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BRNO UNIVERSITY OF TECHNOLOGY

FAKULTA ELEKTROTECHNIKY A KOMUNIKAČNÍCH TECHNOLOGIÍ
ÚSTAV MIKROELEKTRONIKY
FACULTY OF ELECTRICAL ENGINEERING AND COMMUNICATION
DEPARTMENT OF MICROELECTRONICS

COMPARISON OF SOLDERS FOR POWER MODULES

POROVNÁNÍ PÁJEK PRO VÝKONOVÉ MODULY

BAKALÁRSKÁ PRÁCE
BACHELOR'S THESIS

AUTOR PRÁCE MAREK SPAČEK
AUTHOR

VEDOUCÍ PRÁCE Ing. EDITA HEJÁTKOVÁ
SUPERVISOR

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Bakalářská práce

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Student:	Marek Spaček	***ID:***	134614
Ročník:	3	***Akademický rok:***	2014/2015

NÁZEV TÉMATU:

Porovnání pájek pro výkonové moduly

POKYNY PRO VYPRACOVÁNÍ:

Prozkoumejte a vyhodnoťte pájení substrátu DBC (direct bonded copper) výkonového IGBT modulu s jeho základovou deskou, použitím konvenční bezolovnaté pájky. Porovnejte ji s vysoko-spolehlivostní pájkou speciálně vyvinutou firmou Henkel. Pájené spoje mají být posouzeny z různých pohledů spolehlivosti vytvořeného spoje (smáčení, pevnost) a vyhodnoceny ultrazvukovou mikroskopií a průřezy pro přítomnost intermetalických fází.

DOPORUČENÁ LITERATURA:

According to the instructions of the supervisor

Termín zadání: 10.2.2015 ***Termín odevzdání:*** 4.6.2015

Vedoucí práce: Ing. Edita Hejátková
Konzultanti bakalářské práce: Ing. Miroslav Pittner, SEMIKRON s.r.o.

doc. Ing. Jiří Háze, Ph.D.
Předseda oborové rady

UPOZORNĚNÍ:

BRNO UNIVERSITY OF TECHNOLOGY

Faculty of Electrical Engineering and Communication

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Bachelor thesis

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Microelectronics and Technology

Student: Marek Spaček ***ID:*** 134614
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TITLE OF THESIS:

Comparison of solders for power modules

INSTRUCTION:

Examine and evaluate soldering of a DBC (direct bonded copper) substrate of an IGBT power module with its base plate, using a conventional lead free solder. Compare it with a high-reliability solder specially developed by Henkel. Solder joints are to be considered from various reliability aspects (wetting, strength) and evaluated by ultrasonic microscopy and cross-sections for presence of intermetallic phases.

REFERENCE:

According to the instructions of the supervisor

Assigment deadline: 10. 2. 2015 ***Submission deadline:*** 4.6.2015

Head of thesis: Ing. Edita Hejátková
Consultant: Ing. Miroslav Pittner, SEMIKRON s.r.o.

doc. Ing. Jiří Háze, Ph.D.
Subject Council chairman

ABSTRAKT

Táto práca podáva náhľad na výkonové polovodičové moduly, technológie v nich požívané a niektoré procesy používané na ich výrobu. Popisuje aj niektoré kvalitatívne kritériá pre spájkovaný spoj medzi DBC substrátom modulu a jeho základovou doskou a metódy používané na ich inšpekciu. Na koniec porovnáva vlastnosti 6-zložkovej vysoko spoľahlivostnej spájky 90iSC vyvinutej firmou Henkel so štandardnou spájkou požívanou na výrobu modulov vo firme SEMIKRON pri použitím rôznych spájkovacích programov, použitím röntgenovej inšpekcie, SAM a metalurgických rezov.

KLÍČOVÁ SLOVA

Výkonový IGBT modul, spájkovanie, spoľahlivosť, voidy, metalurgický rez, intermetalické zlúčeniny

ABSTRACT

This work gives and overview on semiconductor power modules, technologies used inside of them and some processes used for their manufacture. It describes some of the quality criteria for the solder joint between the module's DBC substrate and its base plate and methods used for their inspection. Finally, it compares the qualities of a 6-component high reliability solder alloy 90iSC developed by Henkel to the standard solder alloy used for module production in SEMIKRON using different soldering programs with use of an X-ray inspection, SAM and metallographic sections.

KEYWORDS

IGBT power module, soldering, reliability, voids, metallurgical section, intermetallic compounds

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PROHLÁŠENÍ

Prohlašuji, že svoj semestrální projekt na téma „Porovnání konvenční bezolovnaté pájky s vysoko spolehlivostní bezolovnatou pájkou“ jsem vypracoval samostatně pod vedením vedoucího semestrálního projektu a s použitím odborné literatury a dalších informačních zdrojů, které jsou všechny citovány v práci a uvedeny v seznamu literatury na konci práce.

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V Brně dne 4. května 2014 ....

podpis autora

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Ďakujem vedúcej semestrálneho projektu Ing. Edite Hejátkovej za jej účinnú metodickú a pedagogickú podporu pri spracovaní projektu. Taktiež veľmi ďakujem aj môjmu skvelému nadriadenému Ing. Miroslavovi Pittnerovi za všetku prejavenú podporu, dôveru, technické a odborné rady vždy keď som to potreboval. Taktiež ďakujem Martinovi Sahúlovi za inštruktáž pri príprave metalografických výbrusov, Miroslavovi Dudovi za jeho vedátorstvo, pracovníkom firmy SEMIKRON za ich ochotu a ústretovosť a v neposlednom rade mojim milovaným rodičom, bez ktorých by som nebol tým, kým som.

V Brně dne 4. května 2015 ....

podpis autora

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INTRODUCTION

Semiconductor power modules play an important role in power regulation in various applications - motor drives, wind and solar energy being among few of them. The first power semiconductor module was introduced back in 1975 by German company SEMIKRON.

The now developed industry always strives to improve upon the current generation of modules with better properties, whether it be their switching performance (current, voltage handling capabilities, highest switching frequency), expanded operating temperature range, reduced power losses during operation, reduced cost and improved reliability and service life, many of which are tied with the module's capability to effectively dissipate the heat produced by its operation.

In insulated power modules the electrical part of the module is insulated from the heat dissipating base plate (BP) by insulating substrate onto which the power semiconductor devices are mounted. This substrate can be connected to the base plate by several technologies, the most common of them being soldering. The reliability of the joint between the base plate and the insulated substrate plays a crucial role in the overall module's reliability and service life. In this work, the effect of using a high reliability lead-free solder alloy developed by Henkel, instead of conventional lead-free solder for this joint from the point of its reliability and quality is being explored.

1 POWER SEMICONDUCTOR MODULES

Power semiconductor modules or simply power modules are electronic devices which combine several power semiconductor devices such as diodes, thyristors, MOSFET or IGBT transistors into one assembly. They are used for variety of applications where power regulation is necessary, such as motor drives, solar and wind energy applications, power storage applications, welding applications and many others in which large currents and voltages are regulated. They have separated paths of current flow and thermal flow provided by insulating substrate with good heat dissipation capability, onto which the power semiconductor devices are mounted. One of the most common configurations for power modules is half-bridge, which allows for any typical circuit in power electronics to be created by connecting several of these modules. The first power module SEMIPACK, introduced in 1975 also used this configuration [1] [2]. Basic principle of the current flow and heat flow is illustrated on a half-bridge module in Fig. 1.1, whose schematic layout is pictured in Fig. 1.2.

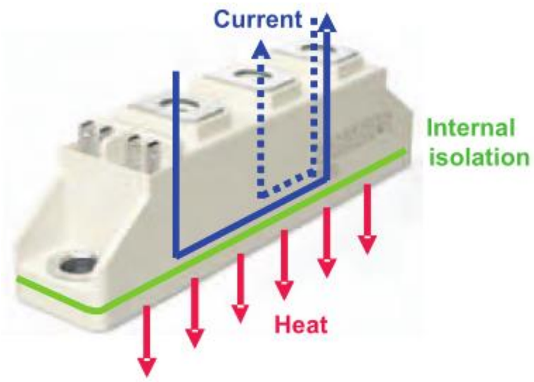


Fig. 1.1: Basic principle of separating current and heat flow in a power module [1]

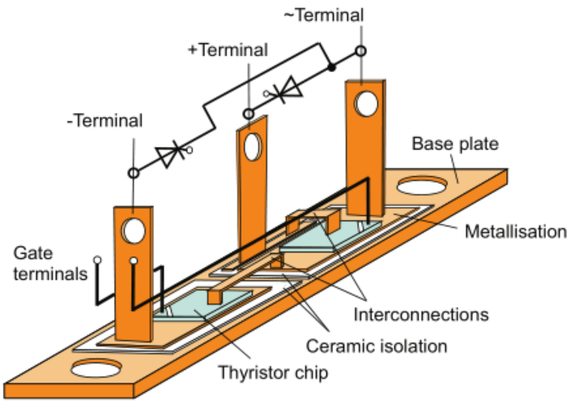


Fig. 1.2: Schematic layout of thyristor half-bridge module [1]

1.1 SEMiX modules components and technologies

SEMiX power modules or simply SEMiX, is a product class of insulated power modules produced by SEMIKRON as both IGBT and rectifier modules. They are produced in 600 V, 1200 V and 1700 V variants for currents ranging from 75 A to 600 A in different circuit topologies and housing sizes [3]. They fit in a group of modules with 17 mm housing height, which is one of industry's standards. As the whole SEMiX portfolio covers a wide range of applications, it was chosen as a fit candidate for testing the new solder alloy 90iSC developed by HENKEL, which is to be compared with the currently used one. In this part, overview of the technologies and components used for SEMiX modules but also examples of alternative technologies are be given.

All of SEMiX modules use:

- Power hybrids (PHs), which are insulated direct bonded copper (DBC) substrates with chips already soldered on top and connected by bond wires and with prepared solder pads for soldering of power terminals. Depending on the housing size, several PHs can be paralleled inside of a module for increased current handling capabilities. These are currently produced in SEMIKRON Germany
- Separately soldered negative temperature coefficient (NTC) temperature sensor (thermistor) for monitoring the operating temperature (Fig. 1.3)
- Nickel galvanized copper base plate onto which the DBC substrate is soldered
- Soldered contacts for main power terminals (through which the regulated current flows during operation) and interconnections between individual power hybrids
- Spring pressure contacts for auxiliary terminals (which are used for switching the transistors/thyristors)
- Soft-mold silicone filling to ensure protection of the internal components from the outside elements, and to ensure better dielectric strength between the components inside of the module, as the operation voltages exceed the dielectric strength of air at these small distances
- Plastic material housing which also provides sealed in washers for mounting the module onto a heat sink

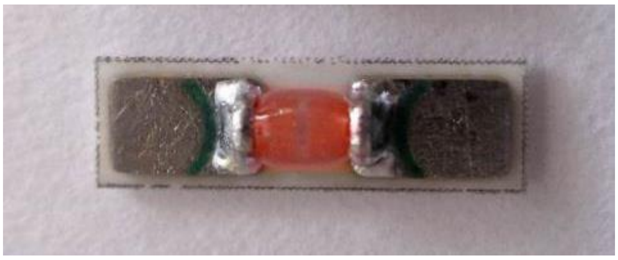


Fig. 1.3: SEMiX temperature sensor

SEMiX 4 module torso in which identical PHs are paralleled, can be seen in Fig. 1.4. By module torso, base plate with PHs, internal connectors, power terminals and temperature sensor soldered on is meant.

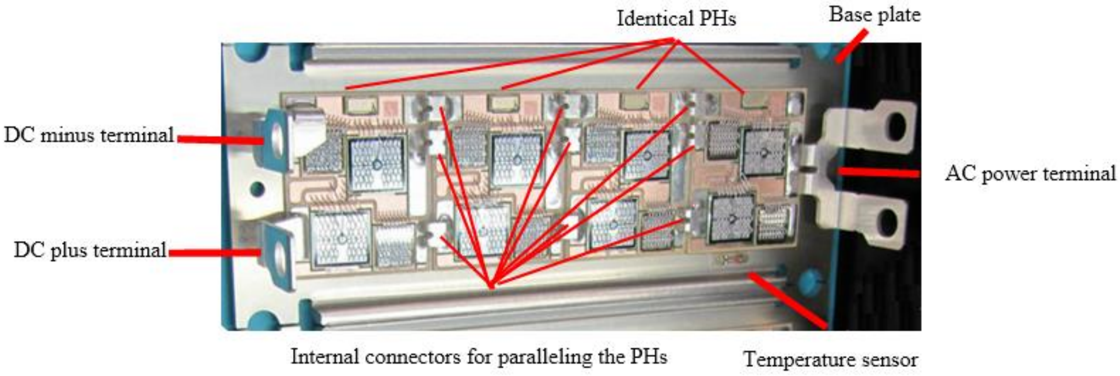


Fig. 1.4: SEMiX 4 module torso

Out of the SEMiX portfolio, the SEMiX 2 module size was chosen for the comparison of the two alloys, as it is one of the most produced ones. It uses two PHs and thus has two DBC – base plate solder joints.

1.1.1 Insulating substrate

The insulating substrate separates the current flow paths and heat flow paths inside the module and thus is very important from the point that it provides cooling to the module, while allowing the heat sink onto which the module will be mounted in application, to be potential free. The type of insulating substrate used in a power module depends on the desired properties such as its heat spreading capability, thermal expansion coefficient and cost. Several types of substrates may be used.

One of the substrate types which however is not soldered and used for SEMiX modules is an Insulated metal substrate (IMS), which consists of copper foil, which is structured by etching, attached onto a layer of epoxy or polyimide which is in direct contact with the module base plate. It has an advantage of low cost but is restricted to low power ranges due to the low thermal spreading capability of the thin copper layer. Furthermore, due to the thin insulation layer of this substrate, its coupling capacitance towards heat sink is high [1]. Illustration of IMS can be seen in Fig. 1.5**Chyba! Nenašiel sa žiaden zdroj odkazov.**.

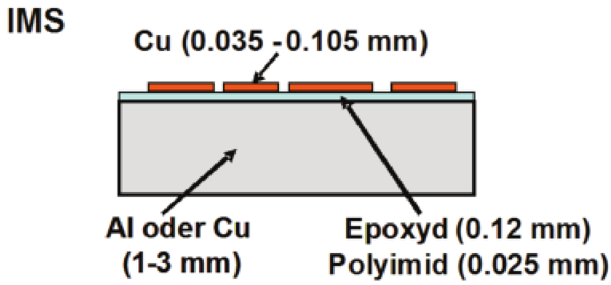


Fig. 1.5: Basic structure of an IMS substrate [1]

The most commonly used type of substrate which incorporates ceramic is a direct bonded copper (DBC) substrate. It uses Al_2O_3 (aluminum dioxide), AlN (aluminum nitride) or Si3N4 (silicon nitride) as a ceramic insulation layer with copper layer on both the upper and lower side. The connection between metal and ceramic is made at temperatures of just above 1063°C with the help of low-viscosity copper / copper oxide eutectic [1]. DBC is illustrated in **Chyba! Nenašiel sa žiaden zdroj odkazov.**.

