Quality of pressure sintering

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Abstract.

Pressure sintering is relatively new joining technology with very good performance and reliability, making it the technology of choice for automotive power electronics. But the automotive industry demands high quality and reliability and this drives research into better understanding of parameters that influence reliability and failure mechanisms, in order to control quality. In this paper we present an overview of the currently known parameters that influence the quality as well as a number of (potential) measurement and inspection systems that quantify leading and indicative parameters for quality and reliability.

Introduction

Pressure-sintering is a new and disruptive die-attach technology which offers unsurpassed performance and reliability. Compared to traditional technologies such as soldering it offers extremely high thermal and electrical conductivity (Siow, 2014). Because of this high performance it does not only offer opportunities for cost-down (~ smaller products with comparable performance) but it's also an enabling technology for packaging solutions in wide-band-gap materials (SiC, GaN). As a result, Ag-sintering is the packaging technology of choice for most new automotive power electronics in electrical cars (EVs). The main applications are die attach, clip attach, substrate to heatsink and also power modules on inverter.

New technologies also bring new challenges. The automotive industry has high requirements for yield, zero-defect production and traceability. In order to fulfill these requirements, a thorough understanding of all related processes and materials is required. Relevant failure mechanisms need to be identified and reliable measurements methods need to be developed to quantify the probability (the onset of) of relevant failures.

The silver sintering technology has been pioneered by several solder material companies for a number of years (Siow, 2014). Early focus in various publications has been on the superb heat conductivity and high reliability compared to alternative bonding technologies like soft soldering (Greca, 2016). With increased application in the automotive industry the focus shifted gradually towards reliability and hence quality (Le Henaff, 2016; Siow, 2019, p125). The reliability of a sintered joint is affected by a number of parameters:

- The primary process parameters: temperature, pressure and time
- Surface conditions of materials to be joined (cleanliness, metallization)
- Sinter material properties, including shape, homogeneity and distribution of (nano) particles
- Design of assembly to be joined (shape, CTE, mechanical and thermal pressure in assembly)
- Presence of (small) failures (delamination, voids, dendrites)
- Assembly process control

In subsequent paragraphs we will deep dive all of these parameters and discuss their influence.

Temperature, pressure and time.

Temperature, pressure and time are the most import parameters that control the sinter process (see fig. 1). Sinter material consists of agglomerates of small particles (typically nanometer or micrometer sized, or distribution thereof), with a relatively large porosity. Under the influence of pressure and temperature the material is for a certain duration (time) compressed to a higher density with increased electrical and thermal conductivity and adhesion. Accurate control of these parameters can especially be challenging for high volume (industrial) production. Process areas up to 350 x 270 mm^2 are loaded with a high number of products requiring full control to assure the same process parameters over the total surface area.

Temperature: values up to 300º C within a few degrees for the full process area at both the top and the bottom tool via high level tool design; at the same time fast heating and cooling is required for the highest Units per Hour output (UPH).

Pressure: the pressure on all individual dies needs to be well controlled: equal and accurately controlled pressure on defined areas. Pressures are typically in the range of 10-30 MPa. Real-time logging of the pressure on any position assures the required level of quality control.

Time: process times down to 60 seconds assure a high output combined with a high quality of the sintered layer.

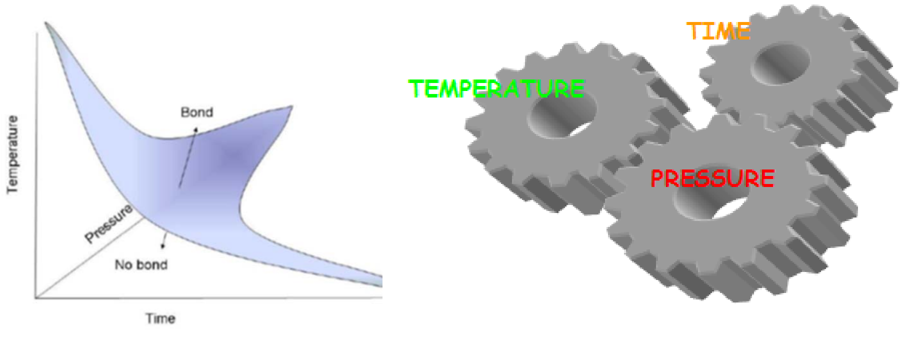

Fig. 1 Schematic view of the three main process parameters for sintering.

