages to hydraulic power assist systems, one disadvantage is that the hydraulic pump is driven via a pulley which as mentioned is driven by the engine therefore, there is always energy drawn from the engine by the pump even when the assist to steering isn't needed, as a result this method isn't considered highly fuel efficient (Dell et al., 2014). In fact, hydraulic power assisted steering, as a system isn't particularly fuel/cost efficient.

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. EPAS is becoming more prevalent and there is more widespread deployment of EPAS within the automotive industry; this is because it allows improved assistive control, by reacting faster to steering alterations than hydraulic assist. EPAS also provides economic benefits, as it is cheaper to install and run throughout its lifecycle, the use of EPAS eliminates the large, heavy hydraulic components, therefore reducing the mass and size of the steering system and providing a reduction in overall vehicle mass (Crolla, 2009).

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).

Due to global emission standards, the automotive industry is under extreme pressure to reduce vehicle emissions and therefore reducing the mass and amount of energy used in each sector of the vehicle will help to reduce the vehicles overall energy consumption and ultimately reduce engine load to become more efficient and reduce its emission output, in order to aid this global mission – the requirement for downsizing doesn't just restrict engines but also other vehicular systems i.e. steering – a lighter and less energy consuming system will reduce the overall load on the engine (Kahfagy, 2017).

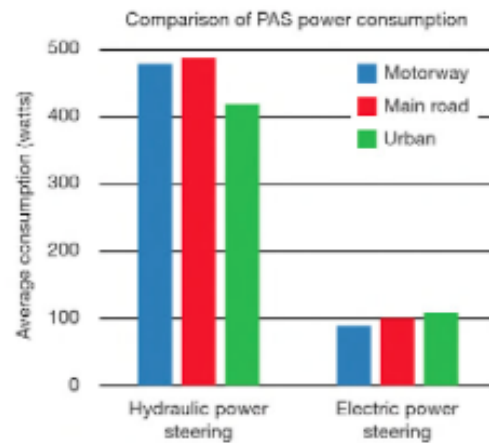


Figure 3: Hydraulic vs Electrical Power assisted steering (Source: Denton, 2014)

It can be seen from figure 3 that hydraulic power steering uses significantly higher average energy consumption than electric power, based on figure 3, on average of motorway, main road and urban hydraulic uses approximately 360 watts more than electric.

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.

HPAS is larger, heavier and has more parts than a EPAS system, therefore it could be suggested that there is a larger chance of potential failure with HPAS, for example, hydraulic fluid leakage, which could lead to the system being without oil therefore, moving parts that require oil for lubrication such as the rotary valve could cease and be damaged (Dell et al., 2014). Mechanical issues such as parts ceasing, i.e. rack and pinion gears etc. usually result in a decrease in steering ability, preventing full steering ability until fixed, however allowing the vehicle to be manoeuvred to a safe place – complete loss of steering is very rare in this circumstance (Thompson, 2013).

However, as mentioned EPAS systems can have inherent issues also, mechanical issues remain a potential concern due to moving parts. 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.

An analysis will be carried out to determine the performance characteristics of the power control module following extensive thermal stress testing.

The power module is used within a column assist type EPAS, which uses a power assist unit, controller and torque sensor. The power module is used within the power assist unit to power the electric motor, the controller receives information from the torque sensor which monitors load on the steering wheel, the controller uses the load feedback from the torque sensor to determine the amount of assist required by the power assist unit (motor) (Kershaw and VanGelder, 2017).

Electrical components can become subject to thermal fatigue due to thermomechanical and thermoelectric stresses caused during operation, in this instance the power module will be within an engine bay of a vehicle, therefore will undergo a range of different temperatures due to its subsequent environment, therefore the use of thermal cycling will accelerate the thermal fatigue process.

Applied thermal stress, can lead to both mechanical and electrical failures – the electrical failures can be caused by thermal fatigue to the power module internals such as transistors and capacitors, in this instance the MOSFET's, if damaged, can result in reduced performance or failure due to thermal fatigue which can result in electrical over-stress (Băzu & Băjenescu, 2011).

The power module can also experience electrical failure, caused by mechanical thermal fatigue. Different thermal properties of materials can mean that different materials react to thermal stresses and changes differently, thermal stress within power modules 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).

Thermal stress isn't just limited to the electrical components i.e. integrated circuits, thermal stress can also cause defects and failure to the encapsulate material i.e. the plastic moulding enclosure, which acts as a protective barrier to the components and wire bonds, however excessive thermal stress could possibly lead to delamination of the plastic, compromising its structural integrity, therefore could result in the internals, in particular the wire bonds, being subject to further stress, through reduced protection from thermal stress, water ingress, vibrations and electromagnetic interference (Yao et al., 2011).

Potential failures, causes and effects are critically analysed and reviewed prior to manufacture of the project using a DFMEA (Design Failure Mode and Effects Analysis), therefore all potential failure modes of a full power assisted steering system would have been considered. A DFMEA is a complex methodology completed by engineers, it consists of a list which is compiled of potential failure modes and their effects, it is important to ensure that the potential failure modes and effects are identified as early as possible i.e. design verification, to ensure any failure modes directly determined by the design are identified and all endeavours are made to alter design to minimise risk (Quality-One, 2017).

The DFMEA for the power module was completed by the design team at KSR, due to intellectual property the DFMEA documents are company confidential, and therefore are not disclosed within this project. All potential failure modes such as loss of steering etc. would have been rated out of ten in

three categories in accordance with its severity, likelihood of occurrence and detectability which multiply together to give a risk priority number (RPN) for each potential failure mode. The initial DFMEA will highlight the severity of the all the potential failure modes and the effects it would have if occurred in the field and its effect on customer and/or manufacturing assembly in accordance to safety and/or regulatory requirements (General Motors Corp, 2008).

Upon review of the initial DFMEA, design, process and quality engineers work on reducing occurrence and improving the detectability of each failure mode to reduce the RPN of each failure mode, therefore all the potential failure modes associated with thermal stress would have been considered and the risk of high occurrence and low detectability would have been improved to reduce the overall RPN.

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 defect DBC was identified at the end of the production line during manufacturing, it was discovered that many of the power modules were found to have missing thermal stress relief dimples on the back of the DBC as seen in figures 4 and 5.

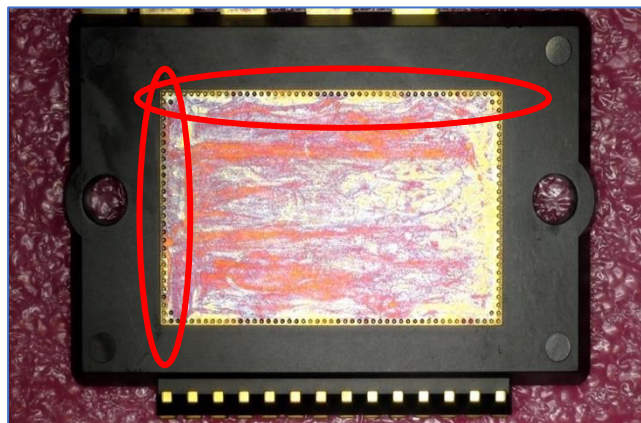


Figure 4: DBC with no missing dimples (Source: KSR and Thomas, 2017)

A controlled sample of power modules with no missing dimples i.e. non-defect parts, as seen in figure 4, will also be analysed to determine the effects of thermal cycling, and the consequent stress from thermal loading, has on the surface flatness and performance of non-defect parts to provide a comparison of the effects on the defected power modules with missing dimples on the DBC.



Figure 5: DBC with missing dimples (Source: KSR and Thomas, 2017)

In figure 5, it can be seen that there are a number of dimples missing on the DBC, the pattern shown isn't a direct trend in all 6 defect parts collected for this investigation, and some have less/more dimples missing than others. The project aims to determine the implications of the missing dimples on the DBC and power module, firstly while looking at a company (KSR) point of interest, it is important to determine the implications of a product produced and supplied to a customer with a quality concern, it's important to ensure that a quality concern does not have any effect on the working performance of the product and/or customer parts/assemblies.

A defect part reaching a customer could lead to a customer complaint/return, investigations, loss of contract therefore loss in revenue etc. And/or negatively affect the reputation of the company (Uzun, 2002).

There were many DBC's found with missing dimples, although, no power modules have been found without any dimples at all on the DBC. For further study, a recommendation would be to carry out an analysis of a comparison between DBC's with no dimples at all. Therefore, this would provide a best (no defect) and worst scenario comparison.

To provide a detailed evaluation on the critical analysis of the effects of thermal stress on the flatness and performance of the power control modules with missing thermal relief dimples, a sample of 6 defect parts have been selected for testing and analysis along with a sample of 6 controlled parts as a comparison.

2.3. DBC Substrates

The DBC substrates are supplied to KSR for the use within the power module, the DBC substrate is an integrated circuit which is 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).

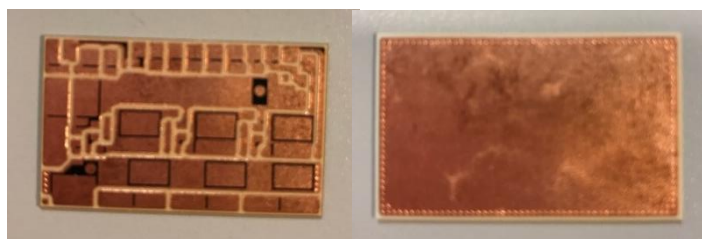


Figure 6: DBC substrate (Source: KSR and Thomas, 2017)

Al_2O_3 although a brittle material, is widely used for this purpose due to its low cost and use within the microelectronics manufacturing, it has a thermal conductivity of 24 W/mK @ 20°C which isn't a perfect thermal conductor however the DBC with the ceramic and copper layers has a very low coefficient of thermal expansion which is significantly lower than copper alone - as a result provides excellent electrical insulation (Dong et al., 2010).

However, copper and Aluminium Oxide have different thermal expansion properties, therefore due to excessive thermomechanical stress caused when operating within exaggerated operational conditions which is induced through thermal cycling, delamination and cracks can form between the copper and aluminium oxide causing warpage and performance reduction (Lei et al, 2009).

To increase the thermal reliability of the DBC, thermal relief dimples are etched into the copper. The copper is cut forming dimples using a photochemical etching process which uses a cover plate to hide areas which don't require etching and areas which require etching are left exposed to an etching acid (Madou, 2007).