Active metal brazing substrates (AMB) are very similar to DBC substrate, but instead of direct bonding, the ceramic metal connection is created by the use of titaniferous hard solder.

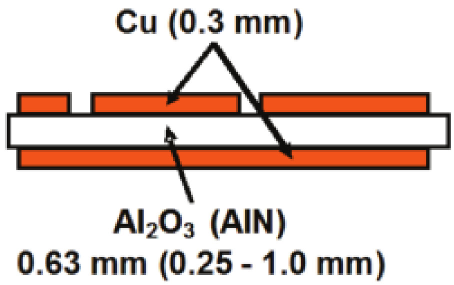


Fig. 1.6: Basic structure of a DBC substrate [1]

For all mentioned types of substrates, the upper copper layer is structured by etching. For both the AMB and DBC substrates, the underside may either be soldered to the module base plate or pressed with the use of thermal grease directly onto the heat sink surface, depending on the module casing design.

The DBC substrate of SEMiX IGBT modules uses Al_2O_3 ceramics with a thickness of 0,38 mm and a copper layer with a thickness of 0,3 mm on both sides. Its drawing can be seen in Fig. 1.7.

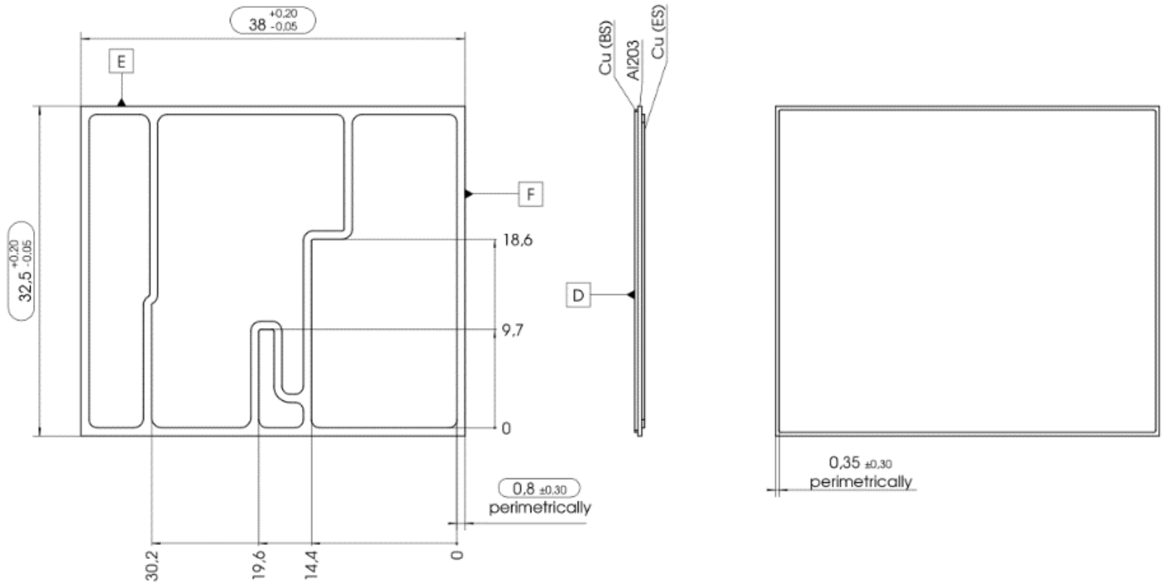


Fig. 1.7: Drawing of a SEMiX DBC substrate

1.1.2 Base plate

The power modules can be manufactured with or without base plate depending on the desired properties. Both have their advantages and disadvantages and specific design challenges. Modules with base plate usually use few larger chips mounted onto several insulating substrates that are interconnected. Among their several advantages is that they are mechanically more robust and thus easier to handle during transport and assembly. Furthermore, they have higher thermal mass which helps them handle short-term overloads better. Their disadvantages are:

- Higher thermal resistance between chip and heat sink $R_{th(j-s)}$ due to more layers and the thicker thermal grease layer necessary to compensate for unevenness of the base plate which tends to bend because of the stress caused by operation

- Worse slow thermal cycling capabilities due to the fatigue of solder between insulating substrate and base plate

- Increased weight

Modules without a base plate on the other hand usually use smaller chips mounted onto one large insulating substrate to ensure better heat spreading. Among their advantages are their lower thermal resistance due to the omitted layers of solder ad base plate, a thinner layer of thermal grease necessary and their superior thermal cycling capabilities. They have also several disadvantages such as virtually no heat storage, limited chip size and increased requirements for thermal paste application, as the insulation substrate (usually DBC) is susceptible to cracking if the paste is not applied evenly. This also brings higher demands for the evenness of the pressure used for mounting them onto a heat sink compared to modules with base plate which can be mounted only in few points. In Fig. 1.8, the large DBC substrate can be seen. Side profile comparison of modules with and without base plate can be seen in Fig. 1.9.

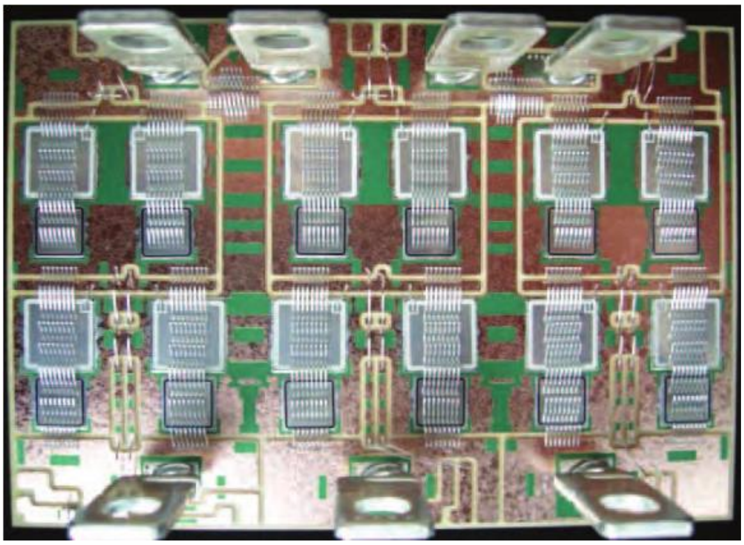


Fig. 1.8: One large DBC substrate of a base plate less module

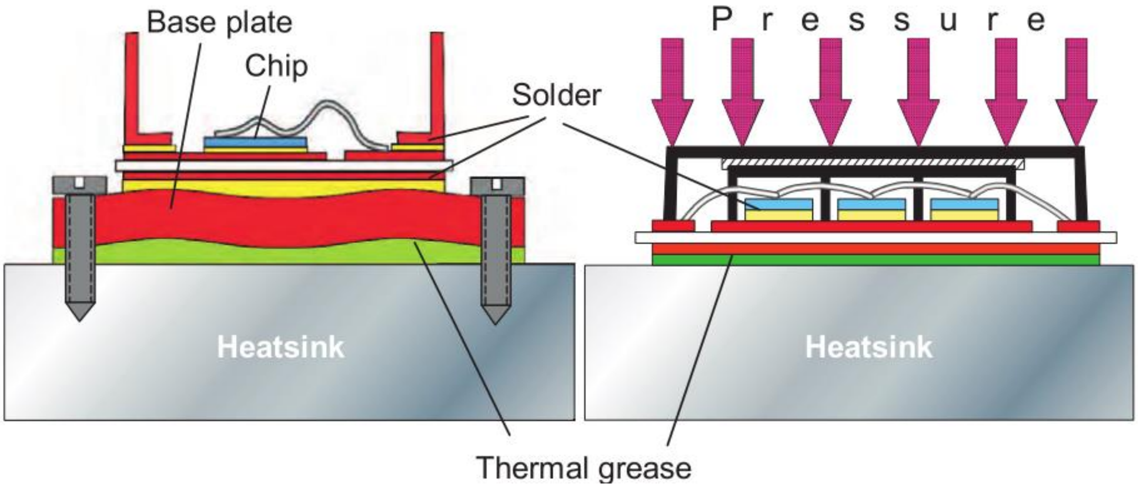


Fig. 1.9: Profile comparison of a module using a base plate (left) and a base plate less module)

The base plate for a SEMiX 2 module, is made out of SF-Cu F25 rolled copper, with the hardness of 70 - 90 on Vickers HV5 hardness scale. It has a nickel galvanization of 2-8 µm on the flash face (the one onto which the PHs are soldered) and 3-11 µm on the rear side. Its drawing can be seen in Fig. 1.10.

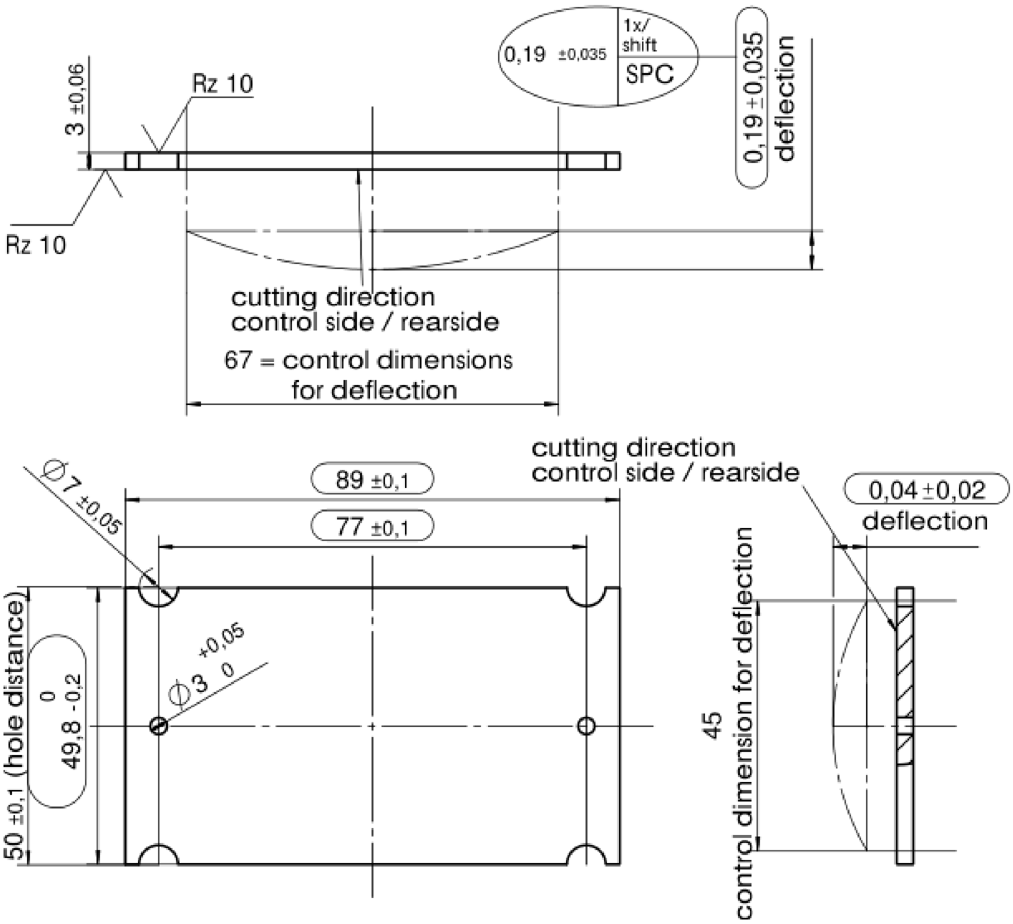


Fig. 1.10 SEMiX 2 base plate drawing

1.1.3 Wire bonding

Wire bonding is a process in which wire is cold-welded onto a surface using ultrasonic energy. For power modules, aluminum wire is used most commonly, between 100 µm and 500 µm thick. It is used to connect chip faces and other elements on the module substrate. Due to the current levels the power modules handles, several wire bonded connections have to be made on the face of the chip with parallel stitches for even current distribution (Fig. 1.11).

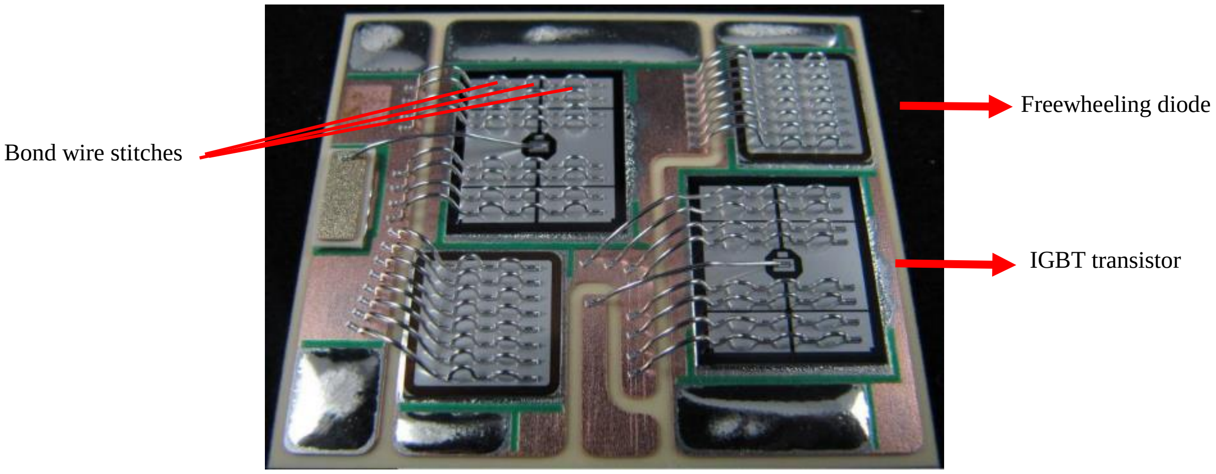


Fig. 1.11: Parallel bond wires on chip surfaces

1.1.4 Pressure contact technology

Pressure contact technology as the name suggest uses pressure to create a contact between components rather than using metallurgical joints which are created by soldering, diffusion-sintering or wire bonding. The parts in contact can move in relation to each other, which eliminates the stress between the parts, caused by different thermal expansion coefficients that occurs in metallurgical joints [2]. Due to this fact, pressure contacts are not subjected to fatigue which the metallurgical joints undergo during temperature cycling processes and consequently provides higher reliability rates for parts connected by pressure. Large-surface and small-surface pressure contact should be differentiated. The SEMiX modules use exclusively small-surface contacts for its auxiliary contacts. These spring contacts are illustrated in the Fig. 1.12.

Fig. 1.12: Spring auxiliary contacts in SEMiX modulse [4]

Large-surface contacts, use high force to connect two larger areas together. The surfaces have to be clean and planar and cannot be made of materials which are prone to cold welding, which would prevent them from moving and would expose them to stress. This is ensured by selecting suitable surface material pairs. Example of large-surface contact is a module mounted onto a heat sink.