In an industrial setting a number of challenges arise even to measure these basic parameters accurately. The process time is typically minimized, optimizing the industrial output but minimizing the available time to measure all other parameters. The total process (tooling) area is maximized – again to optimize industrial output – but that makes it difficult to measure pressure and temperature per individual product that needs to be sintered. Industrial sinter presses utilize a limited amount of concepts to transfer temperature and pressure (see fig. 2) and typically forces and temperatures of a limited amount of positions are measured (cq closed-loop controlled) inside the tooling. The dynamic insert technology enables a defined and homogeneoous pressure on a defined surface area. For optimal quality control (and traceability) of each individual product, Boschman has therefore developed a proprietary sensor technology (patent pending) that integrates an individual sensor unit mounted on the dynamic insert (see fig. 2, right side) for each individual product position that records as a function of time pressure and temperature as close as possible to the actual product. Fig 3 shows a measurement of a single sinter step on a single product for approximately 6 seconds. There are 3 distinced phases visible in the measurement. Intintially the product is loaded into an open tool. After appr 3 seconds, the tool is closed and the product is positioned against the (unpressurized) dynamic insert. After 6 seconds the dynamic insert is activated and the product is subjected to appr 25 MPa pressure during appr 5.5 seconds. After this sinterstep the dynamic insert is de-activated and and approximately 3 seconds later the tool is opened and the product can be removed.

It is during setup of the sinter process often important to measure these parameters in a high level of detail at mutiple positions. Boschman has to that extend developed an Advanced Smart Scope function that allows up to 300 internal + 12 external (sensor) parameters for real-time and precision measurements in high resolution (1 ms) inside the sinter process (tool) area to facilitate process optimization. Once the process is optimized and stabilized, it suffices to fall back to existing (industrial) internal process control and measurments (see fig. 4).

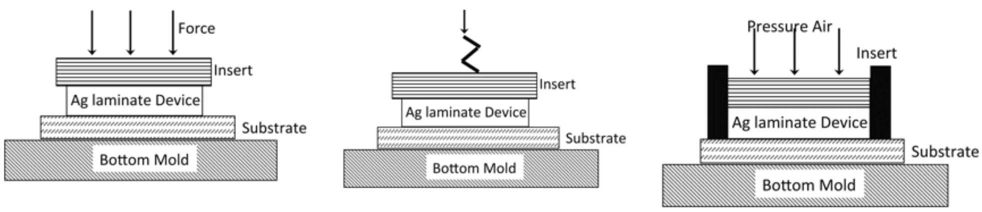

Fig. 2 Industrial sinter mechanisms. Left: static insert, middle: spring-loaded insert and right: dynamic insert technology. Courtesy of Siow, 2019. The dynamic insert technology guarantees a defined and homogeneous pressure on a defined surface area.

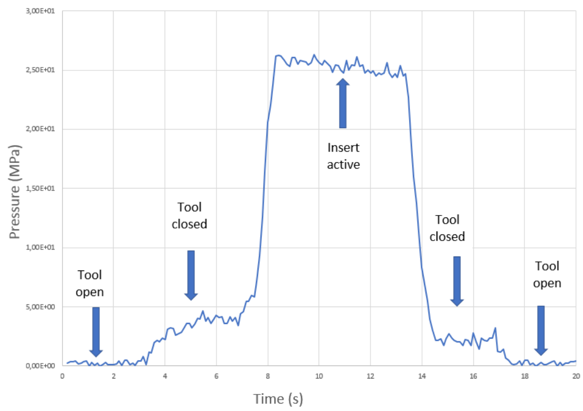

Fig. 3 Detailed pressure measurement on an individual die using a proprietary sensor technology (patent pending) integrated into the dynamic insert technology. Further explanation in the text.

Fig. 4 Boschman Sinterstar Inline F-XL-HC, an advanced industrial sinter press with accurate process control for temperature, pressure and time. The use of dynamic insert technology enables maximum assembly control and verifiable handling.

Surface conditions.

Different sinter materials require different sinter surface conditions. At present mostly silver (Ag) is being used in industrial processes. Copper (Cu) sinter material receives a lot of attention because of its potential reduced costs towards silver, but at present is only used in R&D environments. The easiest surface for Ag to bond to is Ag itself. If Ag cannot be used, noble materials such, as Au, Pd, or Pt are the next useable materials. All these elements can be sintered under normal atmospheric conditions. It is possible to sinter Ag to Cu surfaces, but typically only under protective conditions (eg N_2 shower) to avoid oxidation of the Cu surfaces. There is still little research done to quantify the ppm level of O_2 that needs to be achieved during these protective atmospheric conditions and therefore conditions are often qualified using trail-and-error. It is unfortunately not possible to bond to surfaces that have got dense oxide structures such as Nickel and Aluminum, nor can bare Si or another semiconductor material be used.

