Materials Considerations for Automotive Radar Designs: Increasing Reliability in Automotive Safety Systems

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Abstract
Radio Detection and Ranging (radar) sensors require specialized materials and specific tolerances in order to optimize their function. However, although not new to many markets, such as the military and telecommunications, some of these materials and design sets are novel to the automotive industry. Their use is growing rapidly with the increase in autonomous driving and safety systems. Nonetheless, the specific design and fabrication bring challenges to the automotive supply chain.

As the automotive industry takes steps toward fully autonomous vehicles, there is a respective progression of increased safety systems in vehicles. The increase in quantity and function brings significant change to the electrical content and its level of sophistication. Historically, automotive circuit board assemblies were not considered complicated as they did not require fine features or advanced components. Now these aspects are a necessity as many systems require high density interconnect (HDI) designs with advanced packaging to support the processing and function of the safety systems. The processing speeds involved in making safety critical decisions effect design, fabrication, and reliability of the components delivered into the automotive supply chain.

Degrees of autonomy are described in levels from 0 to 5, with 5 being fully autonomous. Today, most cars function on a level of 1-2 with rapid growth in level 3 devices that provide the user conditional automation. This paper will discuss the current areas of growth that support level 3 autonomy, with a focus specifically on radar modules that bring perspectives of distance and speed to surrounding objects. The various systems used to support the automation of driving are housed under the phrase **A**dvanced **D**river **A**ssistance **S**ystems or ADAS.

Advanced safety systems require the car to react in response to external changes surrounding the vehicle. This takes the decision-making process away from the driver, and therefore, reliability is of greater importance than ever. This paper will investigate the chemical process changes needed to improve reliability, specific for radar module builds. It will discuss how radar designs challenge Printed Circuit Board (PCB) fabrication, what reliability requirements are needed, and review certain improvement options necessary to create a reliable system, including packaging considerations.

Introduction

As the automotive industry moves to full autonomy, government bodies, car manufacturers, and their supply chain are preparing by taking steps to develop regulations, technology, and performance requirements for a completely self-reliant vehicle. The ultimate goal is to create a safer traveling environment for those inside and outside the vehicles, which will in turn support improved survivability, less injury, reduced road congestion, and enhanced fuel usage. The journey to this end is described by the Society of Automotive Engineers (SAE) and adopted by the US Department of Transportation in levels of autonomy from 0 to 5. Level 0 incorporates no automation, levels 1-3 have varying degrees of partial assistance to the driver where the automobile, for example, can control steering, acceleration and deceleration, and even interfere with the driver. Finally, in full autonomy, level 5, the car drives on its own and makes all decisions and reactions to its surroundings [1].

The automotive market uses a combination of sensors to make these critical decisions. Sensors rely on varying technology nodes and work in concert with a central computer to understand the cars external surroundings and define the safest driving path. There are multiple types of sensors including ultrasonic, radar, lidar and cameras. Each type has its strengths and weaknesses. Due to the longer-range capabilities and its resistance to all weather conditions, radar designs are the fastest growing sensors in ADAS today [2]. This research will focus on radar designs, specifically long-range 77GHz radar, to showcase how automotive materials are changing and through the choice of alternatives to those conventionally used in the space, how product life and reliability can be enhanced.

This study will take a holistic view of the 77GHz radar sensors as a printed circuit board assembly (PCBA) build, considering circuit fabrication, assembly materials and packaging materials.

Basics of construction

Circuit board materials

Starting with the backbone of the design, the system requires transmission and reception of radio waves through antennas to gather information on objects around the vehicle. This is made as exposed metal circuits on a dielectric substrate material. The length and width of the trace are specifically defined for the frequency that will be used to propagate the signal. Close attention is paid to the height, width and shape of the trace. The critical nature of this part requires that the information which goes out and comes in as a signal is not lost or altered. To ensure minimal disruption, the antenna is created on a "low loss" substrate material. The term low loss refers to the dissipation factor (Df), which is described in physics as a loss rate of energy of oscillation [3]. This is exactly the technology used in airplanes to inform pilots of their surroundings especially when visibility is limited.