With small-surface contacts, the contact area is line-shaped or dot-shaped. Due to the small area, even small force applies high pressure to the contact area, which is beneficial in removing the pollution and oxide layers from the surface area, providing a reliable contact. Small-surface pressure contacts are usually used for auxiliary contacts providing gate connections for controlling thyristors or transistors.

1.2 SEMiX soldering

Soldering is one of the most commonly used connection technologies inside power modules. Soldering is joining of two metal materials using a liquid metal or alloy with melting temperature lower, than that of the materials being connected. The connection is created by atoms of solder diffusing into the metal surface and creating a thin layer of alloy between solder and the soldered surface. [1] Fluxing agents may be used during soldering to provide cleaning to the soldered surf-aces and prevent their re-oxidation during the soldering process. The purpose of the solder joint inside the power module, depending on where it is used is to provide either:

- Electrical connection
- Mechanical connection
- Heat spreading connection

or combination of these.

Two different soldering agents are used for soldering the connections inside the power modules, one of them being soldering using paste solder which consists of solder in the form of powder or little balls inside a paste-like flux. This process is usually used for soldering the semiconductor chips onto the insulating substrate. Another process involves using a solder preform which is a pre-made shape of solder foil, which is usually rectangular or circular, depending on the shape of soldered surfaces.

One of the main aspects of the evaluation of solderability of a surface, is its wettability. Wettability of the surface is its ability to create a continuous layer of soldering material when coming into contact with melted solder. The prerequisite of the solder is its good capillarity and adhesion, so the whole soldered surface can be continuously covered. Molten solder acts as if its surface was covered by stretched elastic membrane trying to lower its overall surface area. The force causing this action is surface tension. It is always perpendicular to the length on which it acts. The surface of the solder is always trying to assume equilibrium in which it has minimal energy built up on its surface.

If molten solder comes into contact with soldered surface, then due to the wettability of the surface, interaction between the surface tension in solder with the surface tension between solder and the surface takes place. If the surface is wettable, then capillary elevation causes the joint surface to be concave, if it is not, then the surface is convex. During soldering, wettability of both soldered surfaces is critical. Wettability is influenced by several factors such as the composition of the soldering compound, cleanness and oxidation of the soldered surfaces, their roughness and others. [5]

1.2.1 Preparation before soldering

All of the components are assembled into soldering jigs prior to the soldering. The assembly of the components is done in the following order:

1. The module base plate
2. The solder preforms for PHs (DBCs) and temperature sensor
3. The PHs and the temperature sensors themselves
4. The internal connectors
5. The upper jig parts and the main power terminals

Several soldering jigs are placed on handling trays, which are placed into the oven for the soldering process.

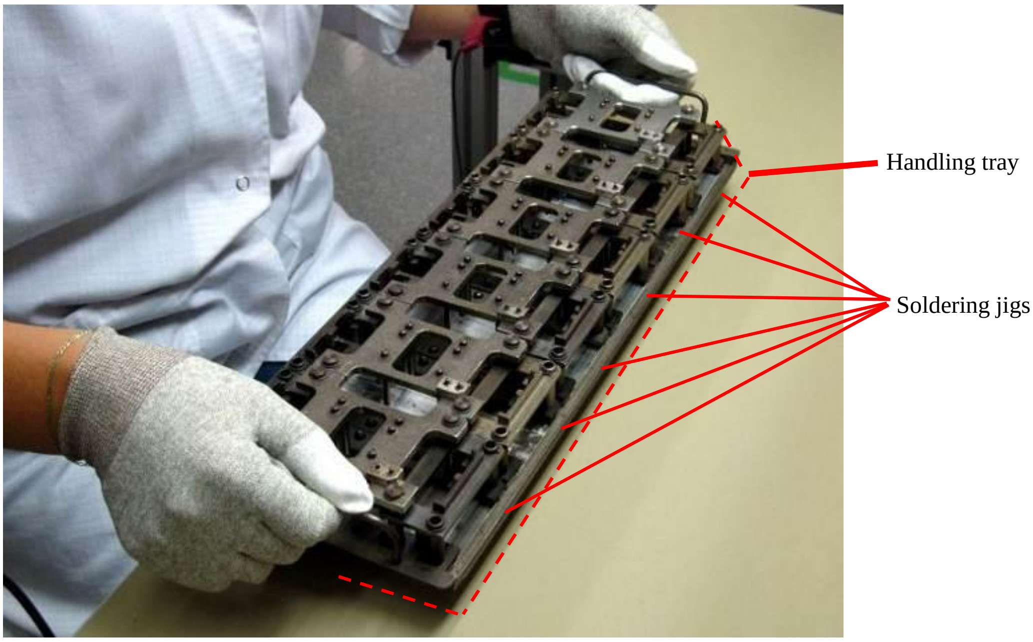


Fig. 1.13 Handling tray with soldering jigs

1.2.2 Standard solder alloy

The standard SEMiX SnCu(3)In(1)Ag(0,1) solder alloy is in form of rolled coils which are 32 mm wide and 0,1 mm thick. They are then cut into pieces of 37,5 mm. It constitutes of 3 % copper, 1 % indium and 0,1 % silver, with the rest made up of tin.

Tab. 1.1: Properties of standard SnCuInAg alloy [6]

Melting point	225 – 310 °C
Density	7,32 g/cm^3
Coefficient of thermal expansion (20°C)	35 ppm/°C
Thermal conductivity	57,3 W/m°C
Electrical Conductivity	8.8 % of IACS (1.72µohms.cm)
Purity	99,99 %

1.2.3 Henkel alloy

Due to the increasing demand for solder joint realiability mainly in automotive industry, Henkel has looked into developing a lead-free solder alloy with equal or lower melting point than SAC305 / 387, with high reliability at high temperature (150 °C) and one that would not use highly toxic or expensive constituents. The theory behind the development was that reducing plastic strain per cycle $\Delta\varepsilon^{pl}$ by increasing creep resistance will increase number of cycles to failure. Effect of combination of these 3 elements were observed:

- Bismuth (Bi) - solid solution hardening, lowers melting temperature
- Antimony (Sb) - solid solution hardening, raises melting temperature
- Nickel (Ni) - dispersion hardening by intermetallic phase formation

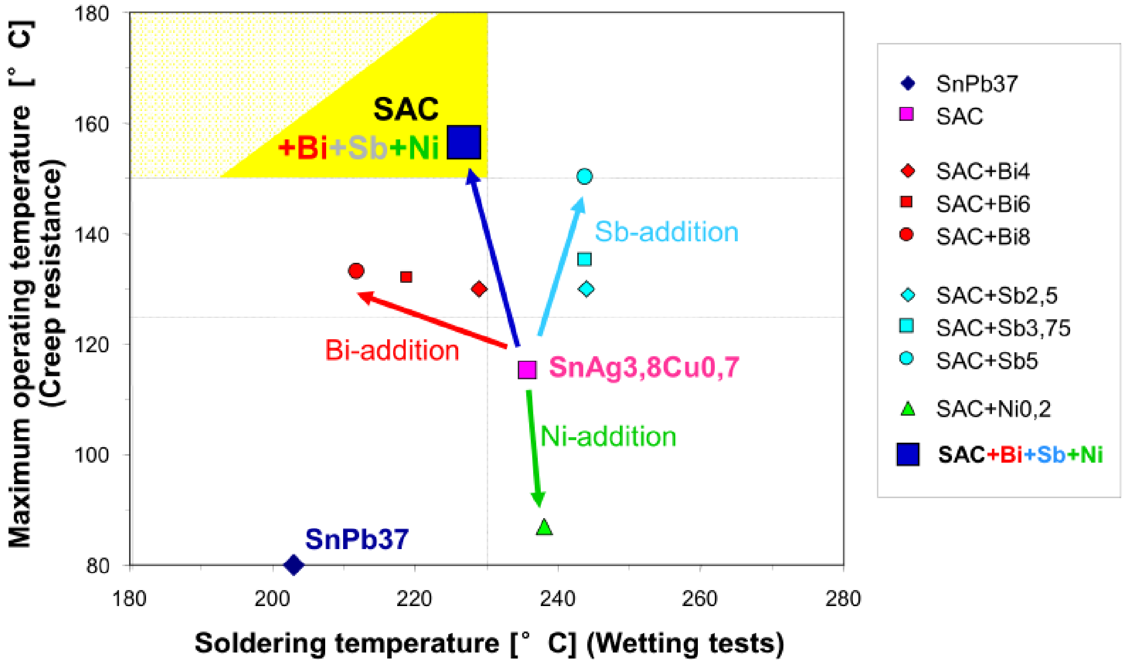


Fig. 1.14: Effects of addition of Bi, Sb and Ni to the SAC387 alloy [7]

Results of alloys comparison for testing number of thermal cycles to 50% joint strength for soldering chip resistors CR1206 and CR2515 can be seen in Fig. 1.15.

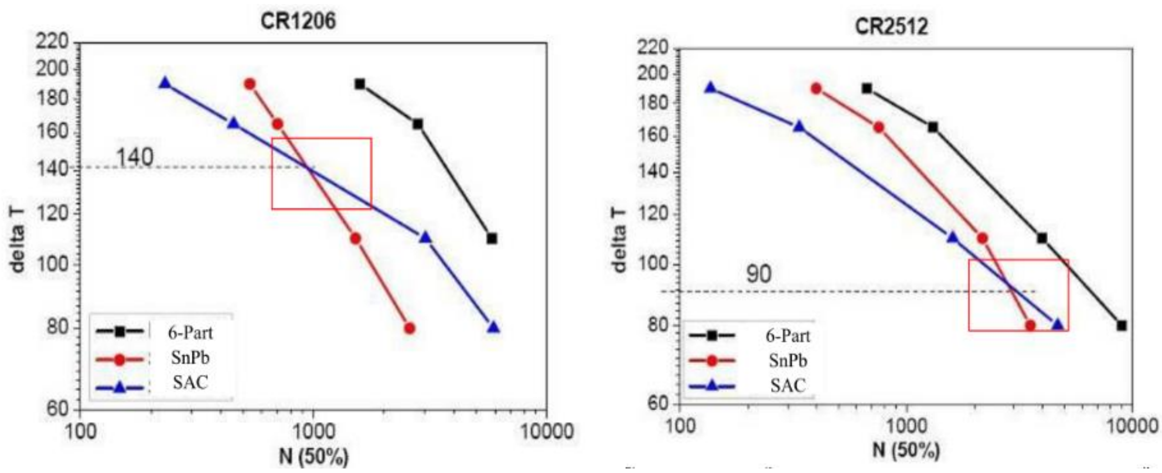


Fig. 1.15: Comparison of 6-component alloy with SAC and SnPb alloys for number of thermal cycles to 50% joint strength [7]

From the Fig. 1.15, it can be seen that the 6-component alloy seems to have a better reliability than both SnPb alloy at high temperature deltas and the SAC alloy at low temperature deltas.

The fully developed alloy was given a name 90iSC and constitutes of 3,8% silver, 0,7% copper, 3% bismuth, 1,4% antimony and 0,15% nickel with the rest made up of tin [7]. Though the alloy was developed primarily for use in solder pastes, Henkel was able to provide the alloy in preforms with a thickness of 0,1mm which is the same thickness as the standard solder.

1.2.4 The soldering process

During the soldering process, the solder melts and creates a connection between DBCs and base plate, DBCs and internal connectors, DBCs and main power terminals and thermal sensor and base plate. This is a so called module torso. The soldering of SEMiX modules is done in a vacuum soldering oven VLO300 manufactured by Centrotherm, which has 5 heating plates with dimensions of 540 x 410 mm^2, while being able to hold up to 15 kg each. Depending on the soldered module type, one plate can take up to 2 or 3 trays with soldering jigs. Each heating plate is equipped with 6 thermocouples for recording and controlling the temperature. It allows for use of pure nitrogen (N_2) hydrogen (H2) or forming gas (N_2/H_2 at ratio of 95:5) and can reach a deep vacuum of 0,1 mbar [8].

The soldering process which is currently used for soldering of SEMiX modules can be seen in Fig. 1.16.

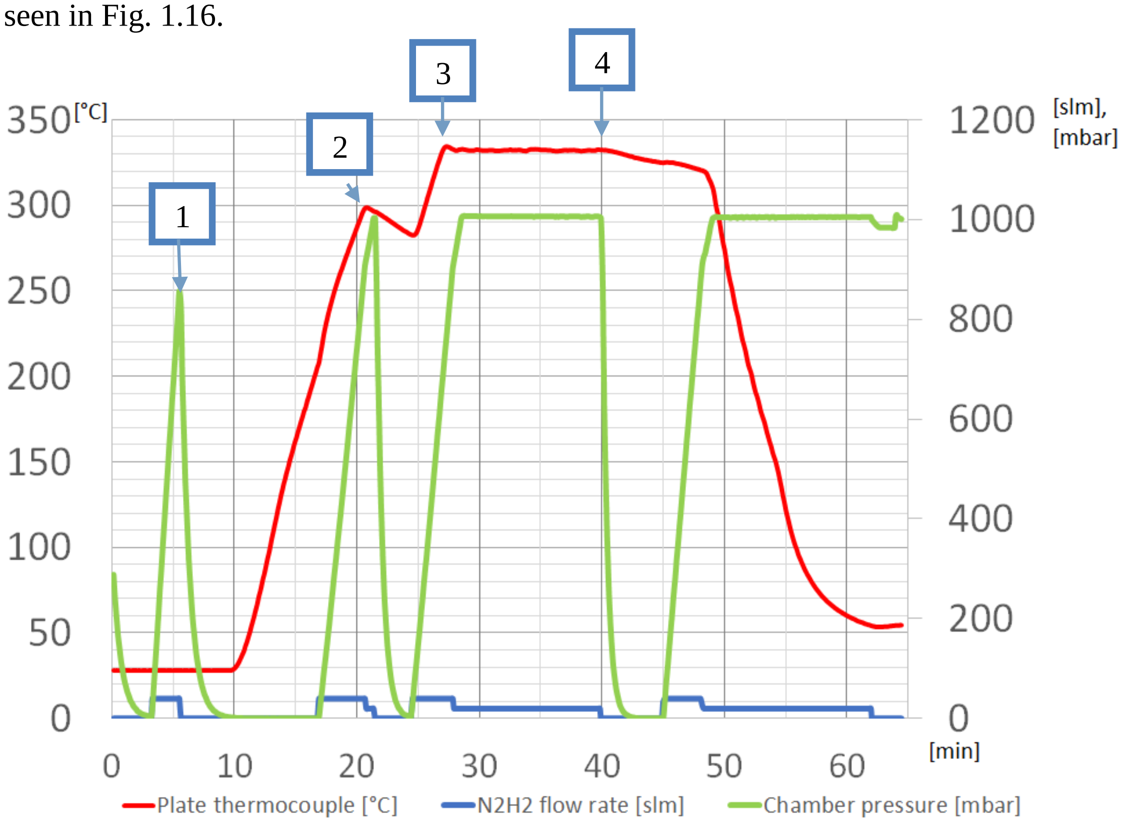


Fig. 1.16: Standard soldering program used for SEMiX

The soldering program can be separated into several steps:

1. The oven chamber is blown through with forming gas (point “1” in Fig. 1.16) to clean out the chamber from any residues
2. The chamber is vacuumed out afterwards, while the plates start to heat up

3. Before reaching the first peak temperature of 300 °C (point "2" in Fig. 1.16), the chamber is filled with forming gas to clean the soldered surfaces and rid them of oxides and allow good wetting of the surfaces
4. With the plate heating off, vacuum is created to remove any trapped air and in turn the chamber is filled with forming gas while ramping up to the main holding temperature (point "3" in Fig. 1.16)
5. The main soldering temperature of 335 °C is held for 12 minutes (until point "4" in Fig. 1.16)
6. Afterwards, the chamber is vacuumed out to remove all the trapped pockets of air from the completely melted solder.
7. The chamber is filled with forming gas again, while the water pump starts to rapidly cool down the heating plates until reaching the temperature of 60 °C, when the program is terminated and the chamber door is allowed to be opened

The given temperatures are the temperatures on the thermocouples of the heating plates, not the modules themselves. As the main mean of heat transfer in the vacuum oven is conduction from the heating plates, through the soldering jigs and through the base plates, the real temperature experienced by the solder joints is somewhat lower. The soldering ovens undergo a regular metrological control, during which the set temperatures are adjusted to the real measured ones. Opened Centrotherm VLO300 vacuum soldering oven can be seen in Fig. 1.17 with the plates loaded by the trays with soldering jigs.