As a result, dies and substrate materials are typically metallized with Ag or Au to facilitate the sinter process. In theory the thicknesses of the metallization can be well below 1 µm because the diffusion of the silver does not penetrate beyond 25 to 75 nm into the surface. But in practice the bond-ability of metalized surfaces depends on the quality (density) of the Ag or Au layer. Sputtered layers typically have a very dense structure and can be sintered with thicknesses up to 1 µm. But electro-less or electrolytic deposited layers tend to have a more porous structure and might require a thickness of up to 5-7 µm for optimum adhesion. Although some research is published in literature to quantify optimum metallization conditions (Chen, 2018), little comprehensive information is available to date and specific metallizations always need to be verified during qualification. Prior to sintering, all surfaces need to be clean and a cleaning step (eg plasma cleaning) is typically integrated into an industrial process flow.

Sinter material properties.

Different sinter material suppliers design different micro-mechanical properties for their materials, leading to various Ag particles of a flake shape or spherical shape from nano to micro size dimensions. There is some research that suggests that specific mechanical properties can have an influence on the bond strength: “We found that Ag filler size influences pore shapes, pore sizes, and shear strength; the micron-Ag joint produced a mixture of irregular and regular spherical pore shapes that reduced bond strength more than the predominantly spherical pores present in the nano-Ag joint.” (Siow, Chua, 2019).

More dominantly however are variations during the sinter process itself. Variations in thickness of the sinter material layer prior to sintering or variations in the sinter pressure inside the material layer (inevitably caused for instance by the reduction of pressure at the circumference of the sinter area) will lead eventually to variations in thickness and density (~porosity) of the eventual sinter joint. This can in turn lead to variation in thermal conductivity, giving rise to inhomogeneities in the temperature distribution on the device (hot-spots). Due to thermal cycling and CTE mismatches these hot-spots can lead to thermal failure mechanisms such as delamination.

Design of assembly.

There are numerous factors in the design of a total assembly that affect reliability and ultimately the quality of an including sintered joint. It is beyond the scope of this paper to discuss these all in great details. We will suffice to mention but a few.

Important design considerations include thermal matching of materials (CTE matching), creep voltages, stress relieve considerations, anchoring of soldered and molded structures, absorption of moisture (MSL-level), suitable metallization to avoid oxidation (lead-frames) or improve wire-bond-ability (dies) and more. There is ample literature available on this topic, see e.g. (Pecht, 1994) and (Lee et al, 2007).

One topic worthy of more attention in this context is the subject of clip-sintering. There is a trend in power electronics towards replacing wire bonds with ribbon bonding and (sintered) clips. Wire-bond lift-off is an important failure mechanism in power electronics, hence replacing them with clips (provided designed correctly) can improve the reliability and at the same time reducing parasitic inductance (reducing electrical losses). It is important however to design sufficient stress-relieve functionality into the clip design. See fig. 5 for some conceptional examples.

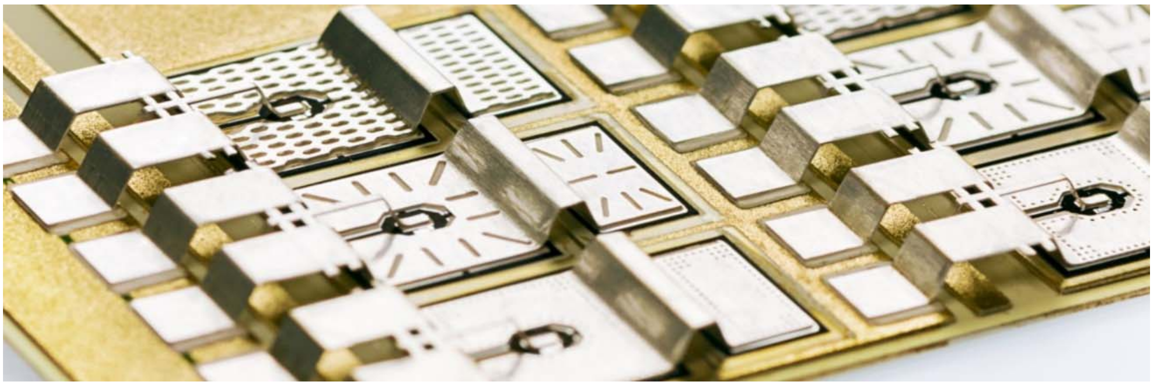

Fig. 5 Several design studies for stress-relieve in clips (Fraunhofer IISB).