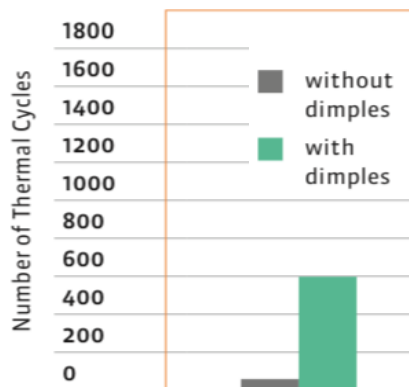


Figure 7: Comparison with/without thermal relief dimples (Source: Curamik, 2014)

The thermal relief dimples work by reducing the mass and overall volume of the copper, copper alone has an extremely high electrical conductivity and also high thermal conductivity, because of this copper heats up when current is passed through it and therefore is more thermal sensitive than the ceramic (Laughton & Warne, 2003). With the reduction in copper, there is a decrease also in the tensile strength – however according to a report written by Schulz-Harder in 2002, the reduction in copper material caused by the forming of the dimples “increases the temperature cycling reliability by 10 times” (Schulz-Harder, 2002).

This theory is also supported by a report written by Curamik in 2014, where it was also stated that the lifetime can be increased significantly as shown in figure 7.

Figure 7, shows the comparison between DBC's with/without dimples, it can be seen that there is a significant increase in the amount of thermal shock cycles the DBC's can endure with dimples compared to DBC's without dimples. Virgin DBC's (not power module) without dimples appear to endure less than 100 thermal cycles before cracks form, however, DBC's with dimples endure approximately 600 thermal cycles before cracks form, therefore the advantages of thermal relief dimples can be seen (Curamik, 2014).

Although, a statement made by Lei, et al., in 2009, is although DBC's with dimples can endure more thermal cycling due to increased reliability, reliability remains a concern at higher temperatures than used within cycling, this is due to the copper and ceramic boundary conditions and different thermal expansion rates (Lei et al, 2009).

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

The flatness of the back of the power module, which includes individual measurements of the surface flatness of the DBC, the plastic moulding and an overall value for the overall flatness of the back of the power module are significant dimensions specified by the customer on the design specification and technical drawing, 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 8.



Figure 8: Power Module attached to customer's heatsink (Source: Thomas and KSR, 2018)

Therefore this dimension has a significant effect on the customers product and as a result, the flatness measurement is controlled using statistical process control (SPC), which is a tool used to control manufacturing processes, SPC works by using the upper and lower tolerances to set upper and lower safe limits in conjunction with quality and process capabilities, the upper and lower safe limits are tighter than tolerances set by the customers specification as this aids in control process capabilities and ensure that all products are meeting specification, this is achieved by introducing control methods such as measuring and collecting statistical data which can be accessed at any time to ensure measurements are within specification (Does et al., 1999). Surface flatness is measured weekly as part of SPC checks to ensure that the weekly shipments are of a high process capability, enough to produce products within specification. The SPC data is collected and submitted to the customer as a certificate of analysis (CofA), which is an “authenticated document” which certifies the quality and quantity of each shipment, validating that the measurements, specifically the surface flatness measurements meet specifications, controlled by SPC checks and certified by the CofA (Kondhare, 2016).

However, using SPC to control dimensions in conjunction with manufacture and product design, could lead to the production of an over-engineered product, although this can be good as it ensures the quality of the product to a high standard, it can increase the overall cost of the product, a higher quality product, comes at a cost such as material and cost of tighter controls such as SPC, therefore the product demands a higher price which can lead to customers changing to a cheaper supplier, therefore many companies are able to benefit from the theory and practice of lean manufacture to improve products and processes that reduce the overall cost, by making modifications to an over-engineered product's design/process (Strutt and Hall, 2003).

Flatness is measured by determining the distance a surface differs from the specified plane (Quality Digest, 2007).

The distance between the surface and the specified plane must be within tolerance, the tolerance is stated on the technical drawing by the customer with the use of geometric dimensioning and tolerancing which is a tool used to accurately state the significance of the flatness dimension and provides guidance of the design expectations, for example as shown in figure 8.

The symbol on the left shows that there is a GD&T flatness dimension and the figure on the right-hand side is the tolerance of the flatness dimension (Pareto Learning LLC, 2017).

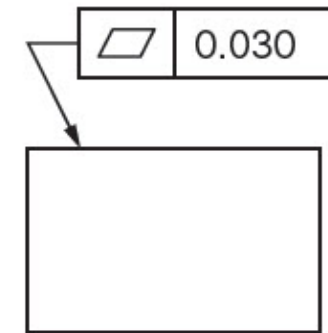


Figure 9: GD&T flatness example
(Source: Pareto Learning LLC, 2017)

Flatness tolerance within the upper and lower limits are extremely important as it ensures all sections of the power modules relationship face with the customers heatsink component are in contact, if the surface wasn't in specification i.e. outside limits, there would be sections of the surface face not in contact with the customers heatsink, which would create micro pockets of air and would increase the thermal resistance between the heatsink and the module, therefore to reduce the thermal resistance and reduce the dependence on thermal adhesive it is critical to ensure the surface flatness meets the specified limits (Lutz et al, 2018). The aim of this investigation is to determine if the thermal stress will negatively affect the surface flatness, i.e. creating a negative impact on the working condition and not meeting the flatness specifications.

2.5. Electrical Performance Parameters

The electrical performance of the power module is an extremely important characteristic, as it provides electrical power to the customers overall EPAS assembly, a reduction in the electrical performance or complete failure would result in no power from the power module, therefore no power to the EPAS system, reverting the system to conventional steering without assist. In order to monitor

and determine the electrical performance of the power module, each power module undergoes an electrical continuity test where the MOSFET's in each module is tested for its voltage, current and resistance outputs. This is an in-line process as part of production, where power modules that pass the test continue down the production line, and power modules that fail the test are rejected from the line. During the manufacturing process of the power module each DBC substrate is populated with 6 MOSFET's, the 6 MOSFETS's are used to control the voltage and current flow by switching and amplifying the source signal (Baliga, 2014).

The voltage, current and resistance of the 6 MOSFET's are parameters which will be analysed to determine the overall electrical performance of the power module.

Resistance is an extremely important parameter; this is because during current flow it is important to have a very low resistance, to increase voltage gain and overall functionality of the MOSFET and power module (Dehghani, 2013).

Resistance is thermal sensitive, and inversely proportional to temperature changes; resistance is reduced when temperature increases and increases when temperature falls (Vassighi & Sachdev, 2011). Considering ohm's law, $Voltage = Current \times Resistance$, due to changes to resistance as a result of temperature changes, it would be expected to see changes to the current and voltage also, and therefore effect the electrical performance of the power module (Luryi & Xu, 2010). In relation to the resistance of the MOSFET's, ideally the resistance would need to be low during switch on, to reduce restriction of current, and prevent electrical over-stress (Korec, 2011).

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.

The power module manufactured, as mentioned is used within an EPAS system, however, it ultimately is a power module which provides power to an assembly or ECU etc. Therefore, the concerns of thermal stress is a concern in all electrical components and circuitry, electrical resistance is sensitive to thermal changes, and according to ohm's law, current is inversely proportional to resistance, therefore, applied thermal stress could affect the electrical performance as discussed above (Cook, 2010).

In relation to thermal stress causing distortion/warpage, this is a concern in all applications where a material is thermal sensitive, specifically during thermal cycling which will accelerate the thermal changes, and the material will expand and contract, this applied thermal stress will then contribute to distortion/warpage of the material and/or cracks (Fischer, 2013)

3. Methodology

All live practical testing was carried out at KSR Swansea in a laboratory environment and various tools and equipment were used, therefore appropriate PPE (personal protection equipment) was used and all company health and safety guidelines were followed with the adequate and appropriate supervision.

3.1. Thermal Shock Cycling

Application of thermal stress to the controlled and defect samples, were carried out by placing the power modules inside a thermal shock chamber (figure 10), the process of thermal shock cycling was carried out by objecting the power modules to a total of 1000 cycles.

Thermal shock cycling is a test where a thermal shock chamber is used to subject components/parts etc. to sudden changes in significantly high/low temperatures, achieved by rapidly over a controlled period moving the components/parts from one temperature section of the chamber to the other (Ward & Angus, 1999).



Figure 10: Thermal Shock Chamber (Source: KSR and Thomas, 2017)

The thermal shock cycles were carried out in 250 cycle increments i.e. the power modules endured 4 cycle increments in total, 250, 500, 750 and 1000. 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 $-40^{\circ}\text{C} \pm 5\%$, as shown in figure 11, this was one full cycle, in total this was completed 1000 times.

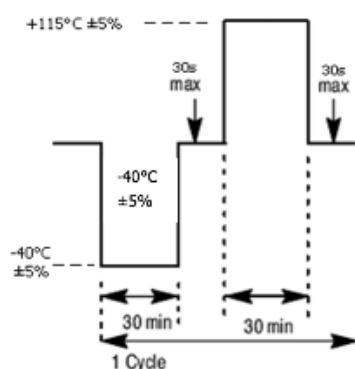


Figure 11: Thermal Cycle Test (KSR, 2017)

The thermal cycling durations are determined by the customers test specification, where the customer specifies the discussed cycle for a total of 500 cycles in 250 increments, at which the power module is inspected using a ultrasound microscope to ensure there is no cracks or damage to solder joints and/or wire bonds on the DBC, also an electrical continuity test is carried out to ensure power modules are still in working order after each 250 cycles. This validation process is completed every month as part of SPC checks

to provide the customer with data to show that the manufactured power modules meet their requirements.

Although the test specification set out by the customer is 500 thermal shock cycles, in this instance – to improve the accuracy and validity of the testing and validation process, the power modules completed 1000 thermal shock cycles as mentioned, and were removed every 250 cycles for inspection, testing and measuring.

The use of thermal cycling is to accelerate the time to failure of the power module, by running thermal cycles it will simulate temperature changes of life in service in an accelerated and controlled time frame, and through repetition it can be used to predict the thermal fatigue life of the product. Although it can be used to predict the thermal fatigue life of the product, it is only a prediction however, as there is no certain connection between the acceleration of fatigue rate through live simulation to full life in service conditions, and therefore manufacturers simulate a number of other tests and sometimes over-engineer a product to ensure that it meets life in service requirements (Liu & Liu, 2011).

3.2. Visual Inspection and Electrical Continuity Test

Following each 250 thermal cycles, the power modules were removed from the thermal shock chamber and inspected by the failure analysis engineer, using a non-destructive method, with the use of Scanning Acoustic Microscopy (CSAM), which uses ultra-high frequency ultrasound to identify any physical failures within the power modules, such as cracks caused by the thermal stress. Other methods of non-destructive testing such as X-Ray could be used, however for this purpose CSAM imaging provides clearer and more accurate analysis due to the high-frequency ultrasound, which allows cracks to be identified much easier (Kessler, 2013).

The electrical continuity test was carried out by the validation engineer, following the CSAM imaging after every 250 cycles also, as part of the non-destructive testing. The electrical continuity test is carried out to ensure that the power module is working correctly. An electrical continuity test is a means of ensuring that current flows through a circuit. Therefore, a voltage is sent through the power module and used to determine if it is in working order (Stewart & Jardine, 1994).