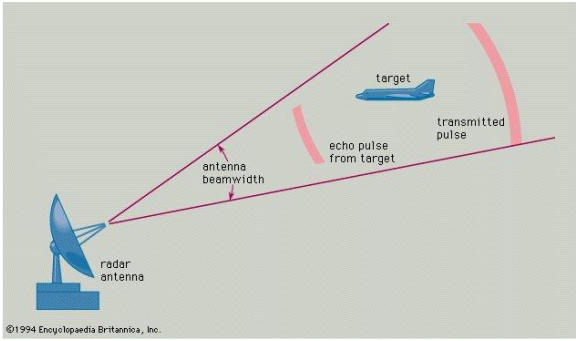

Figure 1: transmit and receive

Initially, radar sensors for automotive applications were designed for a 24GHz frequency with a bandwidth of 250MHz. This is referred to as narrow band (NB). This frequency is shared by scientific, industrial and medical (ISM) uses. For automotive, the 24GHz applications were mostly used for blind spot detection. Using 24GHz was determined to have limitations such as a lack of resolution and accuracy which led to the adoption of 77GHz. The 77GHz frequency delivers improved resolution of the system which enables it to separate closely spaced objects. This improved accuracy delivers a better understanding of objects distance [5]. In addition to blind spot detection they are used for lane departure warning and collision avoidance.

The European Telecommunications Standards Institute (ETSI) and the Federal Communications Commission (FCC) developed regulations to phase out 24GHz use for automotive applications. These regulatory changes and the need for increased performance has caused a shift to 77GHz [6]. The increase in frequency requires a change to the substrate used. As frequency increases, the more the signal is being carried on the outer edges of the conductor. This is known as the skin effect. As the signal approached the edges of the conductor there is more opportunity for dielectric loss due to competing interactions within the design. This includes circuits that are in close proximity to each other.

The 77GHz designs require enhanced low loss dielectric materials to achieve the level of reduced loss over their 24GHz counterparts. As a response, substrate suppliers created dielectric made of Polytetrafluoroethylene or PTFE that are ceramic filled. These are designed to have specific electrical stability, very different from the traditional resin filled glass weave substrates known as FR4 that the automotive industry uses for other applications including infotainment, body control or even engine control. Being in the radio frequency range requires a very low dissipation factor. By comparison, the Df value of FR4 is 0.20 compared to ceramic filled PTFE which is 0.002. With the desired electrical properties, there are some challenges. These materials are higher in cost and require altered fabrication processes. Due to the critical nature of the safety application, the ceramic filled PTFE is by far the most heavily used for 77GHz radar safety designs.

Polytetrafluoroethylene substrates are well established materials for military, aerospace and some telecommunications applications but care should be taken when processing; especially when considering the volume that these designs will approach as autonomy levels increase. The material is deformable, which means it can scratch or bend easily with handling, it is highly chemically resistant, requiring different cleaning and conditioning preparation steps prior to copper plating. Additionally, PTFE ceramic filled material has a very high porosity which can and will absorb solution throughout the PCB fabrication. Some chemicals will attach to the fillers in the substrate. Special attention is to be paid to the process cycle parameters to successfully manufacture the precision required for antenna designs. It is recommended to follow the suggestions detailed by the substrate supplier.

Understanding that the base material is the first source of loss associated to the design, a second opportunity for loss is on the conductor or the metal circuit formed as the antenna. The conductor in this work is copper. The substrate comes to the PCB

fabricator with a thin layer of copper foil which is printed and etched, then plated to the desired thickness with electrolytic copper plating. The width, height and roughness of that copper is important for signal propagation. The final step of the fabrication process is to coat the copper with a finish which will resist oxidation and preserve the rest of the design prior to assembly protecting the exposed antenna in end use. Conductor loss can occur depending on the type of surface finish chosen. For the purpose of this paper, the types of surface finishes and their effect on insertion loss will be discussed. The testing will determine if coating thickness plays a role in performance consistency.

Assembly Materials

The function of an electronic system is driven by semiconductor packages which are attached to the surface of the PCB. Details of the packages will be discussed in the next section, packaging materials. For now, it should be realized that, these components are joined to the circuit board using a solder alloy. Most assemblies are achieved by printing a solder paste, placing the components on that paste, and then forming an intermetallic bond when passed through a reflow oven. During this process flux material prepares the surface for attachment and is volatilized to leave the metal alloy and residual flux residue behind. The resultant solder joint creates a mechanical bond and an electrical pathway between the component and PCB.

Traditionally, tin/lead was the solder alloy used for all of electronics. In 2006, the European Union, China and California banned lead due to the health concerns associated with it [12]. The electronics industry moved to the tin/silver/copper (SAC) alloys used today. The automotive market enjoyed an exemption through 2010 because they are considered a “high reliability” application. Eventually, the exception ran out and the same SAC alloys used by the other markets were adopted.