Fig. 1.17: Centrotherm VLO300 vacuum soldering oven

2 SOLDER JOINT QUALITY ASSESSMENT

As mentioned before, in power modules with base plate, the reliability of the module is heavily influenced by the fatigue of the solder joint between the insulating substrate and the base plate. Choice of the right solder alloy is therefore critical for the module design. Such a change to any of the SEMIKRON products would have to be approved after qualification tests. The most critical tests from the point of stress on this solder joint are:

- power cycling tests, during which the module is subjected to a number of load cycles (10000 load cycled for diode/thyristor modules, 20000 load cycles for MOSFET/IGBT modules) with $\Delta T_j = 100$ °C, T_j being junction/chip temperature [1]
- Thermal cycling tests, during which the modules undergo cycles between maximal allowed storage temperature $T_{stg(max)}$ and minimal allowed storage temperature $T_{stg(min)}$ (25 load cycles for diode/thyristor modules, 100 cycles for MOSFET/IGBT modules) [1]

These tests are very costly and time consuming and are usually only used after the proposed changes are prior tested by other methods to prevent the qualification test failure and increase the chance of its success.

2.1 Peel out test

One of the basic, but widely used methods for evaluating the quality of the DBC – base plate solder joint is a peel out test. It is a destructive test, during which, the mechanical strength as well as the structure of the joint is assessed. For this test, the inspected module torso or baseplate with the DBCs soldered on is fixed in a bench vice and bent, with the force applied perpendicular to the base plate until the DBCs peel out. This process is illustrated in Fig. 2.1.

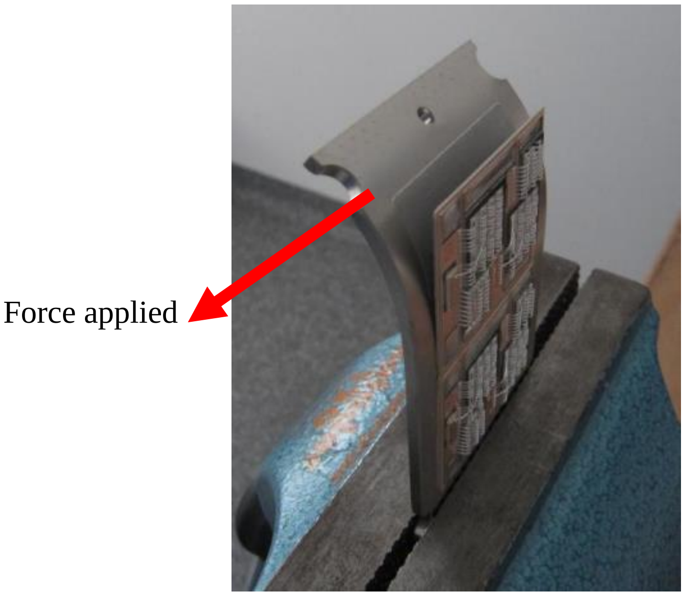


Fig. 2.1: Illustration of the peel out test

The stronger the joint is, the more the base plate resists the bending and the harder the DBCs peel off. After peeling out the DBCs, the structure of the joint is observed – its homogeneity, structure and void presence. The disadvantage of this test is that the joint strength can be assessed only comparatively between the different samples as no direct force is measured. With ideal joint strength, the DBCs would not peel off even after extreme bending and the inner ceramic would crack alongside the bent base plate. An example of a base plate with DBCs after peel out test can be seen in Fig. 2.2. Here, the DBCs did not completely peel off even after extreme bending of the base plate.

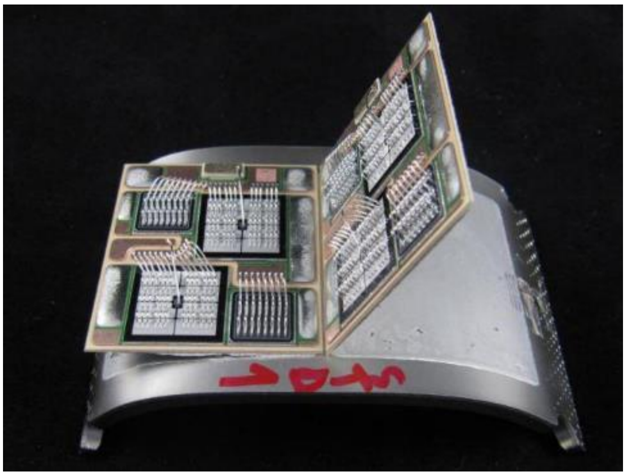


Fig. 2.2: Example of a torso after the peel out test

2.2 X-ray inspection

The X-ray is a non-destructive method of evaluating the soldering of a power module, where the module or its torso is placed inside of an X-ray inspection system chamber onto a sample carrier between the source of radiation – the X-ray tube and the detector. The system then creates real-time 2D images of the analyzed object based on the differences in the radiation intensities that hit the detector [9]. Illustration of an X-ray inspection system can be seen in Fig. 2.3.

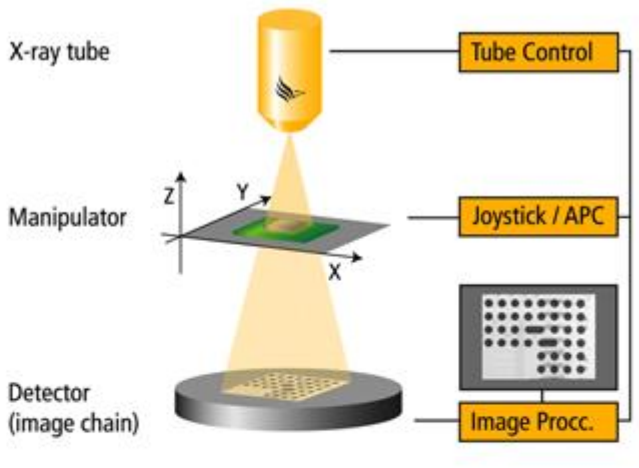


Fig. 2.3: Illustration of an X-ray inspection system [9]

The systems used for the X-ray inspection in SEMIKRON are Phoenix PCBA analyser and Phoenix PCBA inspector with the analyser model having the higher resolution and finer image, but smaller viewing area. They both display positive of the image, in other words, the more radiation permeates through the specimen, the brighter the image in that particular area. This is in contrast with the standard radiography with sensitive film, where the opposite is the case – the less obstruction the material presents to the radiation, the darker the resulting image [10]. X-ray image of a part from a SEMiX module can be seen in Fig. 2.4.

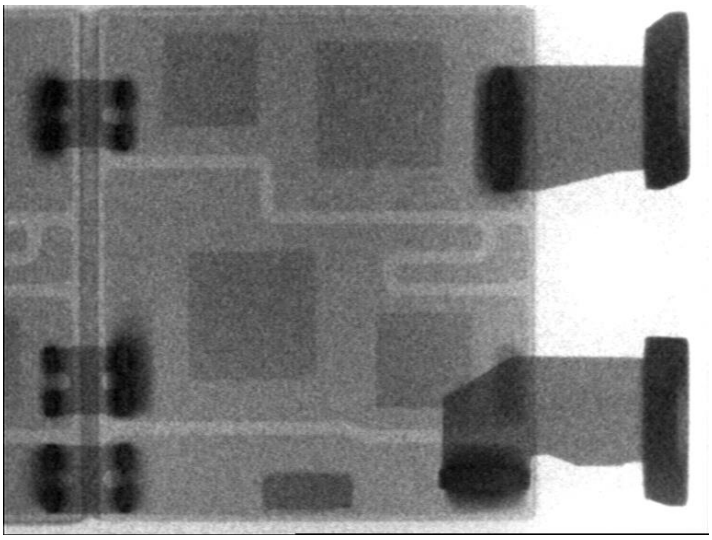


Fig. 2.4: X-ray image of a SEMiX module

2.3 Scanning acoustic microscopy

The scanning acoustic microscopy (SAM) is similarly to an X-ray inspection, a non-destructive method of inspecting the soldering of the DBC. Using it, the material can be analyzed under its surface in several layers. It uses ultrasonic transducer which emits ultrasonic waves at high frequencies into the material, which can be scattered, absorbed, reflected or transmitted by the object [11] – its schematic diagram can be seen in Fig. 2.5.

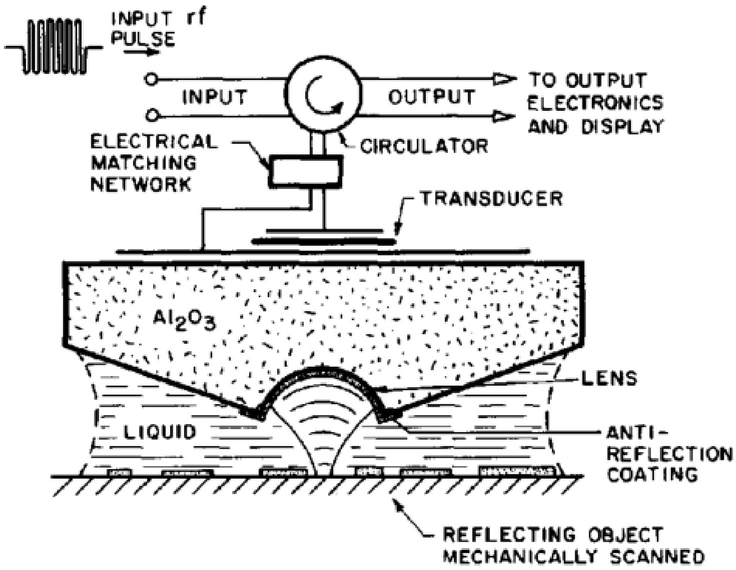


Fig. 2.5: Schematic diagram of a SAM transducer lens system [8]

The returned pulses are picked up by a detector, and used to modulate the intensity of the scanned point. In this manner, the whole area of interest is scanned point by point and added to the resulting image which represents the differences in the material reflectiveness across the specimen [11]. Using SAM, the inspected specimens can be scanned in several layers and thus, the defects in them can be assessed by a pro layer basis.

2.4 Metallographic sectioning

Other method which can be used to evaluate the solder joints is metallographic sectioning. It is a destructive inspection method in which a representative sample of a specimen is cut into convenient size with a method that does not damage the specimen thermally or mechanically, this is then mounted into resin, to allow uniform grinding and polishing across the whole cross section. In this way the sample may be prepared for microstructure/macrostructure evaluation using light microscopy but for other tests as well, such as electron microscopy or energy-dispersive spectroscopy [12]. The resin mounted samples can be ground/polished manually or using specialized machines. The grinding and polishing is done in order from a coarse grain down to very fine grains. The grain size of the final polishing is highly dependent on the size of the area to be analyzed and the magnifications needed.

3 TESTING THE NEW SOLDER

As the solder preforms from Henkel came in dimensions of 38 x 38 x 0,1 mm, they had to be first cut down into the size used in SEMiX modules (32 x 37 ,5 x 0,1mm).

3.1 Initial tests

During initial testing, 5 torsos of SEMiX 2 module for each alloy were used to test the soldering with the standard soldering program and evaluate the joint strength, void presence and the structure of the solder. The soldering jigs were put together onto one heating plate inside a soldering oven to ensure as equal conditions as possible. All the samples were inspected using X-ray for void presence and afterwards a peel out test was performed.

In the following pictures, side by side comparison of X-ray imagery with the PHs peeled off will be made to illustrate the size of the voids present.