Figure 12: CSAM ultrasound (Source: KSR and Thomas, 2017)



Figure 13: Electrical Test Machine (top) and Internal contact points (bottom) (Source: KSR & Thomas, 2017)

An electrical continuity test 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 13) has been specially made for production to carry out the electrical continuity test on the power module during production. The continuity test measures 6 parameters on the MOSFET's, which reflect the electrical specifications and their performance.

It has specific contact points which line up to each terminal on the power module keys, each key corresponds to specific MOSFET's and their parameters, via wire bonds, with it being a production line tester, it is automated, and therefore reducing human contact and

subsequently reducing human error and increasing accuracy and validity of results (Cresswell, 2002).

3.3. Flatness Measurements

Flatness measurements were also be completed after every 250 cycles to determine the surface flatness of the back of the power module. Flatness measurements were taken to determine surface flatness changes, indicating if there was any warping occurring of the power module and if the missing dimples have any accelerated effect on the change in flatness - due to the thermal stress occurring during thermal shock cycling.

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 14) 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 flatness measurements are recorded by measuring specific points across the surface, on each power module 29 points are measured, consisting of 15 points across the DBC and 14 points across the plastic moulding. The



Figure 14: OGP machine (Source: Thomas, 2017)

programme automatically takes an average of the points to determine a flatness measurement for the overall, DBC and plastic moulding flatness.

The OGP machine uses a specific programme to complete automated measurements, this could be completed using a manual touch probe CMM which is less expensive than the OGP machine used. However, 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). The flatness measurements will be extracted from the integrated software into Microsoft Excel for analysis, and the results after each 250 thermal shock cycles will be reviewed and analysed, a comparison will be made from start to finish of testing with controlled and defect DBC's.

4. Results and Analysis

By using 12 power modules, with a total of 6 controlled and 6 defect for comparison, a vast amount of data is able to be collected and therefore increases the validity of the critical analysis, compared to if only one of each power module was tested. A bigger sample tested increases the testing practice and provides an increased validity of the results, therefore improving the overall analysis and evaluation (Wei et al., 2013).

Bench mark data was taken prior to testing, therefore before thermal cycling each of the 12 power control modules were measured to determine it benchmark surface flatness, the electrical test was carried out to determine the average and standard deviation of the voltage, current and resistance of the MOSFET's on each module. As well as measurements and electrical test, all power modules were inspected using CSAM imaging and no cracks or damage was identified as shown in figure 15.

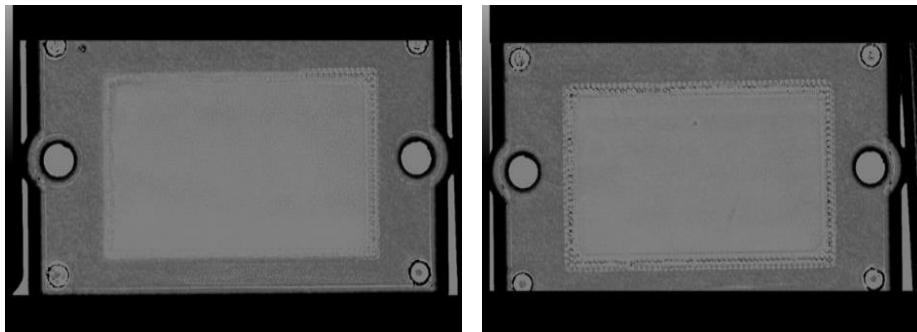


Figure 15: CSAM imaging Defect (left) and Controlled (right) (Source: KSR, 2017)

The flatness of the power modules is measured in microns, as shown in figure 16 and appendix 1 the overall flatness is significantly higher than the DBC flatness, this is because the overall flatness is taken from an average of the 29 total points measured across the power module, the plastic moulding which encapsulates the DBC, and therefore provides a higher distance from the surface plane effecting the overall flatness.

An average of the 6 defect/controlled power modules have been calculated to provide a flatness measurement for the DBC, plastic and overall.

	DBC Flatness (microns)	Plastic Flatness (Microns)	Overall Flatness (Microns)
Controlled Part 1	33.5	64.3	72.5
Controlled Part 2	36	66.6	72.4
Controlled Part 3	33.5	67.5	70.5
Controlled Part 4	32.4	69.5	68
Controlled Part 5	39.3	69.6	74.6
Controlled Part 6	36.9	74.3	79.2
Average	34.9	67.5	71.6
Standard Deviation	2.47	2.79	3.85

Defect Part 1	37.8	64.5	71.2
Defect Part 2	38.3	67.9	73.6
Defect Part 3	33.7	63.9	61.3
Defect Part 4	34.4	68.2	69.6
Defect Part 5	32.3	67.2	63.7
Defect Part 6	36.7	65.2	69
Average	35.5	66.2	68.1
Standard Deviation	2.42	1.85	4.66

Figure 16: Benchmark flatness measurements (Source: Thomas & KSR, 2017)

The overall average flatness for the controlled power modules is 71.6 microns and defect is 68.1 microns, this compared to the customer's specification tolerance which is 120 microns is much lower. As part of SPC, KSR have an upper control limit of 90 microns, 30 microns lower than the specification tolerance set by the customer, the benchmark results show that even with defects the power module meets both customer and KSR specifications.

The average DBC flatness was measured as 34.9 microns for the controlled, and 35.5 for defect, again significantly lower than the specification tolerance for the DBC of 100 microns with a KSR upper control limit of 80 microns.

The plastic has a tolerance specification of 200 microns with a KSR upper control limit of 150 microns; the average flatness for the plastic is significantly lower again as shown in figure 16 as 67.5 microns and 66.2 microns.

The MOSFET's were tested for their voltage, current and resistance, all 6 MOSFET's on each power module was tested. Therefore, with a total of 12 power modules, 6 MOSFET's, there are a total of 72 sets of data. To remain consistent, an average and standard deviation for each power module's MOSFET's were calculated to provide a comparison for analysis.

	Drain Current (amp)	Drain Voltage (V)	Drain Resistance (Ω)
Controlled Part 1	6.8×10^{-8}	43.4	1.881×10^{-3}
Controlled Part 2	7.9×10^{-8}	43.9	1.89×10^{-3}
Controlled Part 3	6.9×10^{-8}	43.7	1.881×10^{-3}
Controlled Part 4	7.5×10^{-8}	43.6	1.88×10^{-3}
Controlled Part 5	6.9×10^{-8}	43.7	1.882×10^{-3}
Controlled Part 6	7.1×10^{-8}	43.5	1.893×10^{-3}
Average	7.2×10^{-8}	43.6	1.885×10^{-3}
Standard Deviation	4.2×10^{-9}	0.2	5.46×10^{-6}

Defect Part 1	5.9×10^{-8}	43.2	1.873×10^{-3}
Defect Part 2	1.3×10^{-7}	43.7	1.886×10^{-3}
Defect Part 3	6.4×10^{-8}	43.1	1.889×10^{-3}
Defect Part 4	1.6×10^{-7}	43.7	1.894×10^{-3}
Defect Part 5	6.1×10^{-8}	43.3	1.913×10^{-3}
Defect Part 6	6.8×10^{-8}	43.6	1.874×10^{-3}
Average	8.9×10^{-8}	43.4	1.888×10^{-3}
Standard Deviation	4.3×10^{-8}	0.3	1.475×10^{-5}

Figure 17: Benchmark electrical test data (Source: KSR, 2017)

The benchmark data doesn't allow for critical analysis; however it does provide a comparison for the data collected every 250 cycles. It can be seen that from figure 17 and appendix 2, the data doesn't vary a lot with each power module, and this may not become more apparent until compared to data taken following thermal cycling.

In order to determine the “electrical performance” characteristics of the power module, the drain to source current, voltage and resistance will be analysed.

In order to benchmark the internal condition of all the power modules, as mentioned CSAM imaging was carried out also shown in figure 15 and appendix 3.

4.1. Post 500 Thermal Cycles

Firstly, looking at the data for after the first 500 cycles, this is because 500 cycles is the specification set by the customer as discussed; the extra 500 thermal cycles are for further analysis and guarantee the quality of the power module.

Following 500 thermal cycles the power modules as discussed were measured for their surface flatness and tested for their electrical performance, this was also completed at 250 cycles.

The flatness data was recorded as shown below in figure 18, this was taken from the raw data in appendix 1, averages have been made for the 6 controlled and the 6 defect parts for DBC, Plastic and overall flatness.

	Post 250 Cycles			Post 500 Cycles		
	DBC Flatness (Microns)	Plastic Flatness (Microns)	Overall Flatness (Microns)	DBC Flatness (Microns)	Plastic Flatness (Microns)	Overall Flatness (Microns)
Controlled Average	37.78	74.44	80.25	39.17	76.22	82.53
Standard Deviation	2.37	1.76	1.63	0.88	1.65	2.44
Defect Average	38.83	74.23	81.05	40.63	75.97	83.8
Standard Deviation	0.78	1.72	1.41	1.87	1.18	1.68

Figure 18: Flatness measurements post 250 and 500 thermal cycles (Source: Thomas & KSR, 2017)

In comparison from figure 16 and in figure 18 from 250 to 500 cycles, it can be seen that the surface flatness of the DBC, plastic and as an overall has risen, following the 500 cycles.

For example, the average DBC flatness for controlled has risen from 34.9 microns to 39.17 microns, and the average defect DBC flatness has risen from 35.5 microns to 40.63 microns, it can be seen that the defect part has had a larger increase in the surface plane, decreasing the flatness capability.

Overall the flatness as a whole has increased with thermal cycles respectively with the exception of the plastic as shown in figure 18 and 19.