The most obvious challenge for a solder alloy (in automotive applications) includes harsh operating conditions as devices operate close to the engine and are exposed to extreme weather conditions. Concerns surrounding product life and reliability are directly connected to the environmental exposures and the expected high-performance processing and function required for life critical functions.

It is well documented that thermo-mechanical forces put stress on the solder joint. Heating of the solder joint is realized two ways, from the function of the design and/or the location of the systems. For example, devices close to the car engine can see operating temperatures approaching 150°C. Thermo-mechanical stress can result from multiple aspects, such as vibration of the unit, or exposure to temperature fluctuations. The most common in all electronic systems is movement of dissimilar materials as a result of heat. The dissimilar rates of expansion between a stiff component and that of a PCB creates a coefficient of thermal expansion (CTE) mismatch that degrades the solder joint over repetitive temperature cycles. Ultimately, the majority of stress from everything moving is directed to the solder joint which then fractures rendering a loss of electrical contact from component package to the circuit board [8].

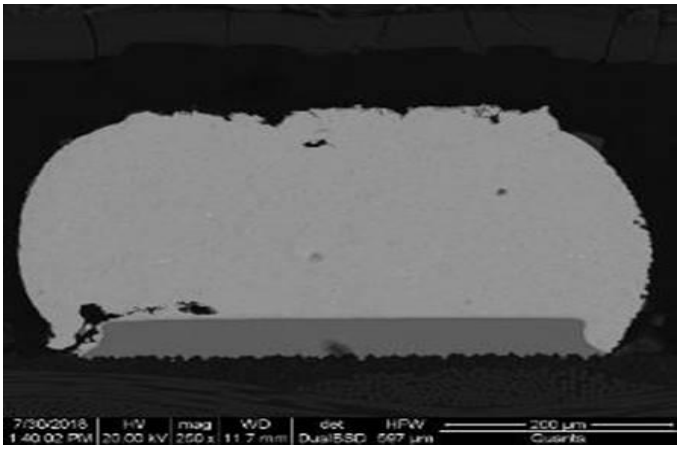

Figure 2: solder joint crack

When an alloy is exposed to prolonged thermal or mechanical stresses, it will experience a deformation called creep. Creep will occur at elevated temperatures when the atoms are most mobile [9]. In the early 2000s, an industry consortium was created to address the challenges in automotive electronics as a result of greater environmental stresses and increased component performance needs. Car makers, tier ones, and material suppliers organized a consortium to develop new alloys that could improve thermal resistance, specifically thermal cycling, while maintaining SAC305 reflow temperatures. The resulting alloy, Innolot, was patented in 2003 and comprised a SAC based material with alloying additions to alter the microstructure and enhance creep properties at higher operating temperatures [8].

Alloy development incorporates four major areas of focus: solid solution strengthening, diffusion modifiers, grain refinement and precipitate strengthening. Differences in composition will result in microstructure difference which in turn effect mechanical properties. The Innolot alloy was able to realize not only an improvement to thermal exposure, but also resistance to high stress, before it will fracture or rupture.

Table 1. Physical property comparison of SAC305 and Innolot

Physical Property	Units	SAC305	Innolot
Melting Temp. Range	°C	217/221	212/220
Thermal Conductivity	W/mK	62	55.2
Specific Heat	J/gK	0.23	0.22
Density	g/cm^3	7.37	7.46
Hardness	VHN	7	15
Young's Modulus	GPa	49.9	46.5
Tensile Strength (25°C)	**MPa**	**35.23**	**83**
Yield Strength (25°C)	**MPa**	**23.2**	**60**
Elongation (25°C)	%	33.5	17.8
Tensile Strength (150°C)	MPa	15.7	23
Yield Strength (150°C)	MPa	15	21
Elongation (150°C)	%	46.5	20
Creep Elongation at Rupture (150°C)	**%**	**38**	**21**
Creep Rupture time (150°C)	**Hrs.**	**9.1**	**18**

This work will further illustrate that the choice of solder alloy, Innolot, will extend the life of a product even when exposed to significant thermal stresses. Testing will include the surface finishes examined in the insertion loss study mentioned above.