Presence of failures.

Comparable to soldering, typical failures associated with sintering are voids and delamination, although objectively to a lesser degree. Another type of failures for sintering is the potential (growth) of dendrites. Small imperfections (nuclei) can under the influence of power and temperatue cycling through diffusion, creep and other physical processes grow and eventually lead to failure. It is therefore important to identify these imperfections with the highest possible resolution in order to eliminate products with the potential for early failure. Voids can be analyzed using X-ray analysis. Provided the resolutions and measurement capacity is sufficient this can also be done in-line but sufficient care has to be taken to ensure radiation safety in the line. Other existing measurement technologies such as for instance Automated Optical Inspection (AOI) or Scanning Acoustical Microscopy (SAM) are for several reasons not always able to fulfill all necessary measurement requirements in the Ag-sinter process. AOI has virtually no capability to visualize buried structures and SAM is difficult to integrate in-line in the production process since it requires the products to be submerged in water and the data can be difficult to interpret. Laborious setups allow for SAM measurements in line while measuring through an impinging water jet and comparing the data to previous measurements of a “golden sample”. See also (Brand, 2016). Therefore, new methods are being developed, including Pulse-Infrared Thermography (PIRT) and Thermo-reflectance (TR). See (Wargulski, 2019). These methods offer fast, contactless and non-destructive full-field thermometric measurement capabilities that can potentially enable 100% in-line production monitoring and thus guarantee quality and provide full traceability. They have shown to be able to achieve a similar reliability in detecting delamination as SAM and X-ray analysis. See in fig. 6 a schematic setup for an in-line PIRT failure analysis.

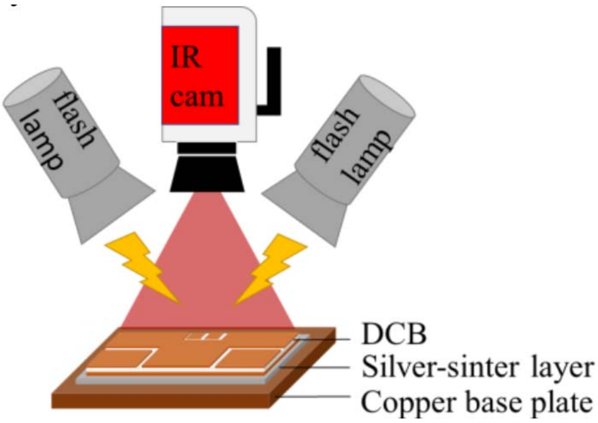

Fig. 6 Schematic of the pulsed infrared thermography failure analysis, courtesy of Berliner Nanotest und Design GmbH.

Silver dendrites are a failure mechanism where under the influence of temperature, voltage and possibly humidity over time small needle-like structure grow through diffusion in between structures of different electric potential. This failure mechanism typically reveals over life time and is not present at "zero-hours". In power electronics the sintered joints are typically fully encapsulated in either epoxy transfer molding compound or potting material. Especially the transfer molding compound prevents dendrites from growing and thus prevents this failure mechanism all together. But in other application such as high-power LEDs, the anode and cathode can merely be separated by a very small air gap (~200-300 μm) and therefore susceptible to dendrite growth. It is imperative to understand the root cause of dendrite formation and take sufficient precautions in the design. See also (Munson, 2014).

Assembly process control.

Handling and positioning during assembly and sintering can have a profound effect on quality and reliability. Sintering usually involves three steps: application of the sinter material, pre-positioning the components (tagging) and finally the actual sinter step.

Application of the sinter material can be done through dispensing, screen-printing or Die Attach Film (DAF). All these methods have corresponding advantages and disadvantages, making them the preferred solutions for certain applications: for instance, very small dies (dispensing), intermediate dies (screen-printing) and large surfaces such as wafer level IGBTs (DAF). Other than costs, the main differentiation between these methods is the capability to apply a homogeneous and defined layer thickness of sinter material on a defined surface area of a certain dimension. Imperfections in the applied sinter material can lead to voids or thickness variations in the sinter joint, both leading to potential hot-spots.