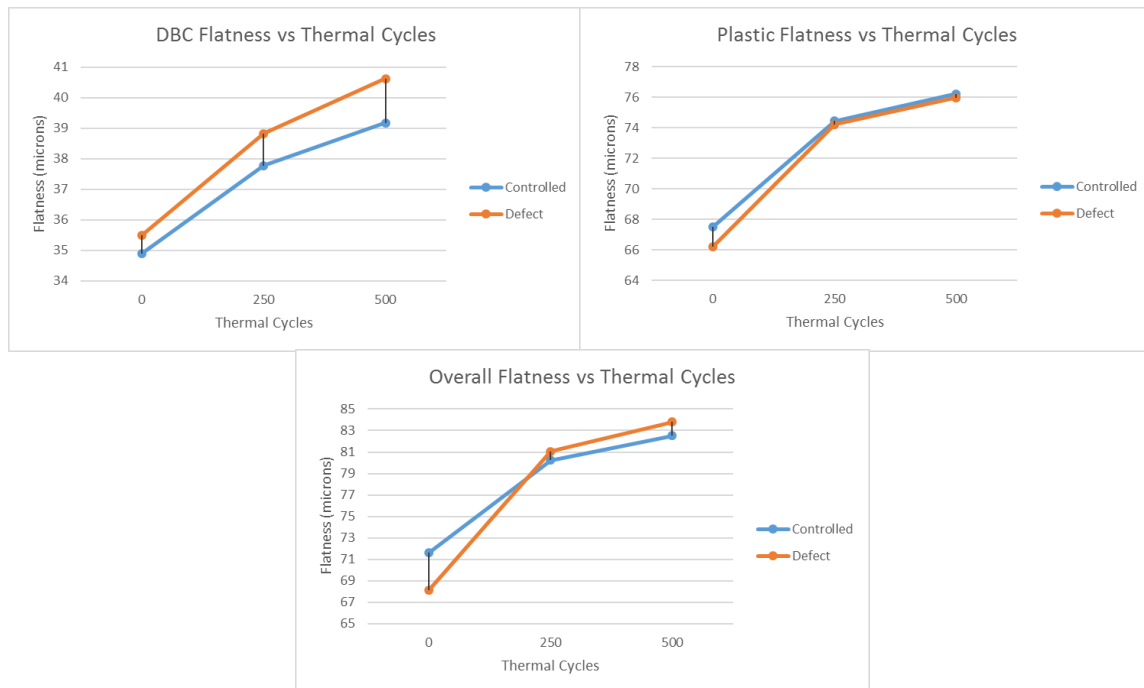


Figure 19: Flatness vs Thermal Cycles post 500

The DBC and overall flatness both increase with thermal cycles respectively, it can be seen that the DBC has an almost linear increase with thermal cycles, and appears to increase significantly more than the changes seen in plastic flatness, this could be due to the difference in thermal expansion coefficients of the materials with the polyethylene resin pellets having a lower thermal expansion coefficient compared to varying thermal expansion coefficients of the DBC substrate causing larger thermal dissipation within the material (Singh & Asthana, 2011).

From figures 18 and 19, it can be seen that the defect sample of power modules have a larger increase in the flatness measurement compared to the controlled samples, meaning a lower flatness capability, this could suggest that due to the missing dimples, the power modules aren't performing as well as the controlled samples, which may be due to the reduction in thermal relief.

The CSAM imaging of the power modules following the 500 thermal cycles show no subsequent defects as a result of stress as shown in figure 19 and Appendix 3.

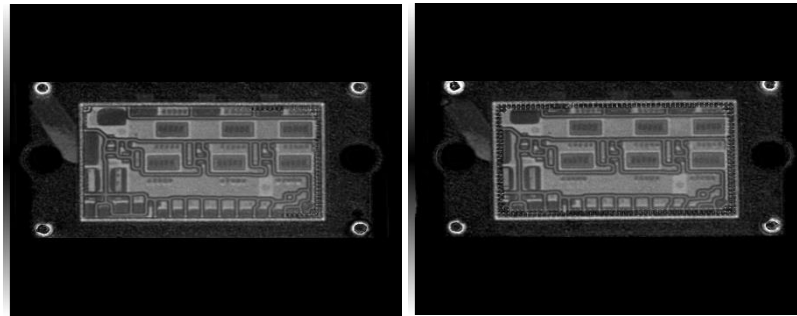


Figure 20: CSAM imaging of defect (left) and controlled (right) parts post 500 cycles (Source: Dunn & KSR, 2017)

It can be seen from the CSAM images taken of a defect part (left) and controlled part (right), that following the 500 thermal cycles, all wire bonds and solder joints are intact and there are no cracks in the material of the DBC or plastic (Dunn, 2017).

	Post 250 Cycles			Post 500 Cycles		
	Drain Current (amp)	Drain Voltage (V)	Drain Resistance (Ω)	Drain Current (amp)	Drain Voltage (V)	Drain Resistance (Ω)
Controlled Average	8.26×10^{-8}	43.64	1.89×10^{-3}	7.99×10^{-8}	43.70	1.89×10^{-3}
Controlled Standard Deviation	5.65×10^{-9}	0.2	7.85×10^{-6}	3.91×10^{-8}	0.38	1.52×10^{-5}
Defect Average	8.51×10^{-8}	43.53	1.89×10^{-3}	7.66×10^{-8}	43.75	1.9×10^{-3}
Defect Standard Deviation	3.7×10^{-8}	0.4	1.79×10^{-5}	4.59×10^{-9}	0.27	6.41×10^{-6}

Figure 21: Electrical test data post 250 and 500 cycles (Source: KSR, 2017)

In relation to the current and resistance values it can be seen that the values are extremely small, and across all three parameters it can be seen that the deviation between power modules and with thermal cycles are extremely small also with the standard deviation ranging from 4.59×10^{-9} and 3.91×10^{-8} amps, 0.2 and 0.4 volts and 6.41×10^{-6} and 1.79×10^{-5} ohms.

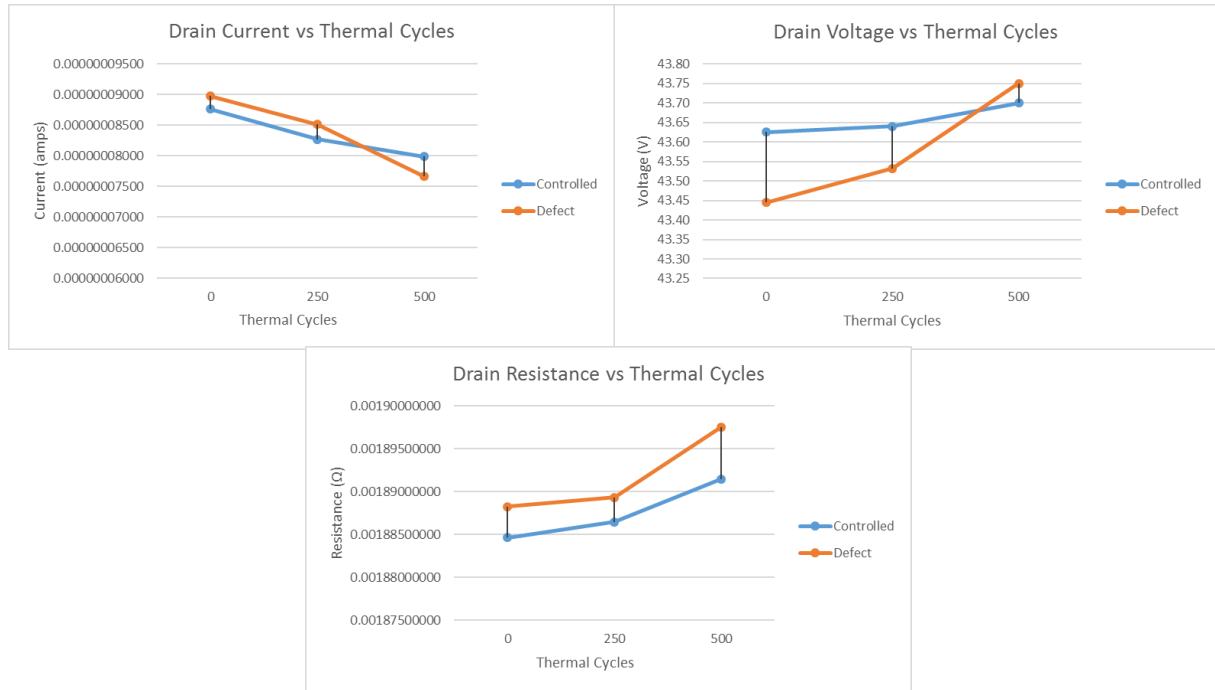


Figure 22: Current, Voltage and Resistance vs Thermal cycles

Applying the equation $\text{voltage} = \text{current} \times \text{resistance}$, it can be seen more evidently in the current and voltage graphs the relationship between voltage and current, with a slight reduction in the drain current of the controlled and defect samples with thermal cycles it can be seen that consequently there is an increase in drain voltage, however with the defect sampled it can be seen that the changes in current, voltage and resistance from 250 to 500 cycles, are more significant, displayed by the larger incline in voltage and resistance and decline in current from 250 to 500 than benchmark to 250 cycles, this could be as a result of the thermal stress causing the MOSFET parameters to experience electrical overstress (Gamota, 2014).

With CSAM imaging portraying and confirming that there are no cracks and all 12 power modules are in good working order, confirmed by the electrical test. Also, flatness measurements significantly below tolerance specification, the application of thermal stress doesn't show significant effects after 500 cycles.

Therefore, all 12 power modules meet quality standards, however as shown in the flatness measurements there was a slight increase in the surface flatness, altering and reducing the overall flatness capability, and it was also seen that voltage, current and resistance values altered with thermal cycles accordingly.

4.2. Post 1000 Cycles

As discussed, the extra 500 thermal cycles completed were to improve the accuracy and validity of the results and provides increased analysis through further testing.

Due to the observation of the changes to the power modules, as a result of the first 500 thermal cycles, a calculated hypothesis would be that the changes continue with thermal cycles respectively.

4.2.1. DBC Flatness measurements

With the DBC being the component with the defect (missing thermal relief dimples), while all parameters are being kept at a constant, the defect and controlled samples were the main variables, therefore an expectation would be to see varying outcomes particularly in the isolated measurements of the DBC, controlled compared to defect.

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

From figure 23 it can be seen that for both controlled and defect sample power modules, on average the surface flatness measurement increases with thermal cycles respectively, with a rise from 34.9 microns to 40.28 microns for controlled samples average, an increase of 5.38 microns. The defect samples average increase is 6.32 microns, which is a larger increase than the controlled samples, 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 24.

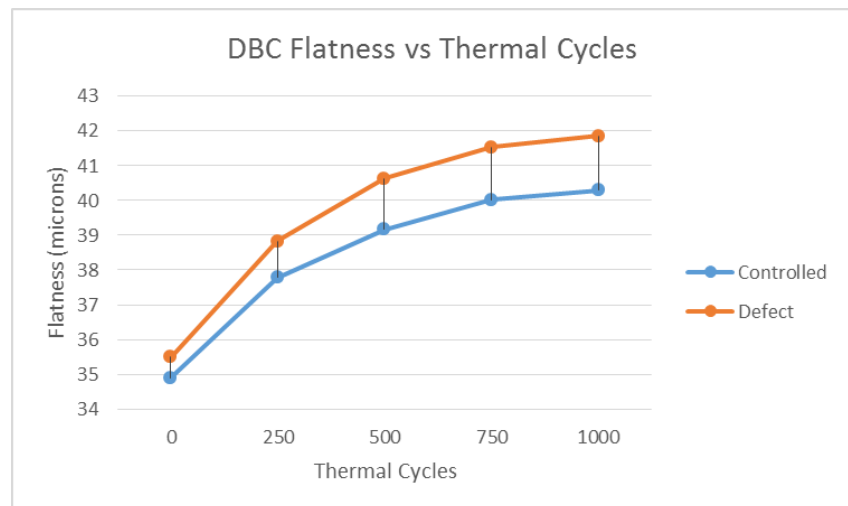


Figure 24: DBC Flatness vs Thermal Cycles

Following the first 500 cycles, the controlled samples average surface flatness increased by 4.27 microns and 5.1 microns for defect samples, however the flatness change from post 500 cycles to post 1000 cycles, didn't increase as significantly. The change for controlled samples between post 500 and 1000 cycles was 1.11 microns and 1.22 microns for defect samples.