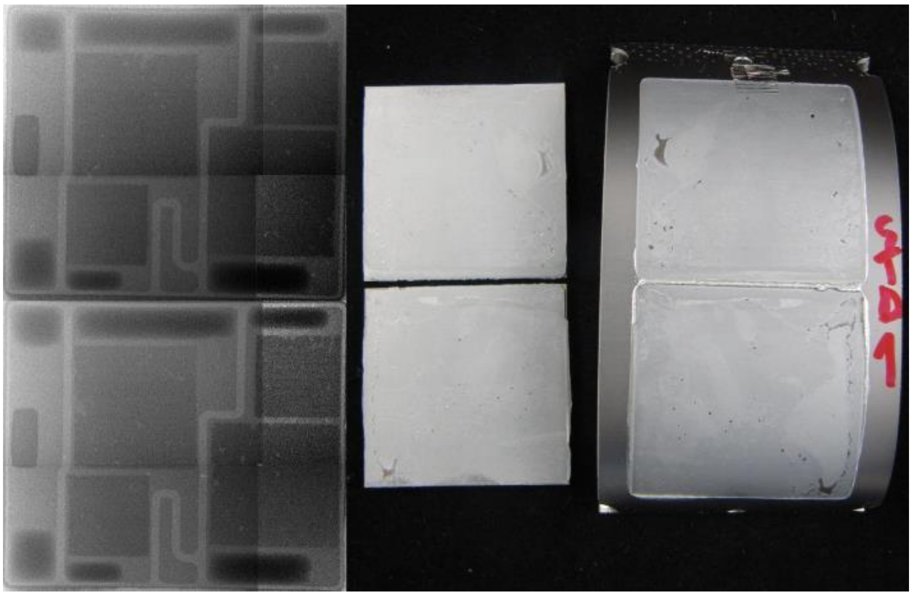


Fig. 3.1: Sample no.1 with standard alloy

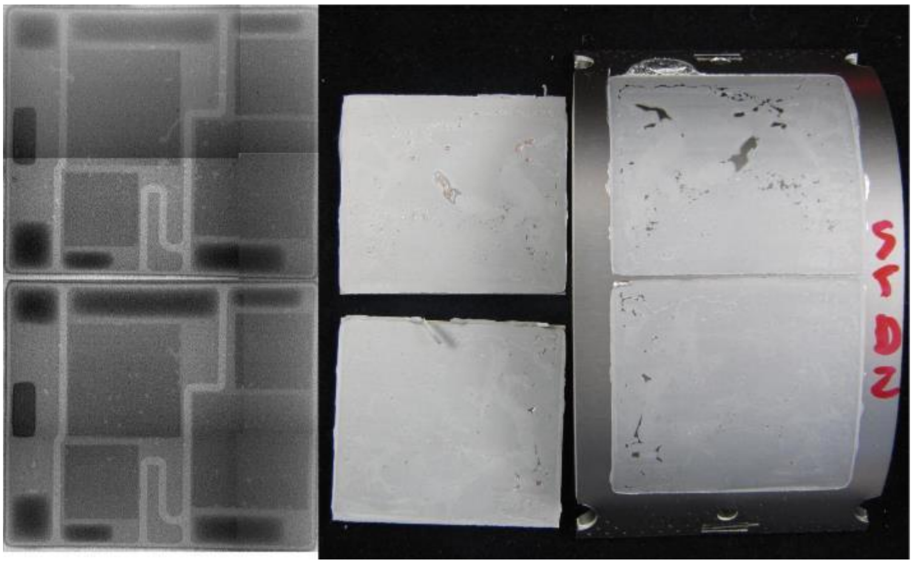


Fig. 3.2: Sample no.2 with standard alloy

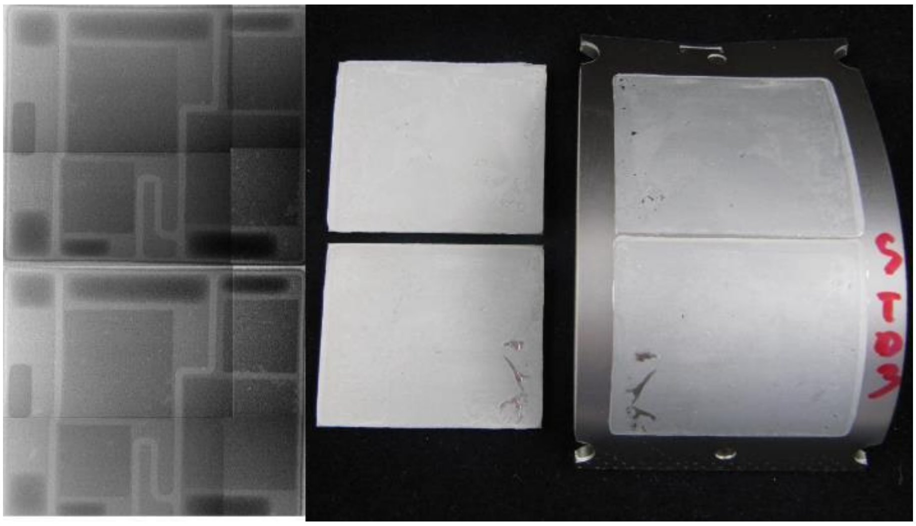


Fig. 3.3: Sample no.3 with standard alloy

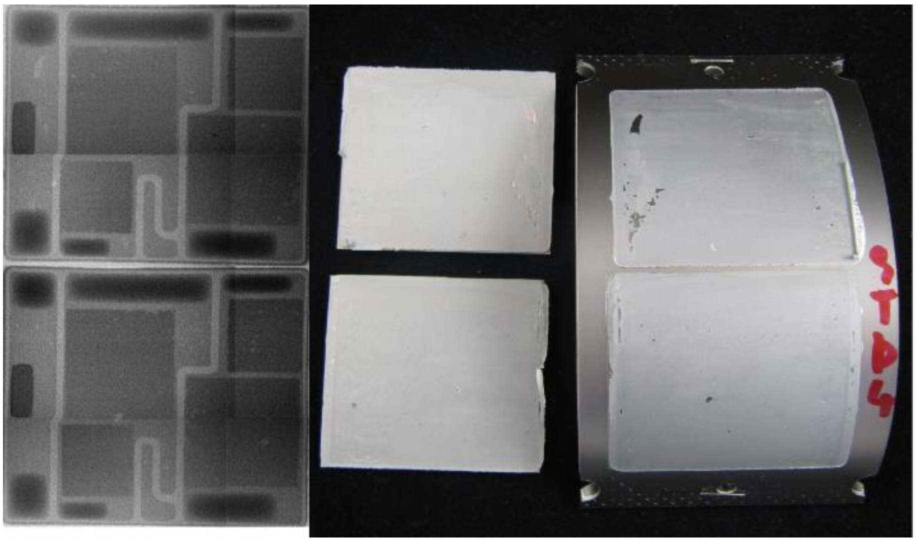


Fig. 3.4: Sample no.4 with standard alloy

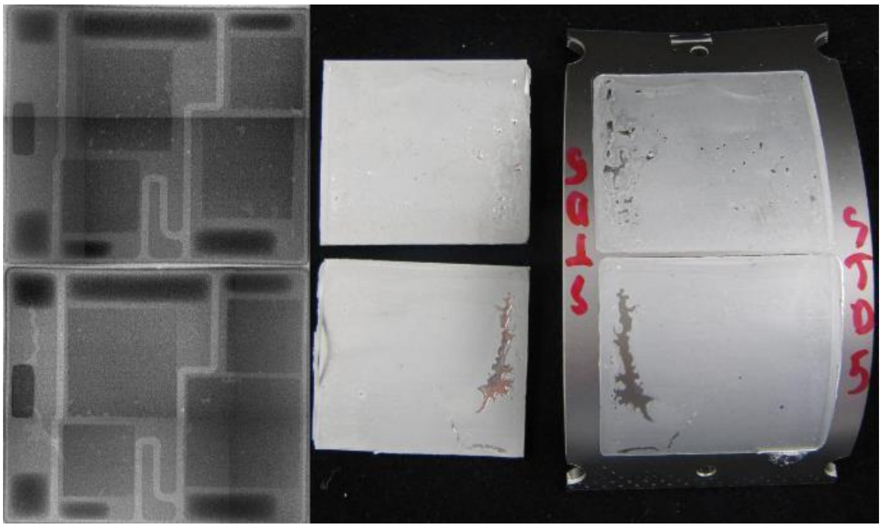


Fig. 3.5: Sample no.5 with Standard alloy

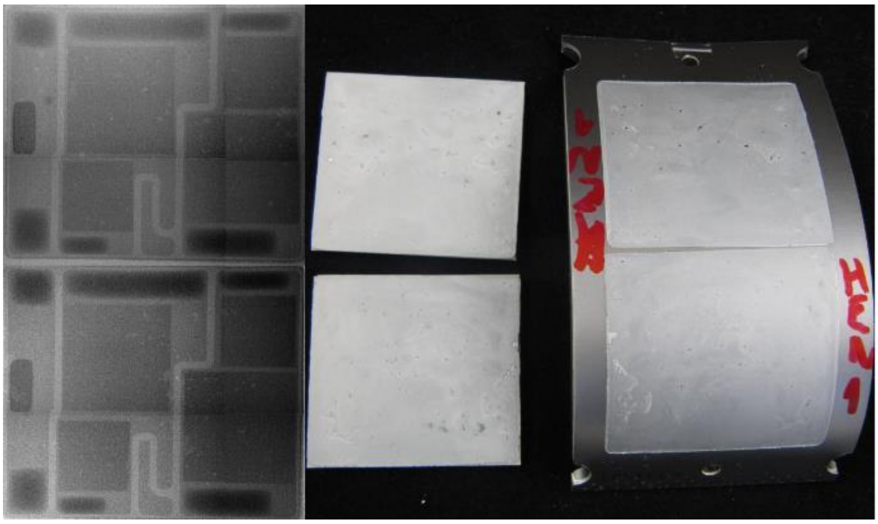


Fig. 3.6: Sample no.1 with Henkel alloy

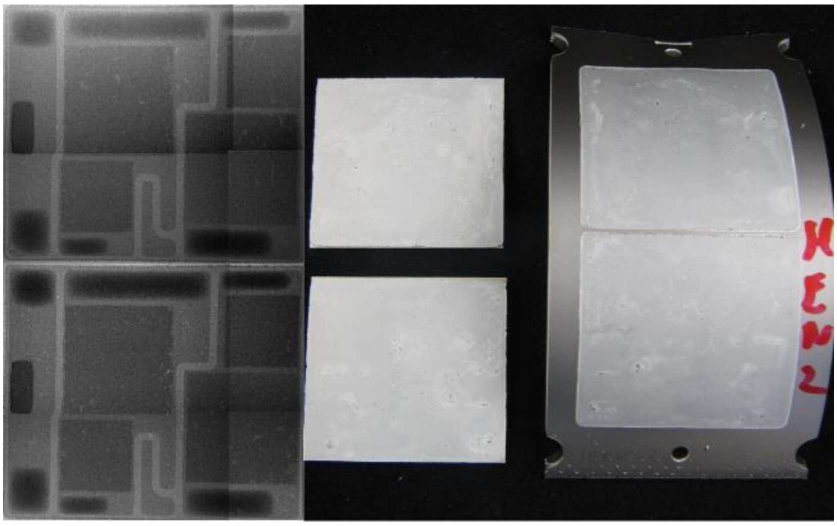


Fig. 3.7: Sample no.2 with Henkel alloy

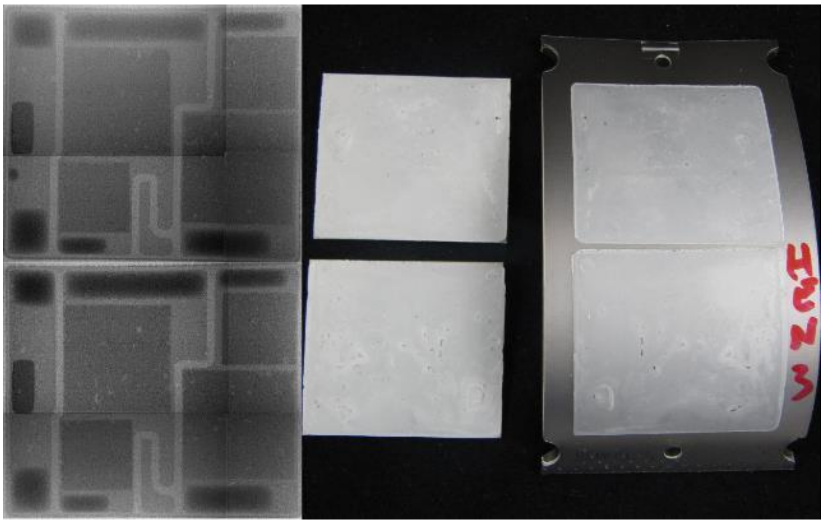


Fig. 3.8: Sample no.3 with Henkel alloy

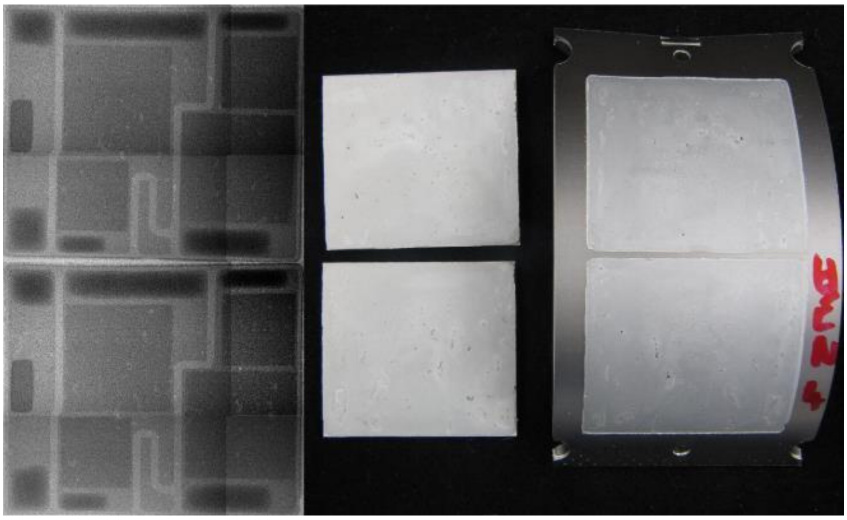


Fig. 3.9: Sample no.4 with Henkel alloy

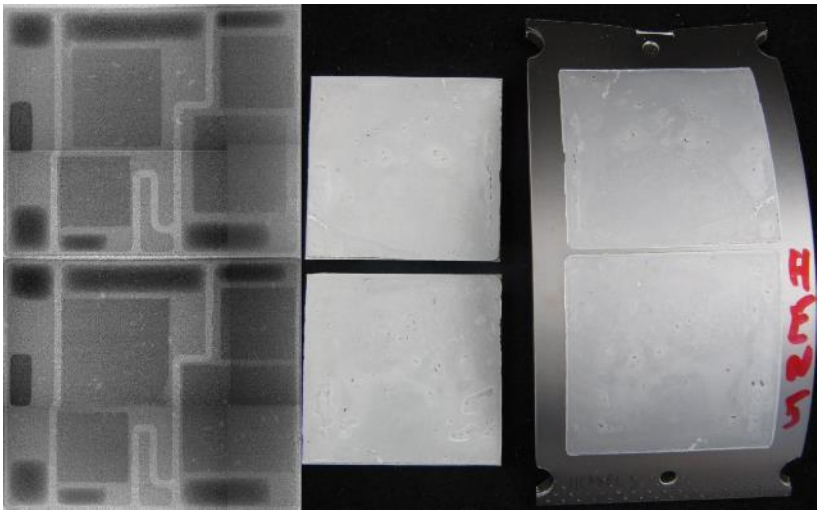


Fig. 3.10: Sample no.5 with Henkel alloy

The X-ray imagery of the test samples revealed higher void presence in the samples with the standard alloy. This may be, however, due the cleanness of the preforms themselves. When, we disregard the large void areas, the overall void presence of the small voids is comparable. The peel out test revealed lower structural strength of the joints on the samples with the 90iSC alloy compared to the standard one as the PHs peeled off only after slight bending of the samples. This was partly expected due to the high soldering temperature. After peeling off the PHs, the revealed solder structure was very similar and mostly homogenous in both groups. After this test it was concluded, that different settings of the soldering program (mainly temperature and holding time) have to be tested for the new alloy.

3.2 Influence of different soldering temperatures

In the second batch of trials, different soldering profiles were tested and the samples were again evaluated using the peel out method and X-ray to compare the settings and decide which profiles are to be assessed by the SAM and the Metallographic sections. After discussing the soldering temperature with engineers from Henkel, lowering to around 270 °C was suggested. This was most probably meant for the reflow soldering using solder paste. Firstly, only changes in temperature were tested and both the first temperature peak and the main holding temperature were changed by the same amount. Only six steps in temperature were chosen as each soldering program last around 60 minutes. For purpose of these test, a separate oven, used specially for development tasks was used, as to not interfere with the demands on the serial production ovens.