After the sinter material is applied, the components (e.g. dies or clips) that are to be sintered are put in place, typically using tagging or pre-sintering. The ultimate purpose is to keep the components in the right position until the actual sinter process has taken place. Pre-sintering involves applying low pressure (< 3 MPa) and slightly elevated temperature (< 120º C) on the assembly to initiate merely the onset of the sinter process, but not more. In this way the components are firmly in (the right) place and can be safely handled until the final sinter process takes place. During pre-sintering it is important not to exceed the relatively low pressure and temperature to avoid that the sinter process proceeds from pre-sintering into sintering since this would hamper the subsequent real sinter process. If the assembly contains surfaces subject to oxidation (e.g. exposed copper), it might be necessary to apply a low oxygen atmosphere like nitrogen or mixed gas during pre-sintering to avoid oxidation.

Prior the actual sinter process the applied sinter paste is still relatively pliable and can undergo deformation as a result of shocks, vibrations and acceleration. It is important to avoid these deformations since they can result in misalignment, voids, delamination or other failures. Therefore, during handling sufficient care has to be taken to avoid deformation through smooth transport and handling of products and carriers.

During the actual sinter process, the products are typically exposed to pressure (15-30 MPa) and temperature (230º-280º C). Similar to the pre-sintering, a low oxygen atmosphere needs to be applied when the assembly contains surfaces subject to oxidation (like Cu). It is important that firstly the pressure is applied before the temperature exceeds roughly 150º C. On a microscopic scale, the nanoparticles need to be under pressure as soon as sufficient free energy becomes available to start the sinter process. This ensures the densification of the sinter joint. Applying high temperature before applying pressure would result in a very porous sinter joint, leading to poor performance and poor reliability. During sintering accurate control and handling needs to be combined with well-defined and homogeneous pressure. This leads to a homogeneous thickness of the sinter joint, no tilt or other misalignment. Tilt or misalignment can lead to hot-spot and consequently to failures. The dynamic insert technology (shown in fig 2) is ideally suited for this kind of mechanical control, in combination with well-designed sinter tooling (see fig 7). In pressure-less sintering the lack of mechanical control (tooling) is a frequent cause of random misalignment and consequently of failures.

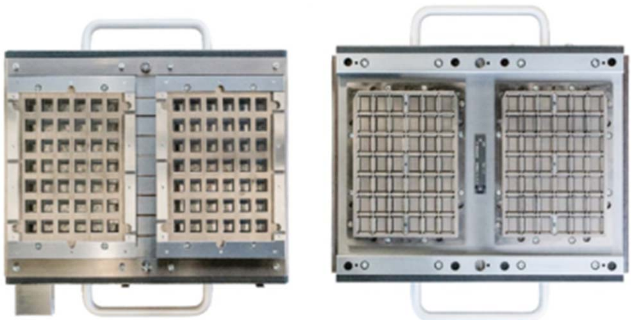

Fig 7. A typical tool design for high volume production of die sintering for power electronics enabling the highest quality control on a surface area up to 350 x 270 mm^2.

After the sinter process misalignment can be measured using Automated Optical Inspection (AOI). Ideally one would not only like to measure the thickness and homogeneity of the sinter joint but also the density of the layer. An indirect measurement of the density can be obtained by measuring the height of the sintered assembly before and after sintering using optical tomography (using the height difference as a leading indicator for the achieved density).

Conclusions.

Pressure sintering has recently become the technology of choice for automotive power electronics. It shows excellent performance and reliability. But the automotive industry demands high quality and reliability and since the sinter technology is relatively young, better understanding of parameters that influence reliability and failure mechanisms is necessary. In this paper we have presented an overview of the currently known parameters that influence the quality such as the primary process parameters: (temperature pressure and time), sinter material properties, design features, presence of failures and assembly process control. Also, a number of (potential) measurement and inspection systems are discussed that quantify leading and indicative parameters for quality and reliability, such as X-ray, Scanning Acoustic Microscopy (SAM), Automated Optical Inspection (AOI), Optical tomography, Pulse-Infrared Thermography (PIRT) and Thermo-reflectance (TR). Not all these inspection methodologies can easily be applied in industrial in-line production lines. Ultimately these quality control methods need to ensure reliability and trace-ability of the products. Under optimum conditions sintering has shown to outperform soldering in performance up to a factor of 3 in thermal conductivity and in reliability up to a factor of 10 in power and temperature cycling, especially at operating temperatures above 200º C, as is shown in several recent publications (Krebs, 2013; Greca, 2016; Le Henaff, 2016; Nagao, 2017; Broughton, 2018; Dai, 2018).

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