Throughout the project, it can be seen from both figures 23 and 24 that the surface flatness measurement of the DBC on both controlled and defect samples increases respectively with thermal cycles, which suggests that the applied thermal stress from cycling is causing the surface flatness capability to decline and due to the rise in measurement of the DBC surface, it suggests that initial distortion of the DBC could well be occurring (Dunn, 2017).

However, while it can be seen that DBC surface flatness has increased with thermal cycles, it can also be seen that the increase is more significant and apparent in the defect samples. Overall, the average DBC defect sample increase was 0.94 microns more than the controlled samples; 0.83 microns more post 500 cycles and 0.11 microns between 500 and post 1000 cycles. 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).

4.2.2. Plastic and Overall Flatness measurements

In comparison to the DBC flatness it would be expected for there to be very little change between controlled and defect samples of the plastic and overall flatness measurements, this is because due to manufacturing process, the condition of the plastic is a constant for all 12 power modules, and as stated previously the defects were associated with the DBC substrates only (thermal relief dimples), however there is no evidence to suggest that the thermomechanical effects on the DBC cannot have a consequential effect on the plastic or overall flatness.

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

Similar to the flatness measurements recorded for the average DBC flatness, it can also be seen that plastic and overall flatness also increases with thermal cycles. The average controlled plastic flatness

risers 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 over 1000 thermal cycles. Plastic flatness follows the same trends as DBC flatness increase, however, the controlled samples appear to have the worse of the two variants of plastic flatness, but the defect samples appear to have increased the most over the 1000 cycles, by a total of 0.45 microns more than the controlled samples. Although, the controlled samples have a larger flatness measurement, 0.85 microns larger, therefore 0.85 microns lesser flatness capability as shown in figure 26.

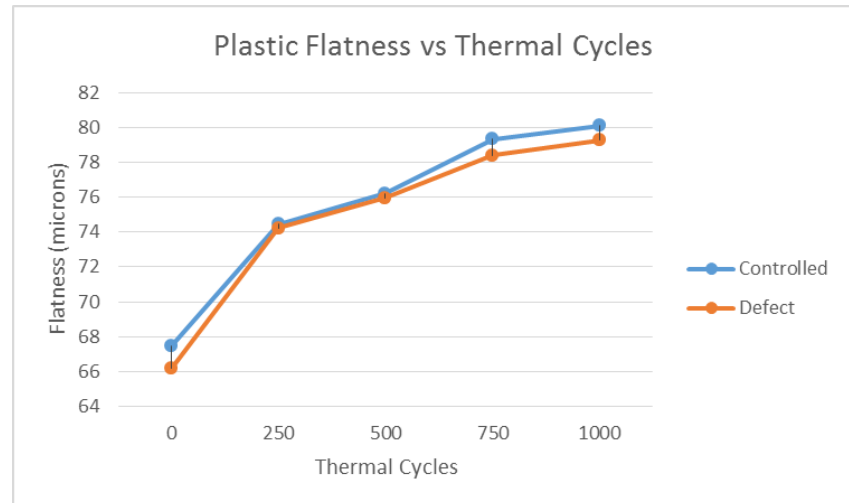


Figure 26: Plastic Flatness vs Thermal Cycles

The plastic increase is far more significant than the DBC flatness increase with the largest increase being 6.32 microns for defect DBC, the plastic increase is nearly double, defect samples increasing 13.07 microns, this could be due to the polyethylene resin pellets having a larger thermal expansion coefficient than the ceramic and copper of the DBC substrates (Ho, & Taylor, 1998).

The overall flatness as discussed also increases with thermal cycles. It's seen in figure 25 that the overall increase for the controlled sample average is 14.68 microns, increasing from 71.6 microns at benchmark to 86.25 microns post 1000 cycles, and for defect samples average, the overall increase is 17.6 microns from 68.17 microns to 85.77 microns, again it can be seen that the defect samples overall have the largest increase in flatness measurement and therefore the largest decline in flatness capability. However, similar to the plastic flatness it can be seen from figure 25 and 27 that the controlled sample average has the largest surface flatness measurement post 1000 cycles.

Although both plastic and overall show the controlled samples average with the largest surface flatness measurement this would indicate that it has the worst

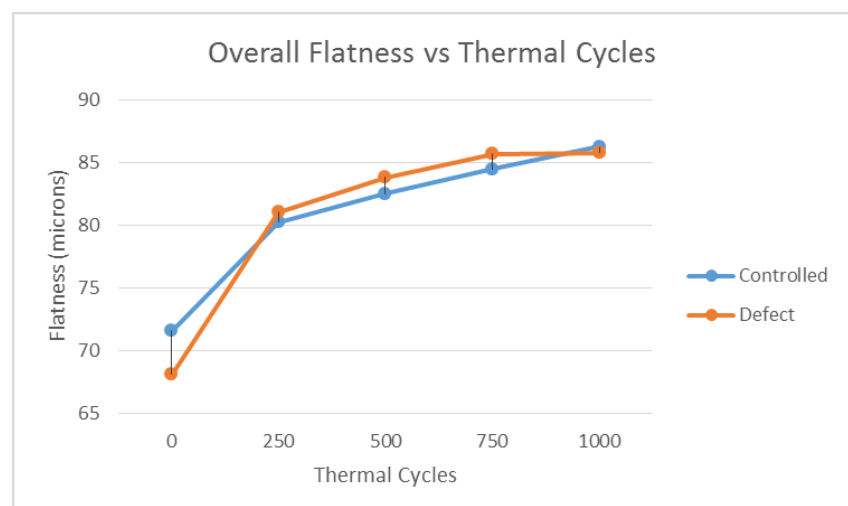


Figure 27: Overall Flatness vs Thermal Cycles

flatness capability, due to the measurement value, this is true – however, the defect sample average shows the largest flatness measurement for DBC flatness indicating the worst flatness capability of the two variants, also comparing all three parameters of flatness, the defect samples appear to have the greatest change from benchmark to post 1000 cycles, with DBC, plastic and overall having the largest decline in flatness capability compared to the controlled samples average, 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, due to a more accelerated change, this would cause more stress on the power module's materials and its components (Lau, 2012).

While all controlled and defect samples are significantly below customer tolerance specifications, including KSR upper safe limits, it cannot be denied that the surface flatness measurements have increased with thermal cycles on all parameters, which raises the overall surface of the power module as a whole and decreases the flatness capability, and increases risk of distortion of the surface. The surface flatness measurements for all three parameters increase with thermal cycles respectively, with an increase in the measurement values, there is a decrease in the flatness capability of the DBC, plastic and the overall power module surface. 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.

4.2.3. Electrical Performance post 1000 cycles

CSAM imaging was carried out prior to electrical test, and it was confirmed by the failure analysis engineer at KSR whom completed the CSAM imaging every 250 cycles, that following 1000 cycles, all 12 power modules were in good working order. 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 28 (Dunn, 2017).

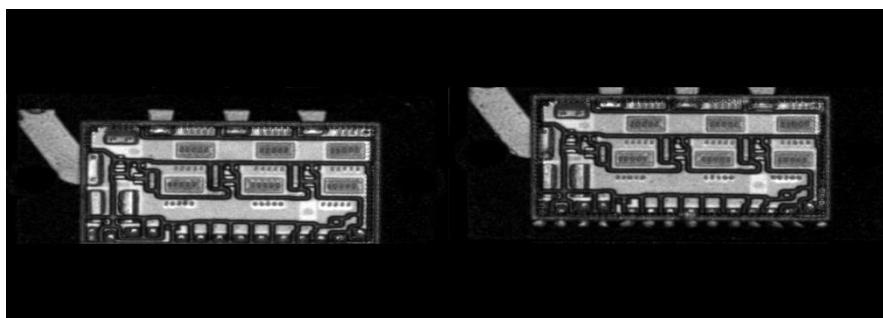


*Figure 28: CSAM imaging of defect (left) and controlled (right) parts post 1000 cycles
(Source: Dunn & KSR, 2017)*

Based on the flatness analysis of the controlled and defect samples, and determining that the defect samples had a more accelerated negative effect as a result of the applied thermal stress; it could be expected for the electrical test data to illustrate a similar pattern.

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

It can be seen from figure 29 that voltage and resistance appears to increase and current decreases in value with thermal cycles respectively.

Due to the relationship between current, voltage and resistance, it would be expected to see an increase in resistance with an increase in voltage and a decline in current with an increase in resistance.

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 it appears that the defect samples appear to have a larger increase in and in this instance has a higher resistance post 1000 cycles as shown below in figure 30, a higher increase in resistance will result in a larger decrease in current, and therefore reduce the electrical performance of the power module.

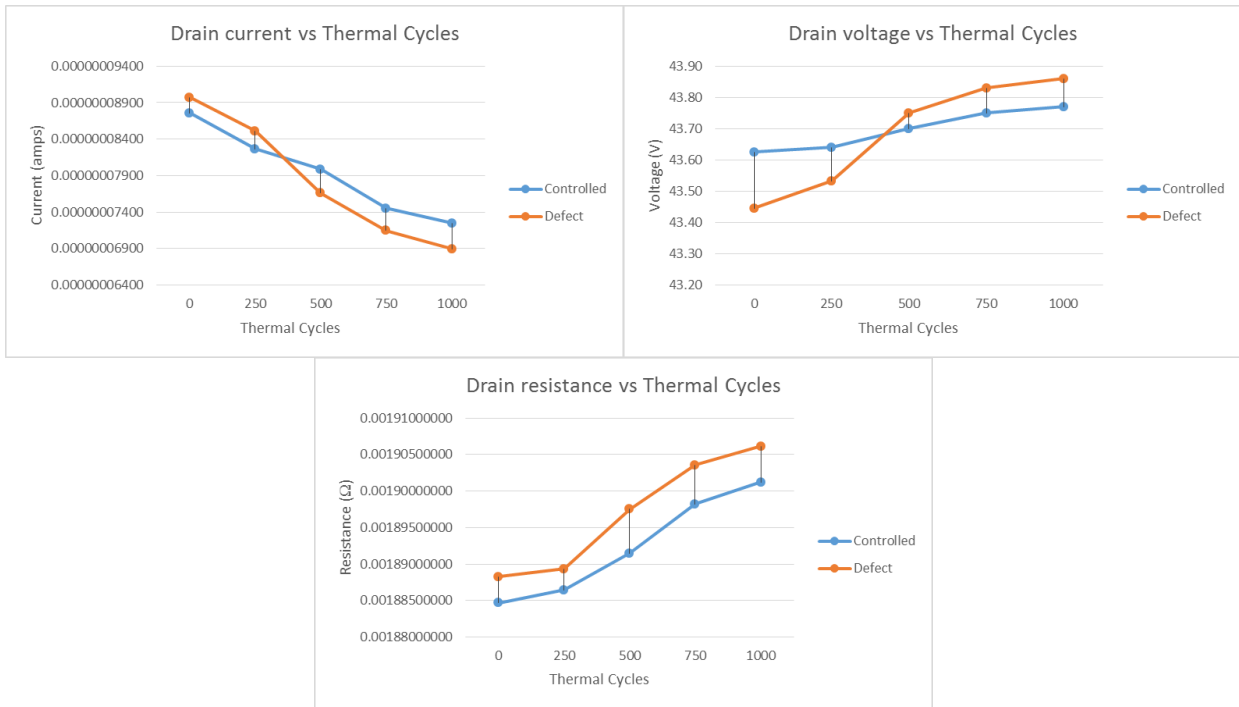


Figure 30: Current, Voltage and Resistance vs Thermal cycles (post 1000)

As a result of the resistance increase and compliance with Ohm's law, it can also be seen that the drain current of both controlled and defect samples decrease with thermal cycles respectively, witnessed in both current and voltage there can be seen that the defect samples intersect the controlled lines, this is due to the large incline/increase in resistance from 250 cycles to 500 cycles.