Tab. 3.1: Testing different soldering temperatures with the 90iSC alloy

Sample no.	**Main holding temp.** [°C]	**Voids presence** (1- the smallest, 6 – the biggest)	**Joint strength** (1- the biggest, 6 – the smallest)	**Solder homogeneity** (1- the best, 6 – the worst)
Sample 1	270	5	4	5
Sample 2	280	6	3	6
Sample 3	290	4	1	4
Sample 4	300	2	2	3
Sample 5	310	3	6	2
Sample 6	320	1	5	1

Results of the testing of different soldering temperatures can be seen in be seen in the Tab. 3.1. Six samples were produced in this test batch, with stepping of the temperature by 10 °C between the ranges of 270 °C and 320 °C. Each sample was assigned a number value for the void presence from X-ray inspection (1 being the smallest and 6 being the biggest), the mechanical joint strength (1 being the biggest and 6 being the smallest) and the solder homogeneity (1 being the best and 6 being the worst) from the peel out test. From the results, the dependency can be seen for the increase of the solder homogeneity and decrease of voids presence with the increasing soldering temperature. The solder joint strength, however seems to be more about finding the right balance. The sample 6 had the smallest void presence and the best solder homogeneity, however the joint strength was quite low. On the other hand the sample 3 had the best perceived joint strength but quite high portion of voids as well as not good homogeneity. The sample 2 soldered at the temperature 300 °C seemed to be the middle ground as is had the second best joint strength, second smallest voids presence and the third best solder homogeneity.

3.3 Samples for SAM and Metallographic sectioning

In this batch the samples for the SAM and the metallographic sectioning were prepared with changes in both the soldering temperature and the main holding time as it also plays an important role in the quality of the joint. Generally, the main holding time, should be only as long as necessary for the complete melting of the solder for creating of a homogenous liquid and any increase above that time is redundant or harmful to the quality of the joint. From the previous test, the soldering temperature of 300 °C showed itself as a good starting point for testing the different soldering time as it was the middle point between the solder joint strength, voids presence and solder homogeneity.

Tab. 3.2: The parameter sets chosen for SAM and metallographic sectioning

	Alloy	**Main holding temperature** [°C]	**Holding time** [s]
Parameter set 1	Standard	335	720
Parameter set 2	90iSC	280	720
Parameter set 3	90iSC	300	720
Parameter set 4	90iSC	320	720
Parameter set 5	90iSC	300	600
Parameter set 6	90iSC	300	840

Samples from the each parameter set were as previously soldered in an oven used for development and were placed onto the same spot of the same heating plate to ensure equal conditions. For each soldering run, the curves of the temperature, chamber pressure and the forming gas flow were recorded. The graph for the soldering process of parameter set 5 which used main temperature of 300 °C and holding time of 600 s can be seen in Fig. 3.11.

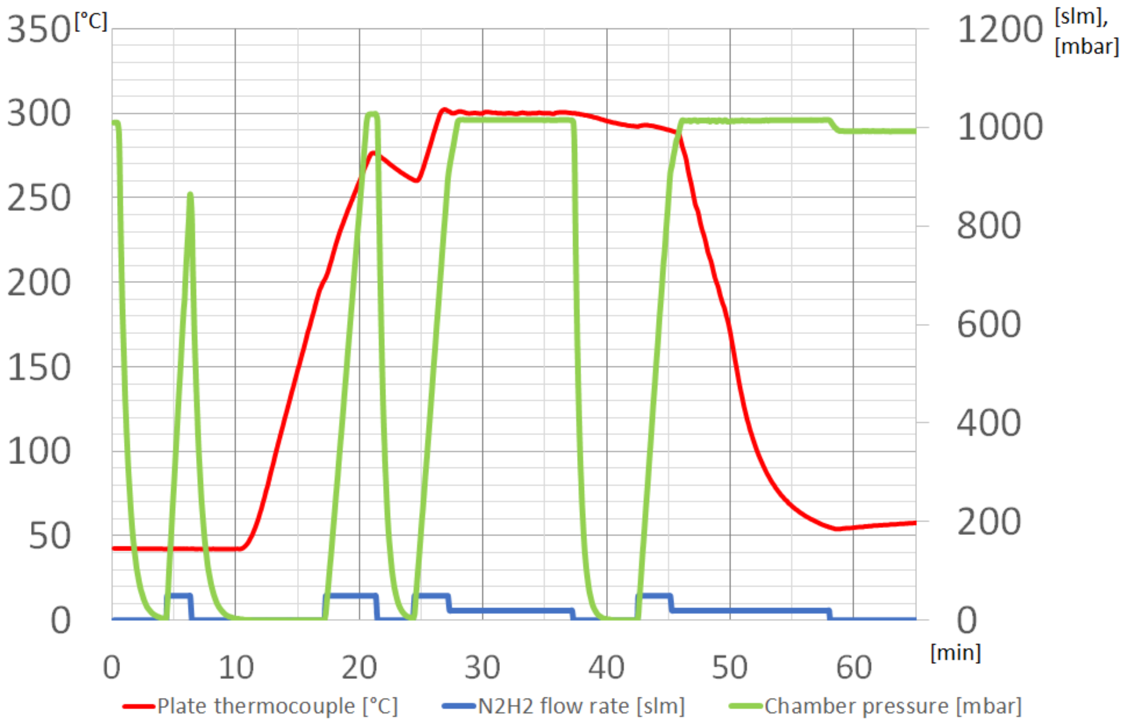


Fig. 3.11: Soldering process of parameter set 5

In this run, four samples were produced for each parameter set. Each one was inspected using X-ray before being analyzed by either SAM or metallographic sectioning. During this inspection, it was found out that some samples from the parameter sets which previously did not show excessive amounts of voids, now had this problem (this was for example the case for the modules from the parameter set 4 using 320 °C and 720s holding time). X-ray images of a sample 4 from parameter set 4 with the big voids highlighted can be seen in Fig. 3.12 and Fig. 3.13.

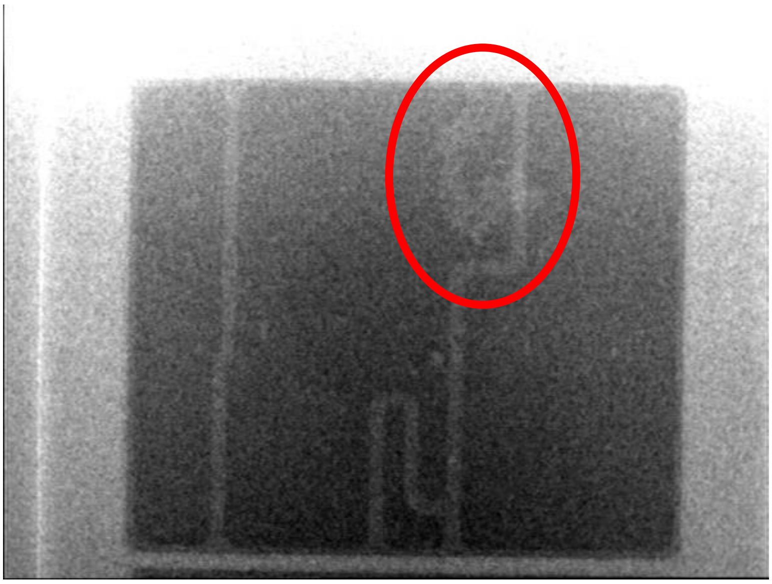


Fig. 3.12: X-ray image of upper PH of a sample 4, parameter set 4

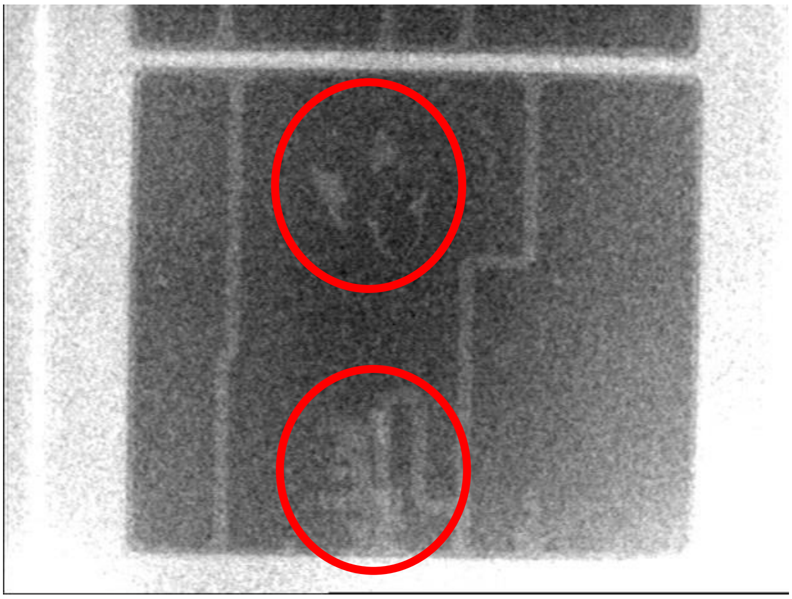


Fig. 3.13: X-ray image of upper PH of a sample 4, parameter set 4

3.3.1 The scanning acoustic microscopy of the samples

The samples number 2 from the parameter sets 1 - 6 were inspected by SAM scanner OKOS VUE 250-P, using a 25 MHz transducer, gate length 30 ns and resolution 80 µm. The scanning was performed with the base plate on the top and the DBCs on the bottom, with the first scans beginning at the base plate – solder interface and then continuing downwards through the sample as shown in The OKOS VUE 250-P scanner in the progress of sample scanning can be seen in Fig. 3.15.

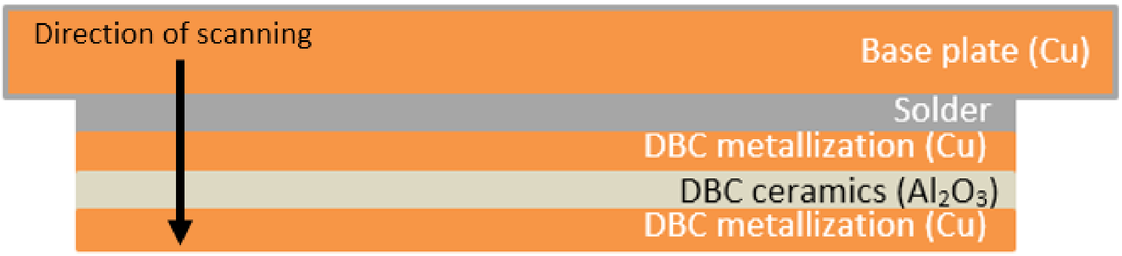


Fig. 3.14: Illustration of scanning direction

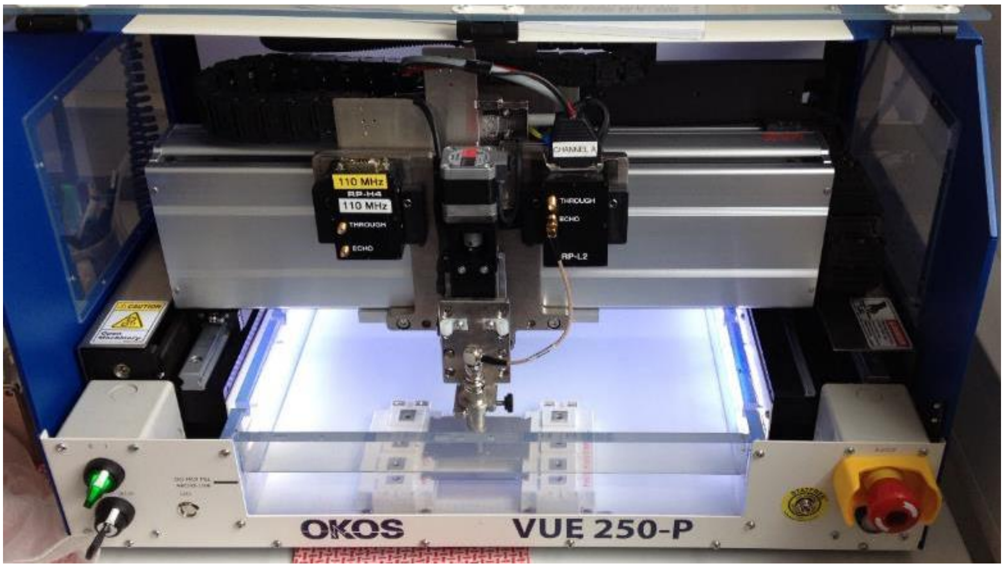


Fig. 3.15: OKOS VUE 250-P scanner in the progress of sample scanning

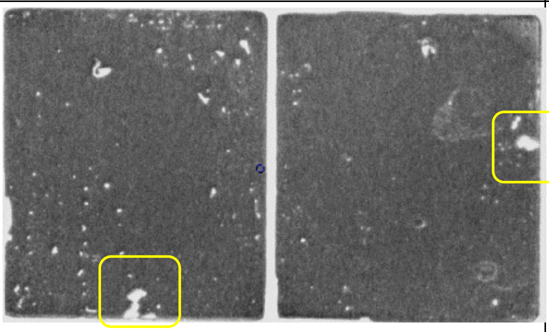
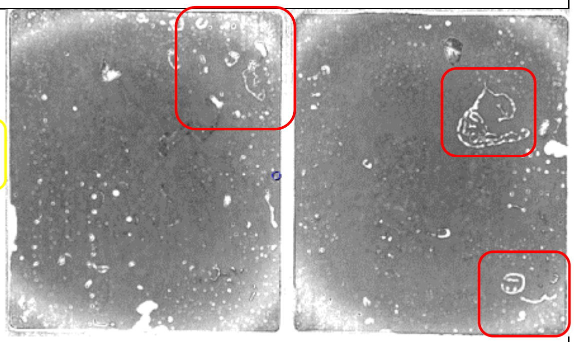
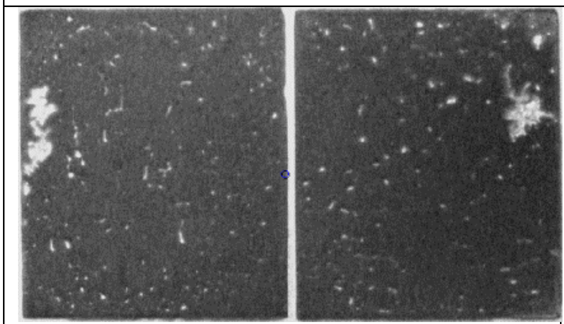
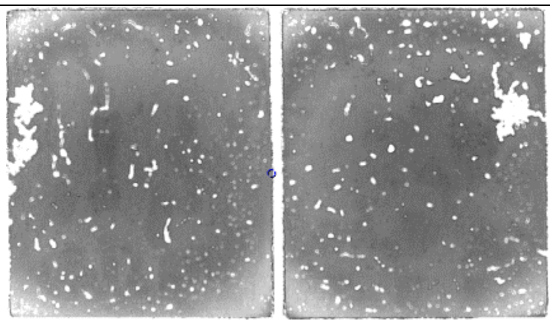
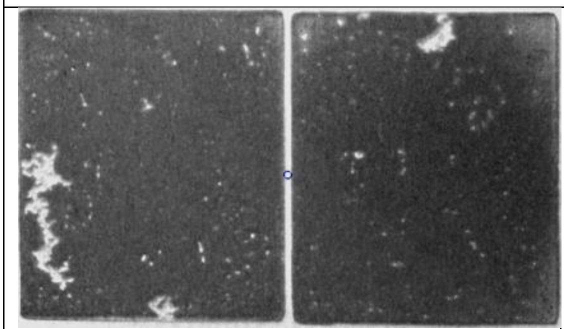
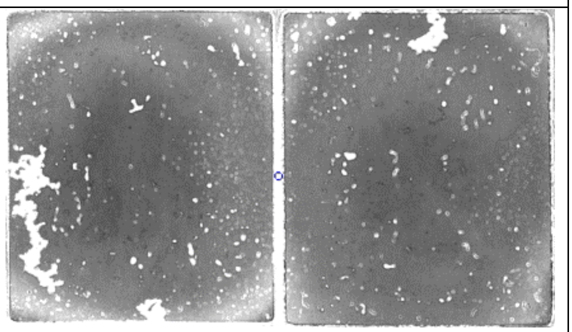
Each sample was scanned in several layers, whose approximate distribution based on their thickness and properties can be seen in Tab. 3.3.