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.

Similar to flatness measurements it can be seen that the greatest changes occur from benchmark to post 500 thermal cycles, and the changes appear to lessen between post 500 and post 1000 cycles.

As illustrated, all power modules have experienced a drain 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).

It was found that the defect samples as an average had the worst DBC flatness and had the largest decrease in flatness capability and it was also found that it had the largest voltage, current and resistance changes compared to the controlled samples. As a result, the data gathered suggests that the defect samples performed worse than the controlled samples and were affected more significantly by the applied thermal stress, this is shown by the accelerated decline in flatness capability, and larger

decline in electrical performance in comparison to the control samples, therefore it would suggest that while all the power modules are negatively affected by the applied thermal stress, the power modules with a number of missing thermal relief dimples experience a larger and more accelerated stress effect.

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.

A basic model of the power module was modelled, accurately incorporating all the dimensions as shown in figure 31.

All the appropriate boundary and contact conditions were completed, and the correct materials selected.

However, due to limitations of the software used (solid works); the simulation wasn't able to be completed as desired.

Solid works was able to run transient thermal loads, however it was limited to a start and end temperature, also the software was able to apply thermal loads to the power module, however the analysis was limited to temperature recording only, and as a result over the specified time period illustrated the model as having a temperature which appeared to be the same all over the power module, this was expected, but the temperature alone has very little use in terms of thermal stress analysis.

It can be seen from figure 32 that the power module is the same colour all over, this is because over a specified time period the power module would reach the specified temperature applied by the thermal loading simulated, however solid works was limited to this, and there wasn't an opportunity to scale the time period to determine which parts of the power module reacted to the temperature faster/slower than other areas. Again, only temperature as shown in figure 32 was provided for analysis and there was no other parameters available to analyse such as stress.

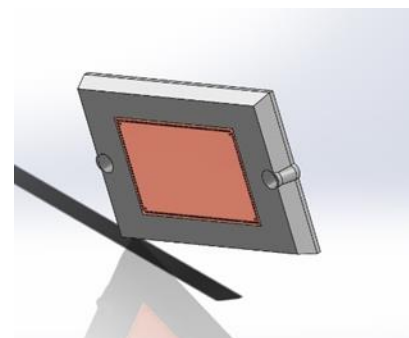


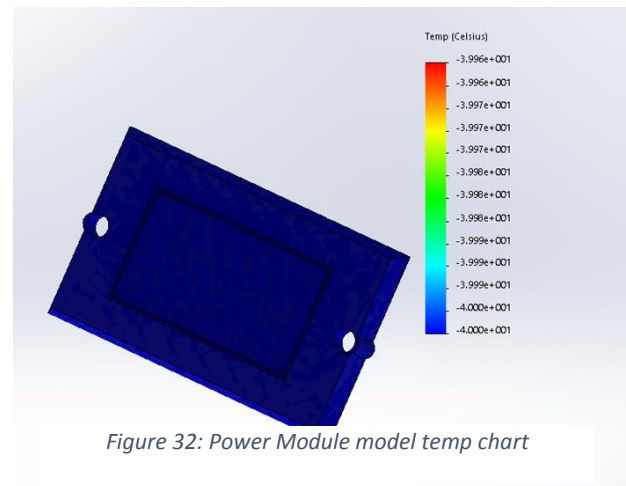
Figure 31: Power Module Model

Due to the unsuccessful efforts of CAD validation, the design department of KSR was contacted to obtain an insight if any, in to the simulation and testing analysis that would have been carried out during the design validation process of the power control module.

The design engineer who carried out all the simulation and testing on the module advised that firstly solid works isn't the best software for thermal analysis as it is very limited to its abilities of applying thermal loads (Dias, 2018).

It was stated that the only simulation that was carried out was thermo-electrical stress of the MOSFET's through simulation of working condition and no thermal cycle simulation to

determine mechanical stress (flatness), electrical stress (performance) was carried out, it was advised that the engineer wasn't aware of any software that is able to simulate thermal shock testing and complete analysis for thermomechanical stress, and also software for electrical stress analysis can be limited to when applied charge (Dias, 2018).



5. Conclusion

Based on the data collected, and the CSAM imaging and inspection carried out by the failure analysis engineer, it was found that all power modules used within the project, pass the customers and KSR specifications following 1000 thermal shock cycles.

However, 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. In a report written by Deng et al, 2017, this project's finding were also supported, where it was reported that although reliability was increased, shape changes to the encapsulated polyethylene material, increased with thermal cycles. In relation to the conclusion found within the project, where it was found that the defect samples with partly missing dimples on average showed accelerated effects of the thermal cycling, confirmed by the reports written Schulz-harder in 2002 and Curamik in 2014, where it was identified that the etching of dimples, to reduce the overall copper material, increased the reliability and endurance of thermal cycling.

Through analysis of the data collected it was witnessed that the condition of the power modules declined with thermal cycles respectively, although as stated, following 1000 thermal shock cycles, all power modules had no defects/cracks, and the decline in flatness capability and electrical performance was not significant enough to surpass tolerance specification. Therefore as a result it would suggest that the quality of the product and production process is to a high standard, and due to the data proving that the power module is thermally robust, it might indicate an over-engineered product, which could be more robust than required, consequently reducing the efficiency and increasing cost (Shina, 1994). The possibility of the product being over-engineered was also suggested by the failure analysis engineer, and it was suggested that a future project could be improving the process to produce a more efficient design, process and product (Dunn, 2018).

Unfortunately CAD based simulation was unsuccessful and therefore effective and complete validation of the live simulation was only complete using research based literature. However, a suggestion for a future project would be to create or modify programme software that is able to

simulate thermal shock cycling effectively, i.e. able to set effective initial, upper and lower temperature selections and input cycle increments where analysis can be carried out. While incorporating accurate and detailed thermal stress analysis of the thermal loads placed upon assemblies, including analysis aspects such as GD&T to analyse shape changes for example; surface flatness and roughness etc. A suggestion for further live simulation testing, particularly in this major project would have been to complete a durability test of the power modules where the power modules would have endured induced thermal loading during a electrical loading also, this would help determine the performance of the power modules while switched on during application of thermal loads.

To determine if, and by how much the power module is over engineered, the project could have benefited from testing until failure, therefore this would determine at what point the product fails, and the analysis could be used to lean out the production process to a more effective and efficient standard. Unfortunately, the project was limited to 1000 cycles due to cost and time of KSR equipment, without the limitations of testing, CAD simulation and KSR intellectual property the project would have had a vast amount of analysis and validation to identify the effects of thermal cycling and the thermal endurance of the power modules. 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. Although there appears to be initial surface changes found and a small decline in the electrical performance, the data collected unfortunately isn't extensive enough and requires further testing to provide adequate analysis of the effects of thermal cycling on the power modules. Extensive thermal cycling until failure, along with CAD simulation could prove beneficial to the analysis of the overall products thermal capabilities.

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7. Appendices

7.1. Appendix 1 - Flatness Measurements

	C1	C2	C3	C4	C5	C6		D1	D2	D3	D4	D5	D6
Benchmark	0.0335	0.036	0.0335	0.0324	0.0393	0.0369		0.0378	0.0383	0.0337	0.0344	0.0323	0.0367
	0.0643	0.0666	0.0675	0.0695	0.0696	0.0743		0.0645	0.0679	0.0639	0.0682	0.0672	0.0652
	0.0725	0.0724	0.0705	0.068	0.0746	0.0792		0.0712	0.0736	0.0613	0.0696	0.0637	0.069
Post 250 Cycles	0.036	0.0402	0.0367	0.0345	0.0398	0.0395		0.0395	0.04	0.0384	0.0389	0.0381	0.0381
	0.072	0.0736	0.0734	0.075	0.0754	0.077		0.077	0.0725	0.0748	0.0745	0.0743	0.0723
	0.0796	0.0805	0.0796	0.0781	0.0807	0.083		0.083	0.0822	0.0798	0.0816	0.0797	0.08
Post 500 Cycles	0.0381	0.0395	0.0392	0.0382	0.0404	0.0396		0.0384	0.0421	0.0435	0.0397	0.0395	0.0406
	0.0749	0.0742	0.0767	0.0759	0.0767	0.0789		0.0779	0.0759	0.0756	0.0767	0.075	0.0747
	0.0778	0.0834	0.0836	0.0821	0.0841	0.0842		0.0828	0.0862	0.0821	0.085	0.0822	0.0845
Post 750 Cycles	0.0379	0.0423	0.039	0.037	0.0424	0.0415		0.0428	0.0392	0.0398	0.0428	0.0422	0.0424
	0.0774	0.0786	0.0769	0.0799	0.0809	0.0822		0.0782	0.0792	0.076	0.0808	0.0795	0.0767
	0.0848	0.0861	0.0867	0.0845	0.088	0.0874		0.0881	0.0848	0.0816	0.0878	0.0866	0.0857
Post 1000 Cycles	0.0381	0.0426	0.0399	0.038	0.0429	0.0402		0.0431	0.0412	0.0406	0.0429	0.0425	0.0408
	0.0784	0.0797	0.0787	0.0801	0.0815	0.0823		0.0769	0.0803	0.079	0.0812	0.0804	0.0778
	0.0812	0.086	0.0845	0.0826	0.086	0.0865		0.0863	0.0874	0.0831	0.0854	0.086	0.0858

7.2. Appendix 2 – Electrical Test Results

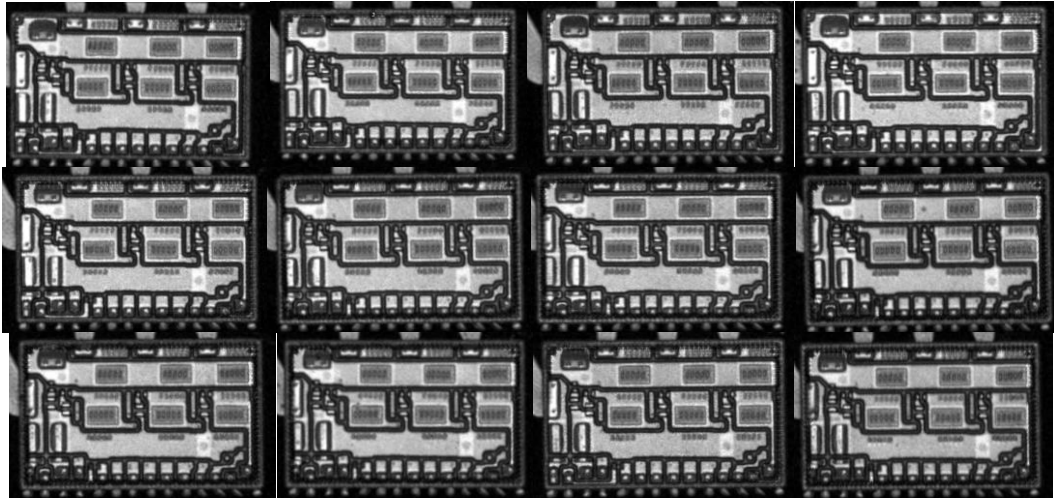
(Defect sample highlighted in red)

Module 1	Benchmark			Post 250 Cycles			Post 500 Cycles			Post 750 Cycles			Post 1000 Cycles		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	4.633E-08	43.263	0.0012649	4.733E-08	43.3	0.0012872	5.833E-08	43.297	0.0012879	0.000000046	43.27	0.0012896	5.033E-08	43.207	0.0012817
MOSFET 2	4.533E-08	43.087	0.0014295	4.367E-08	43.05	0.0014509	5.533E-08	43.057	0.0014514	0.000000045	43.037	0.0014552	0.000000049	42.98	0.0014445
MOSFET 3	0.000000044	43.14	0.0015658	4.633E-08	43.103	0.0015887	5.367E-08	43.117	0.0015882	4.133E-08	43.083	0.0015911	4.767E-08	43.03	0.0015792
MOSFET 4	0.000000072	43.263	0.0021616	7.667E-08	43.337	0.0021745	8.033E-08	43.353	0.0021854	0.000000083	43.317	0.0021734	0.000000073	43.253	0.0021774
MOSFET 5	7.267E-08	43.443	0.0023419	0.000000073	43.253	0.0021774	0.000000081	43.597	0.0023663	8.333E-08	43.597	0.0023545	0.000000073	43.567	0.0023566
MOSFET 6	0.000000071	43.047	0.0024765	0.000000077	42.977	0.0024898	0.000000078	42.983	0.0025003	0.000000079	42.943	0.002488	0.000000072	42.883	0.0024917
Module 2															
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	1.0467E-07	43.803	0.0012792	0.000000097	43.97	0.0012886	1.1967E-07	44.06	0.0012943	9.533E-08	44.087	0.0012889	9.833E-08	44.113	0.0012884
MOSFET 2	9.833E-08	43.737	0.0014456	0.000000094	43.92	0.0014612	0.000000115	44.023	0.0014646	9.233E-08	44.073	0.0014579	9.433E-08	44.077	0.0014558
MOSFET 3	0.000000109	43.607	0.0015812	0.000000101	43.797	0.0015897	1.2133E-07	43.893	0.0015939	1.0667E-07	43.93	0.0015873	1.0333E-07	43.953	0.0015902
MOSFET 4	1.4733E-07	43.57	0.0021716	1.4233E-07	43.74	0.0021773	1.4867E-07	43.867	0.00218	1.3267E-07	43.907	0.0021802	1.3967E-07	43.92	0.0021754
MOSFET 5	1.2967E-07	43.793	0.0023467	1.3967E-07	43.92	0.0021754	0.000000138	44.077	0.002359	0.000000118	44.123	0.0023552	0.000000131	44.147	0.0023538
MOSFET 6	0.000000018	43.63	0.0024921	0.000000161	43.787	0.0024957	1.6667E-07	43.887	0.0025015	0.000000155	43.907	0.0024957	1.5933E-07	43.917	0.0024933
Module 3															
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	4.933E-08	43.193	0.0012783	4.833E-08	43.18	0.0012904	5.833E-08	43.13	0.0012953	4.333E-08	43.09	0.0012881	4.867E-08	43.047	0.0012821
MOSFET 2	0.000000042	42.907	0.001459	0.000000044	42.9	0.00147	0.000000005	42.85	0.0014736	4.033E-08	42.823	0.0014684	4.433E-08	42.78	0.0014611
MOSFET 3	0.000000043	42.91	0.0015892	4.133E-08	42.903	0.0015998	5.367E-08	42.857	0.0016039	3.667E-08	42.827	0.0015993	4.433E-08	42.78	0.0015897
MOSFET 4	7.867E-08	43.08	0.0021891	8.133E-08	43.063	0.0021934	0.000000083	43.03	0.0022022	8.167E-08	42.99	0.0021942	7.067E-08	42.953	0.0021974
MOSFET 5	8.567E-08	43.36	0.0023311	7.067E-08	42.953	0.0021974	0.000000088	43.5	0.0023462	0.000000089	43.483	0.0023373	7.933E-08	43.44	0.0023414
MOSFET 6	8.433E-08	43.31	0.0024901	8.267E-08	43.303	0.0024888	0.000000088	43.28	0.0024994	0.000000083	43.257	0.0024931	7.333E-08	43.217	0.0024915