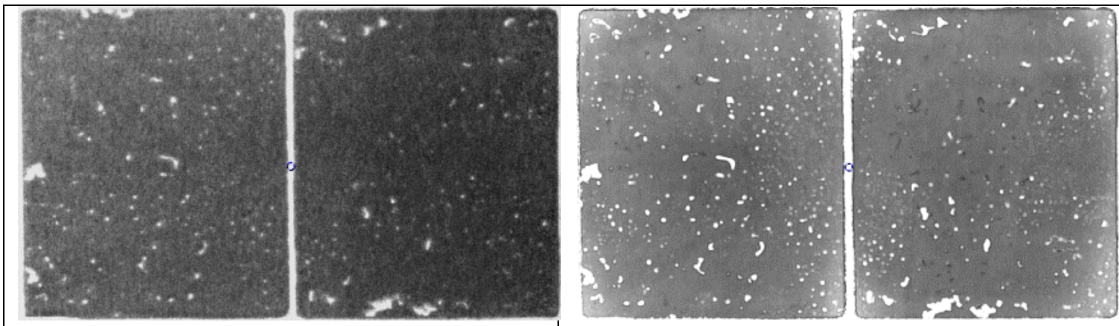
Tab. 3.3 : Approximate scan distribution based on the material thickness and properties

SEMiX 2	**layer thickness** [mm]	**Approximate number of scans**	**Approximate scans distribution**
Cu baseplate	3		
solder	0,1	2,0	scans 1 - 5
Cu metallization	0,3	4,3	scans 5 - 9
ceramics Al_2O_3	0,38	2,3	scans 9 - 10
Cu metallization	0,3	4,3	scans 11 - 14

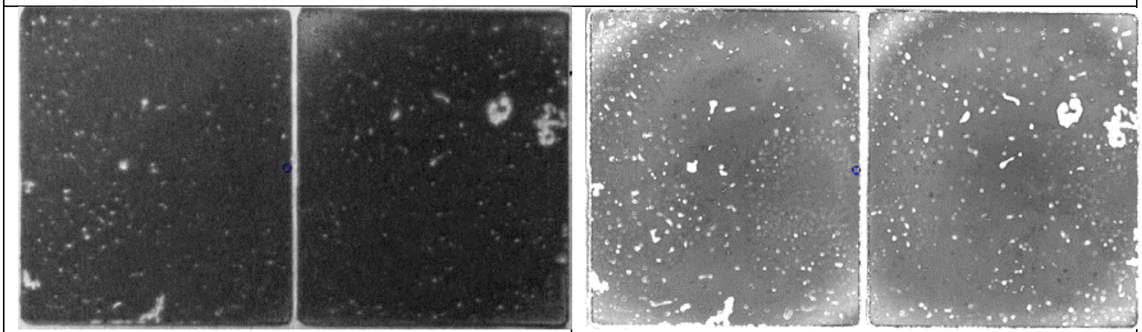
For the purpose of the DBC – base plate soldering evaluation, only 2 scans per sample are needed. These are organized in the Tab. 3.4 with the scan 2 of a base plate-solder interface being in the left column and the scan 5 of a solder-DBC interface being in the right column. As can be seen in the scans big portion of the voids goes through the whole solder layer but some of them are only in the upper/lower solder layers. The examples of voids in lower layer only is highlighted with yellow in the left column and the ones present only in the upper layers highlighted with red in the right column of the Tab. 3.4.

Tab. 3.4: Scans of BP-solder and Solder – DBC interfaces

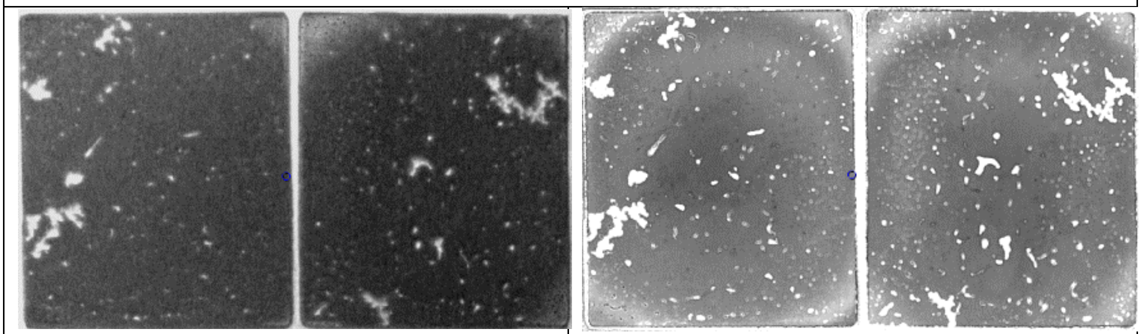
BP – solder interface – scan 2	Solder – DBC interface – scan 5
	
Parameter set 1 sample 2	
	
Parameter set 2 sample 2	
	
Parameter set 3 sample 2	



Parameter set 4 sample 2



Parameter set 5 sample 2



Parameter set 6 sample 2

Only sample from the parameter set 4 can be considered as being without large void areas. Base plate soldering joints in samples from parameter sets 1 and 5 had comparable voids amount, but some larger voids were present. The biggest voids in the soldering joint seemed to be in the samples from parameter groups 2 and 3. It should be noted that large voids in the BP soldering joint are considered more harmful to the thermal conductivity of the module than the little ones. The SAM scans showed voids in all of the samples but some differences can be observed. The estimated evaluation of the voids area is shown in Tab. 3.5 with the 1 meaning the smallest and 6 the largest amount.

Tab. 3.5: Estimated evaluation of the voids area

	Alloy	Main holding temperature [°C]	Holding time [s]	Estimated voids area evaluation
Parameter set 1 sample	Standard	335	720	2
Parameter set 2 sample	90iSC	280	720	5
Parameter set 3 sample	90iSC	300	720	6
Parameter set 4 sample	90iSC	320	720	1
Parameter set 5 sample	90iSC	300	600	3
Parameter set 6 sample	90iSC	300	840	4

The graph in Fig. 3.16 shows the correlation between the soldering temperature and voids area. The two samples (no. 4 and 2) with the smallest voids area in the soldering joint were soldered at the highest temperature values, and on the other hand, the two samples with the largest voids area were soldered at the two lowest temperatures. In other words, the lower the soldering temperature, the larger voids area in the solder joint. This confirms the previous findings where the same dependency was observed using X-ray inspection.

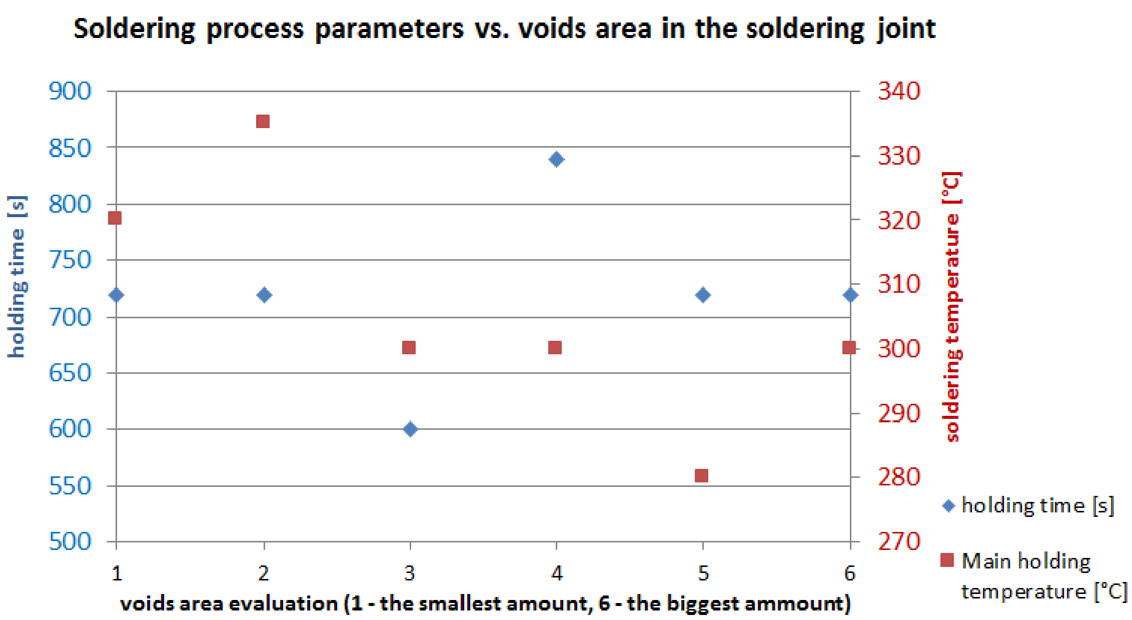


Fig. 3.16: Correlation between soldering parameters and voids area

Results from this small group of samples showed no dependency between the soldering time and the void`s area size. The samples no. 4 and 1, reaching the smallest void`s area, had been soldered at the same holding time as well as the samples no. 3 and 2, reaching the largest void`s area.

3.3.2 Preparation of metallographic sections

Preparation of the samples for the metallographic sections was first tried at SEMIKRON. The samples no. 1 from the six parameter sets were used for this purpose. At first the samples were cut prepared for the casting. This was done with an ordinary hacksaw (Fig. 3.17) with the sample fixed in a bench vice, which is not ideal due to the inability to cool the cut and therefore thermally influencing the sample. At first the top DBC metallization was sawed off and afterwards the base plate, with the solder layer and the bottom DBC metallization. The ceramic layer was then simply broken alongside the cut as it proved too hard to saw (as expected).

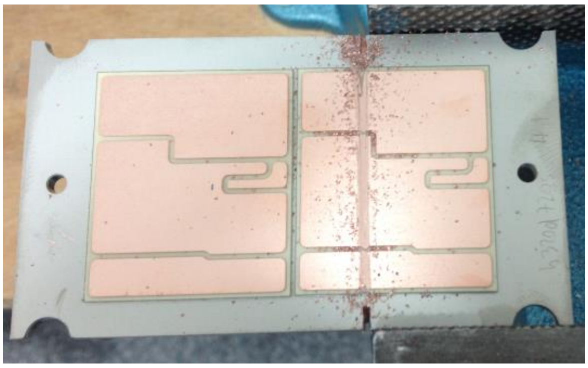


Fig. 3.17 : cutting the samples

The manual sawing process proved very tedious as copper is quite soft material and for the fear of contaminating the samples, no lubricant for the saw blade was used. After cutting, the samples were cast into ordinary two component epoxy using a provisory plastic mold with the samples hanging perpendicular to the mold bottom to prepare them for grinding and polishing.

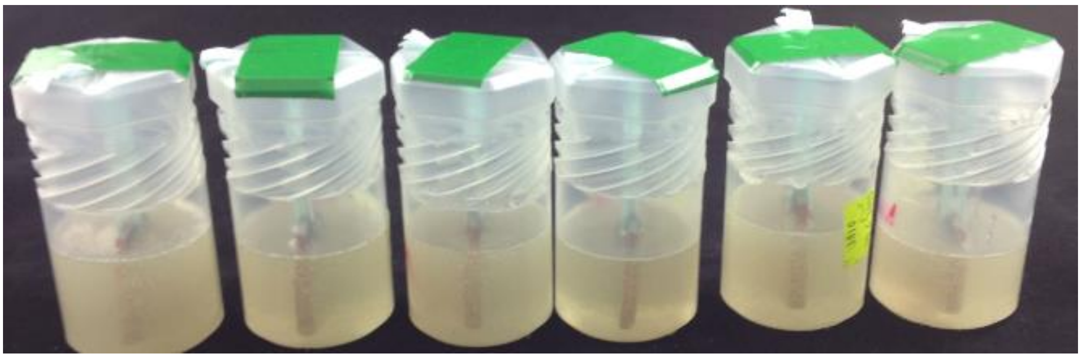


Fig. 3.18: Samples from 6 parameter sets cast into epoxy

To speed up the curing process, the samples were set into a curing oven at 120 °C for several hours.

After removing the samples from the molds, they were then grinded first using rotary grinder with P120 grit sandpaper following with P1000 grit sandpaper for several minutes. Keeping the grounded sample side plane proved very difficult as pressing the sample on the grinding wheel by hand uniformly was not possible.

Fig. 3.19: Grinding the samples on rotary grinder

Following the grinding, the samples were then hand polished using diamond polishing paste spread over plane cloth surface first with an 8 µm and afterwards with 3 µm grain size. The final polishing was done for approximately 15 minutes. The samples were checked under a microscope in between the polishing to check the polish level. Even after several trials of polishing, the sample still showed scratches on its surface and the desired level for solder joint section observation could not be reached. This was caused partly by the fact that the solder joint is only 100 µm across. Maximal polish level reached using hand polishing with 3 µm grain diamond paste can be seen in Fig. 3.20.

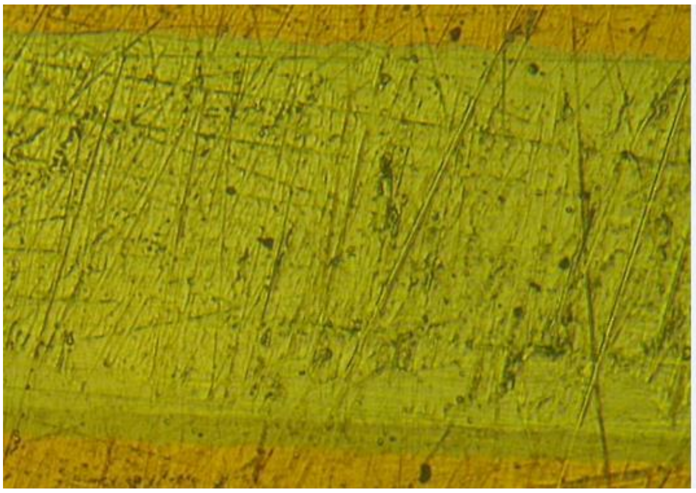


Fig. 3.20 : Maximal level of polish reached by hand polishing

It was judged, that even with smaller grain size paste, the desired polished level for unobstructed solder joint observation could not be reached at the premises of SEMIKRON.

Collaboration with the Faculty of Materials Science and Technology of the Slovak University of Technology was started and three samples were prepared at their laboratories with specialized equipment. The samples chosen were the samples no.3 from the parameter set 1 (standard alloy, 335 °C soldering temperature, 720 s holding time), parameter set 3 (90iSC alloy, 300 °C soldering temperature, 720 s holding time) and from parameter set 5 (90iSC alloy, 300 °C soldering temperature, 600 s holding time).

These samples were cut with a metallurgical cutoff saw with consumable cutting wheel with use of a coolant. The saw with a mounted sample prepared for cutting can be seen in Fig. 3.21.

Fig. 3.21 : Metallurgical cutoff saw used for cutting the samples

After cutting the samples, they were thoroughly cleaned and cast into molds using a two component VariDur® mounting compound. The mounted samples were then ground and polished on a JeanWirtz® Pressair TF250 automatic polishing machine (in process of polishing in Fig. 3.22) with the steps used described in Tab. 3.6.

Fig. 3.22: The JeanWirtz TF250 in the process of polishing

Tab. 3.6 : Steps used to fine polish the samples using JeanWirtz polishing machine

Step	Grit / grain size	Duration
1	P600 sandpaper	4 min
2	P1200 sandpaper	4 min
3	9 µm diamond paste suspension	4 min
4	6 µm diamond paste suspension	4 min
5	3 µm diamond paste suspension	4 min
6	1 µm diamond paste suspension	8 min

Even after all these steps, after checking the samples under a microscope, the finish of the surface still was not sufficient. The final finish was reached with a use of a vibratory polisher VibroMet® 2 made by Buehler® (Fig. 3.23) with a use of a 0,05 µm silica polishing suspension for 30 minutes at 60 Hz.

Fig. 3.23: Vibromet 2 vibratory polisher

After checking the results of this process, the desired finish level of the section surface was reached and the samples could be finally analyzed.

3.3.3 Observing of the metallographic sections

The finished metallographic sections were observed under a Keyence VHX-500F digital microscope using magnifications between the rage of 100x and 1000x with the latter naturally showing the most detail. All the samples showed what could be considered significant amount of intermetallic compounds on the soldered interfaces.

Intermetallic compounds are always created on the soldered interfaces, when the atoms of the elements present diffuse between the two interfaces. Two intermetallic compounds are created on a soldered interface between SAC solder (in our case SnCuInAg and 90iSC alloys, though the base of both of them is SAC alloy) and copper. These are the Cu_3Sn and Cu_6Sn_5 ($Cu_6(Sn,In)_5$ for SAC alloy containing indium [13]) compounds with the Cu_6Sn_5 ($Cu_6(Sn,In)_5$) being created during soldering and the Cu_3Sn during solid state aging [13]. The exact composition of the intermetallic in the solder joint could be measured by Energy-dispersive X-ray spectroscopy (EDX) which this was however not available. The detail of a sample 3 from the parameter set 1 (standard alloy, 335 °C soldering temperature, 720 s holding time) created using 1000x magnification can be seen in Fig. 3.24**Chyba! Nenašiel sa žiaden zdroj odkazov.**. The intermetallic $Cu_6(Sn,In)_5$ and the overall solder thickness are measured using built in Keyence software. Presence of the Cu_3Sn was not noticed as the samples have not yet thermally aged.

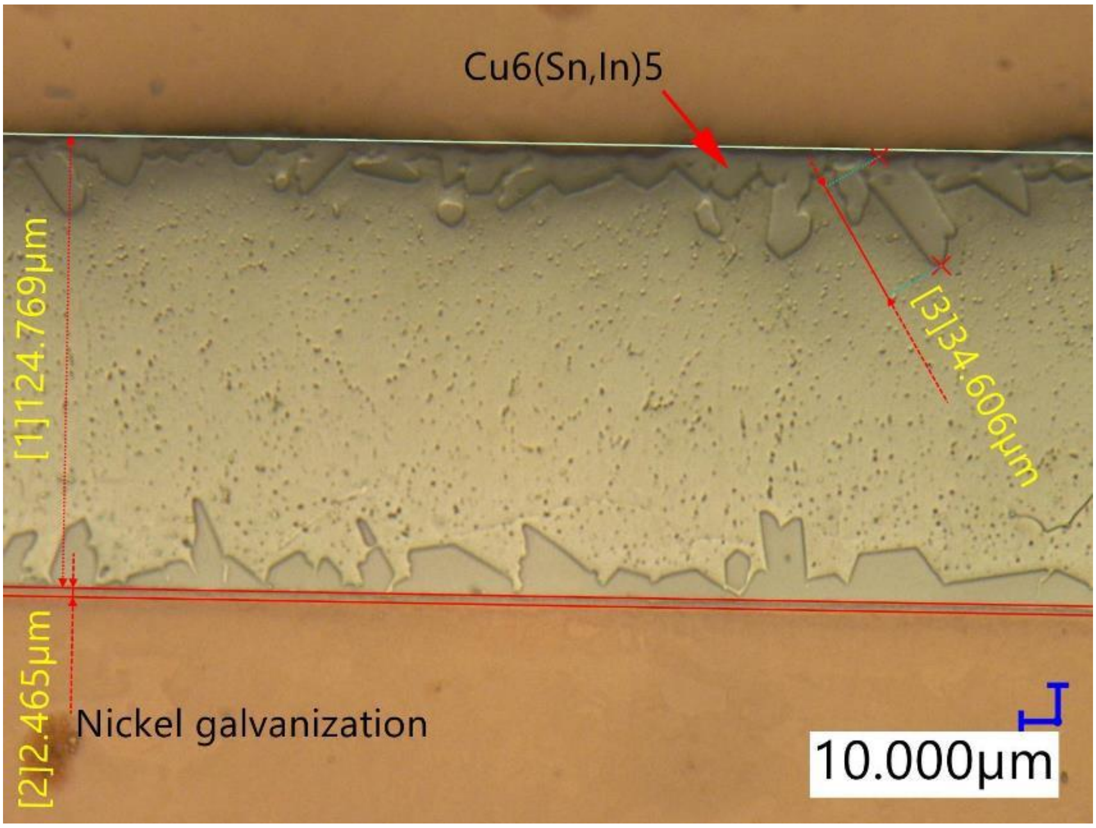


Fig. 3.24 1000x detail of a sample 3 from the parameter set 1

In Fig. 3.25, the same is done for sample 3 from the parameter set 3 (90iSC alloy, 300 °C soldering temperature, 720 s holding time) and in for sample 5 from the parameter set 3 (90iSC alloy, 300 °C soldering temperature, 600 s holding time)

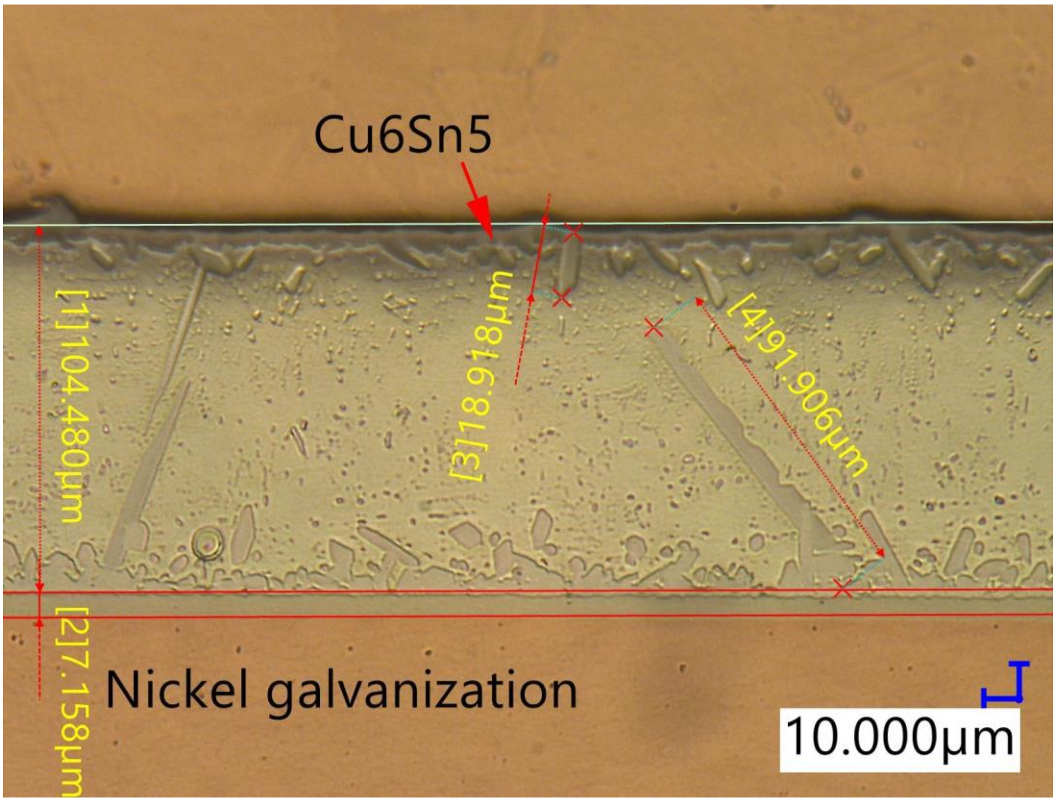


Fig. 3.25 1000x detail of a sample 3 from the parameter set 3

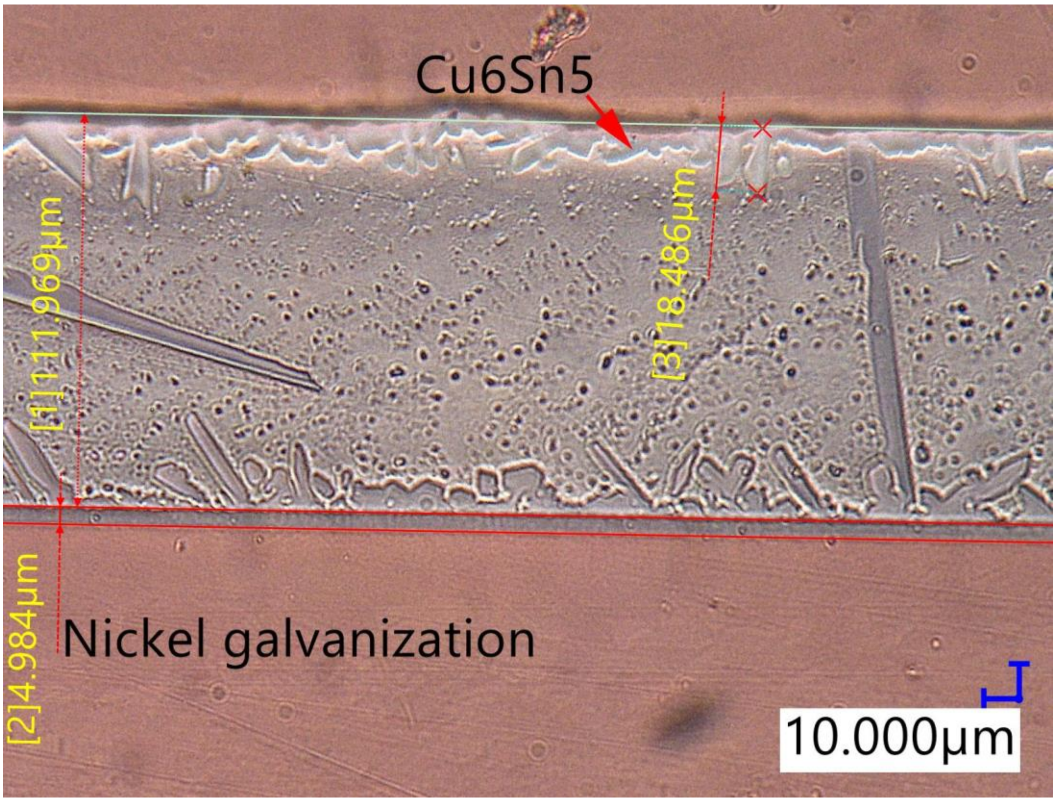


Fig. 3.26 1000x detail of a sample 3 from the parameter set 3

What was observed on the samples is, that the sample from the sample set 1 exhibited larger overall size of the intermetallic on the Cu-solder interface, however it was more homogenous as can be also seen in the above details. The samples from the parameter sets 3 and 5 were largely similar but exhibited many inhomogeneities. The smaller intermetallic size in the samples with the 90iSC alloy was most probably caused by the lower soldering temperature but it was also most probably the cause of the inhomogeneities. It seems then, that the adjustment to the soldering profile, were not optimal for soldering with the 90iSC alloy.

CONCLUSION

Basic description of the power semiconductor modules and mainly SEMiX modules produced by SEMIKRON was given in this work with overview of the technologies used for their manufacturing, with the focus on soldering. Soldering of a direct copper bonded ceramic substrate and a module base plate using a standard alloy and a newly developed high reliability alloy by Henkel (90iSC) was compared, with the reliability of the solder joint in mind, using peel out tests, X-ray inspection, SAM scanning and metallographic sections. As the initial testing showed low mechanical strength of the solder joints with the 90iSC alloy using standard soldering program, influence of the soldering temperature was looked into, with a search for more optimal one. In this testing, increase of the voids presence with increasing soldering temperature was observed. Soldering at 300 °C showed itself as promising, with good compromise between the voids amount and the mechanical joint strength. Samples were then prepared for the SAM scanning and metallographic sectioning with one reference group using standard alloy and soldering process and 5 groups using 90iSC alloy soldered at temperatures of 280 °C, 300 °C and 320°C with 2 groups with changes in soldering time for the temperature of 300 °C. The SAM scans confirmed the dependency between the soldering temperature and voids presence, however a dependency between the soldering time and voids presence on such a small sample group was not observed. Preparation of the metallographic sections was first tried with SEMIKRON facilities, but unfortunately a sufficient polish level of the sections could not be reached. Three samples were then prepared using facilities of Faculty of Materials Science and Technology of the Slovak University of Technology. First one with the standard alloy and process, second one using 90iSC alloy, 300 °C soldering temperature and 720 s main holding time, and the third one using the 90iSC alloy, 300 °C soldering temperature and 600 s main holding time. After analyzing the samples using optical microscope, the intermetallic compounds were observed on the soldered interfaces, with the reference sample having bigger intermetallic layer on the interfaces but overall better volume homogeneity, and the two samples with the 90iSC alloy having smaller intermetallic layer but considerable amount of inhomogeneities. It can be concluded therefore, that even after the changes to the soldering process, the quality similar to the soldering with the standard alloy could not be reached with the 90iSC alloy but it seems that the potential for doing so exists. This, however would have to be proved by further testing.

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LIST OF ACRONYMS AND SYMBOLS

BP – base plate

IMS – Insulated metal substrate

DBC – Direct bonded copper (substrate)

AMB – Active metal brazing (substrate)

PH - Power hybrid