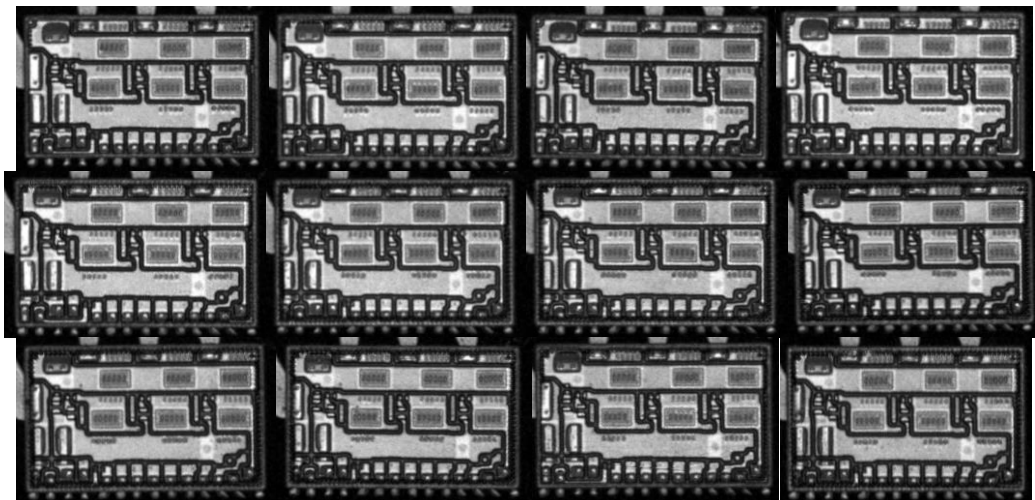
Module 4																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	1.4033E-07	43.443	0.0012899	1.3033E-07	43.607	0.0012971	0.000000153	43.63	0.0013034	1.2367E-07	43.617	0.0012967	1.2833E-07	43.62	0.0012918			
MOSFET 2	1.3467E-07	43.663	0.0014638	1.2433E-07	43.867	0.001467	1.4667E-07	43.877	0.0014751	1.1733E-07	43.85	0.0014686	1.2167E-07	43.833	0.0014617			
MOSFET 3	0.000000144	43.9	0.0015898	1.3133E-07	44.07	0.001589	1.4767E-07	44.19	0.0015993	1.2267E-07	44.213	0.001592	1.2767E-07	44.233	0.0015844			
MOSFET 4	0.000000018	43.843	0.0021785	0.000000159	44.02	0.0021893	1.7467E-07	44.14	0.002183	1.6433E-07	44.147	0.0021793	1.5333E-07	44.17	0.002185			
MOSFET 5	1.7767E-07	43.94	0.0023542	1.5333E-07	44.17	0.002185	1.7767E-07	44.277	0.00236	1.6467E-07	44.323	0.0023531	1.5467E-07	44.35	0.0023581			
MOSFET 6	1.7233E-07	43.34	0.0024849	1.5233E-07	43.493	0.0024934	1.6333E-07	43.567	0.0024925	1.5567E-07	43.573	0.0024831	0.000000148	43.593	0.0024875			
Module 5																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	4.567E-08	42.4	0.0013583	4.467E-08	42.39	0.0013729	6.933E-08	42.403	0.0013778	4.633E-08	42.38	0.0013721	4.967E-08	42.41	0.0013787			
MOSFET 2	4.533E-08	43.557	0.0014593	4.433E-08	43.59	0.0014753	6.967E-08	43.593	0.0014802	4.467E-08	43.54	0.0014748	4.733E-08	43.52	0.0014816			
MOSFET 3	4.667E-08	43.423	0.0015917	4.467E-08	43.503	0.001609	0.000000063	43.48	0.001613	0.000000046	43.423	0.0016067	4.933E-08	43.43	0.0016153			
MOSFET 4	0.000000076	43.607	0.0021957	7.433E-08	43.7	0.0022136	8.467E-08	43.773	0.0022121	6.867E-08	43.747	0.0022094	6.833E-08	43.787	0.0022223			
MOSFET 5	0.000000076	43.607	0.0023626	6.833E-08	43.787	0.0022223	9.033E-08	43.723	0.0023768	6.967E-08	43.7	0.002374	6.933E-08	43.727	0.0023867			
MOSFET 6	7.633E-08	43.63	0.002512	0.000000073	43.693	0.0025282	0.00000008	43.757	0.002525	7.067E-08	43.73	0.0025255	0.00000007	43.77	0.0025369			
Module 6																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	5.367E-08	43.66	0.0012741	0.000000051	43.81	0.0012808	7.433E-08	43.9	0.0012881	0.000000054	43.97	0.001288	5.467E-08	43.99	0.0012828			
MOSFET 2	0.000000054	43.417	0.0014208	5.267E-08	43.587	0.0014296	7.533E-08	43.67	0.0014371	5.433E-08	43.73	0.0014366	5.533E-08	43.73	0.0014284			
MOSFET 3	0.000000051	43.527	0.0015673	0.000000047	43.673	0.0015784	6.633E-08	43.757	0.0016012	0.000000052	43.823	0.001582	5.333E-08	43.837	0.001574			
MOSFET 4	7.733E-08	43.85	0.0021835	8.333E-08	43.98	0.0021823	0.000000091	44.103	0.0021831	0.000000075	44.173	0.0021902	7.767E-08	44.177	0.0021841			
MOSFET 5	9.333E-08	43.61	0.002328	7.767E-08	44.177	0.0021841	1.0567E-07	43.87	0.0023285	8.733E-08	43.93	0.0023323	0.000000088	43.923	0.002325			
MOSFET 6	8.133E-08	43.453	0.0024696	8.533E-08	43.587	0.0024703	8.933E-08	43.683	0.0024712	8.167E-08	43.733	0.0024747	8.233E-08	43.73	0.002466			
Module 7																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	0.000000058	43.557	0.0012648	5.367E-08	43.587	0.0012744	6.533E-08	43.633	0.0012767	0.000000058	43.587	0.0012744	5.633E-08	43.567	0.001279			
MOSFET 2	5.067E-08	43.353	0.0014308	4.767E-08	43.333	0.0014406	5.933E-08	43.363	0.00144	4.767E-08	43.32	0.0014374	5.233E-08	43.313	0.0014436			
MOSFET 3	4.833E-08	43.287	0.0015798	4.333E-08	43.21	0.0015889	5.333E-08	43.21	0.0015897	0.000000046	43.143	0.0015863	4.467E-08	43.12	0.0015916			
MOSFET 4	8.933E-08	43.24	0.0021577	8.533E-08	43.263	0.0021641	8.967E-08	43.317	0.0021764	0.000000008	43.273	0.0021741	0.000000092	43.25	0.0021668			
MOSFET 5	8.467E-08	42.8	0.0023462	0.000000092	43.25	0.0021668	0.000000087	42.77	0.0023697	7.667E-08	42.727	0.002366	0.000000087	42.703	0.0023623			
MOSFET 6	0.000000082	43.983	0.002508	0.000000077	44.017	0.0025153	7.867E-08	44.067	0.0025278	6.933E-08	44.033	0.0025227	0.000000081	44.027	0.0025174			
Module 8																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	6.833E-08	44.1	0.0012855	6.467E-08	44.26	0.001292	7.667E-08	44.38	0.001298	6.833E-08	44.17	0.0012902	0.000000067	44.43	0.0012933			
MOSFET 2	0.000000063	44.027	0.0014436	6.133E-08	44.203	0.0014511	7.033E-08	44.323	0.0014579	6.667E-08	44.353	0.0014489	6.333E-08	44.377	0.0014539			
MOSFET 3	0.000000059	43.81	0.0015776	0.000000055	43.97	0.0015816	0.000000068	44.073	0.0015841	0.000000058	44.09	0.0015765	0.000000056	44.107	0.001582			
MOSFET 4	0.000000102	43.993	0.002193	1.0133E-07	44.16	0.0021906	1.0533E-07	44.343	0.0022052	0.000000093	44.353	0.0022033	1.0567E-07	44.35	0.0021924			
MOSFET 5	9.133E-08	43.747	0.0023432	1.0567E-07	44.35	0.0021924	9.433E-08	44.027	0.0023524	8.267E-08	44.05	0.0023509	0.000000097	44.07	0.0023471			
MOSFET 6	0.000000092	43.843	0.0024948	0.000000089	43.983	0.0024921	0.000000097	44.123	0.0025019	7.967E-08	44.13	0.0025001	9.033E-08	44.153	0.0024885			
Module 9																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	0.000000057	43.633	0.001271	5.367E-08	43.753	0.0012732	6.433E-08	43.867	0.0012831	5.667E-08	43.903	0.0012788	5.867E-08	43.933	0.0012773			
MOSFET 2	5.333E-08	43.767	0.0014434	0.000000005	43.873	0.0014438	6.033E-08	44.003	0.0014484	5.233E-08	44.037	0.0014447	5.433E-08	44.057	0.001442			
MOSFET 3	5.833E-08	43.753	0.0015665	5.433E-08	43.87	0.0015693	6.467E-08	43.993	0.0015784	5.833E-08	44.023	0.0015758	6.033E-08	44.04	0.0015712			
MOSFET 4	0.000000086	43.787	0.0021774	0.000000081	43.9	0.0021779	9.067E-08	44.043	0.0021895	8.233E-08	44.077	0.0021796	8.467E-08	44.093	0.0021743			
MOSFET 5	8.167E-08	43.703	0.0023457	8.467E-08	44.093	0.0021743	8.733E-08	43.963	0.0023564	0.000000078	44	0.0023464	8.067E-08	44.017	0.0023406			
MOSFET 6	0.000000079	43.64	0.0024907	7.433E-08	43.753	0.0024888	0.000000083	43.883	0.0025012	7.867E-08	43.93	0.0024913	0.00000008	43.957	0.002487			
Module 10																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	6.167E-08	43.637	0.0012768	5.267E-08	43.733	0.0012782	0.000000066	43.853	0.0012882	5.667E-08	43.887	0.0012813	5.833E-08	43.907	0.0012798			
MOSFET 2	0.000000058	43.61	0.0014359	0.000000051	43.717	0.0014375	6.067E-08	43.823	0.0014472	5.333E-08	43.853	0.0014397	0.000000054	43.88	0.0014419			
MOSFET 3	5.533E-08	43.553	0.0015739	5.167E-08	43.673	0.0015749	6.367E-08	43.767	0.0015882	5.333E-08	43.8	0.0015768	5.667E-08	43.83	0.0015764			
MOSFET 4	0.000000089	43.563	0.0021727	0.000000075	43.71	0.0021882	8.933E-08	43.813	0.0021917	7.633E-08	43.837	0.0021922	7.933E-08	43.863	0.002183			
MOSFET 5	0.000000093	43.683	0.0023434	7.933E-08	43.863	0.002183	9.033E-08	43.913	0.0023543	8.067E-08	43.923	0.0023531	0.000000081	43.947	0.0023434			
MOSFET 6	9.133E-08	43.713	0.00248	7.933E-08	43.833	0.0024895	0.000000095	43.963	0.0024966	0.000000079	43.973	0.0024929	8.233E-08	43.997	0.0024856			
Module 11																		
	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance	Current	Voltage	Resistance
MOSFET 1	5.167E-08	43.86	0.001284	0.000000048	44.003	0.0012869	0.000000061	44.127	0.0012955	0.000000053	44.177	0.0012864	0.000000053	44.213	0.0012935			
MOSFET 2	4.767E-08	43.857	0.0014431	4.733E-08	44.007	0.0014459	5.633E-08	44.123	0.0014536	5.267E-08	44.16	0.0014466	5.133E-08	44.203	0.0014544			
MOSFET 3	5.267E-08	43.667	0.0015757	4.767E-08	43.817	0.0015771	5.967E-08	43.91	0.0015876	5.067E-08	43.94	0.0015771	5.033E-08	43.98	0.0015828			
MOSFET 4	9.067E-08	43.333	0.0021696	0.000000082	43.507	0.0021758	9.567E-08	43.553	0.0021796	8.533E-08	43.54	0.0021768	9.833E-08	43.54	0.0021694			
MOSFET 5	0.000000082	43.78	0.0023441	9.833E-08	43.54	0.0021694	0.000000087	44.057	0.0023523	7.767E-08	44.093	0.0023538	0.00000009	44.137	0.0023483			
MOSFET 6	0.00000009	43.513	0.0024776	0.000000079	43.663	0.0024804	0.000000094	43.77	0.0024844	7.967E-08	43.797	0.0024821	8.967E-08	43.833	0.0024785			

7.3. Appendix 3 – CSAM imaging

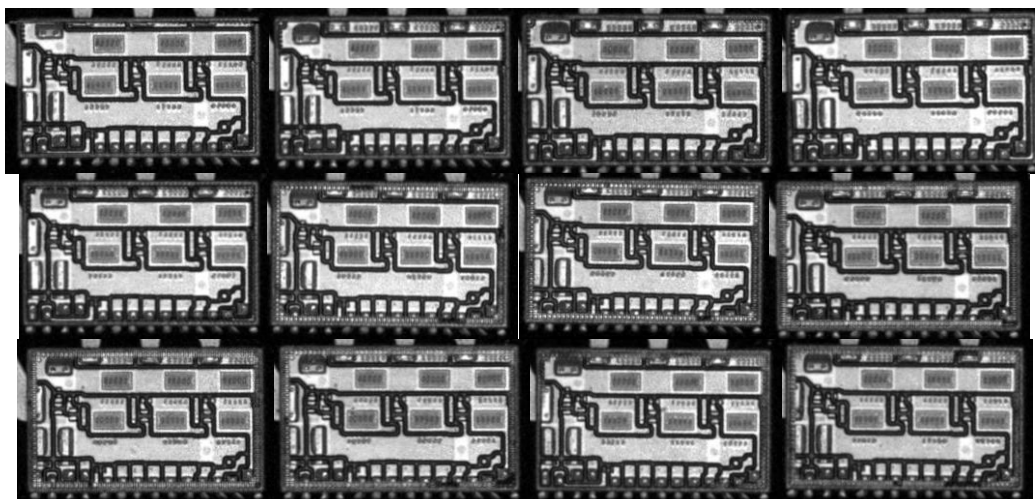
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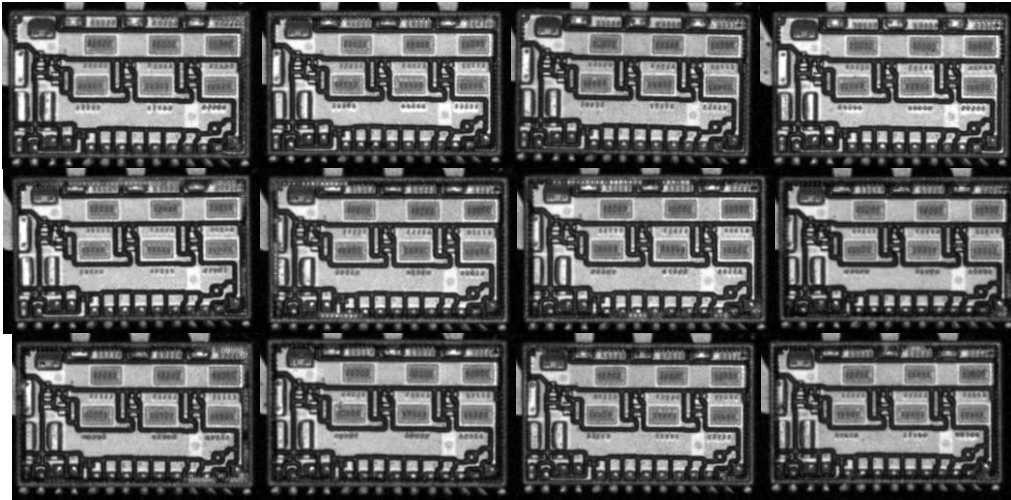
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