Packaging materials

As mentioned earlier, the function of any electrical system comes from the IC substrate packages. The final area of discussion for this work, focuses on material changes to enhance the reliability of these components. In radar sensor designs, it is the components that generate the radio frequency, direct the energy, and identify the information that is retuned. Moving from 24GHz to 77GHz, brings greater resolution to the information gathered surrounding the car. The increased power and processing require a change to the chosen package first. Designs supporting 24GHz, utilize quad flat packs which contained a low input/output (I/O) count on the order of 32 pins.

The 77GHz designs require increased I/O and with that, a transition to a ball grid array (BGA) package with about 180 connections. A ball grid array offers a number of advantages over the leaded component such as increased density, as previously mentioned, but without the concern for solder bridging during assembly and greater heat conduction. Heat can travel more easily to the PCB on a ball grid array. This decreases the heat experienced by the silicon chip during its operating life. Lastly, and likely the most important for the 77GHz radar sensor, the BGA provides low inductance. The short distance between the package and the PCB reduce signal loss or distortion [14].

This main BGA component used to function the antenna is called a MMIC or monolithic microwave integrated circuit. In the construction, the die is attached to the substrate using a solder alloy or a conductive adhesive. The final portion of this study will investigate a thermal conductive adhesive attachment of die to the substrate as a tool for thermal management of the die. Pulling heat from the die will extended the package life. The thermal conductivity will be measured to understand the material differences. In addition to longer package life, the adhesive is another avenue to eliminate lead in automotive designs. Highly filled silver adhesives, such as the hybrid silver sintering die used to attach materials can offer performance benefits above and beyond solder materials.

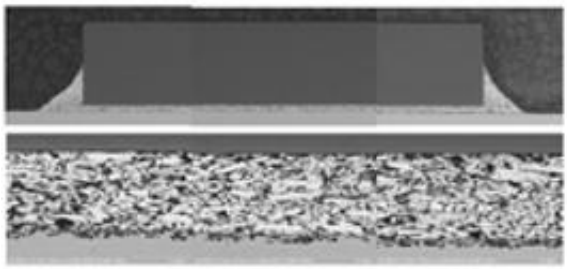

Figure 3: Cross section of die attached by thermal conductive adhesive

One of the first areas of concern is getting a previously stored package through standard assembly processing. The defect of concern is delamination of the epoxy mold compound with reflow exposure. During storage, packages can absorb moisture prior to assembly. There is a risk that the heat from the reflow will volatilize the moisture, thereby putting pressure on the epoxy and pushing that epoxy from the rest of the package, resulting in a defect known as "popcorning."

All packages are rated on a moisture sensitivity level grading as documented by IPC J-Std 020D, a moisture sensitivity classification for non-hermetically sealed surface mount devices [15]. End users want to ensure the components can be stored for extended time prior to assembly and that they function reliably in their final build. Though more of a concern for leadframe packages, attention should be paid to all larger devices especially for critical applications. This testing will ensure that changes made for improved thermal transfer from the die, will not adversely affect overall package construction.

Table 2. IPC/JEDEC J-STD-20D MSL classification

			Soak Requirements			
	Floor Life		Standard		Accelerated	
Level	Time	Cond degC/%RH	Time (hrs)	Cond degC/%RH	Time (hrs)	Cond degC/%RH
1	unlimited	<=30/85%	168+5/-0	85/85	n/a	n/a
2	1 year	<=30/60%	168+5/-0	85/60	n/a	n/a
2a	4 weeks	<=30/60%	696+5/-0	30/60	120+1/-0	60/60
3	168 hours	<=30/60%	192+5/-0	30/60	40+1/-0	60/60
4	72 hours	<=30/60%	96+2/-0	30/60	20+0.5/-0	60/60
5	48 hours	<=30/60%	72+2/-0	30/60	15+0.5/-0	60/60
5a	24 hours	<=30/60%	48+2/-0	30/60	10+0.5/-0	60/60
6	TOL	<=30/60%	TOL	30/60	n/a	60/60

Automotive test conditions

The automotive industry has always relied on accelerated tests such as thermal cycling in air to predict the quality of a design and its model's ultimate product life expectancy. Principles derived from the Coffin-Manson equation enables predictive modeling of solder joint lifespan by accounting for the effect of plastic deformation of a material over a specified temperature range and dwell time [12]. The resulting equation predicts that the rate of deformation of the solder joint will increase as temperature extremes become further apart and cycle time increases. Radar designs serve a critical role in safety as the automotive industry moves towards complete vehicle autonomy. As such, the performance requirements of the devices are held to a higher standard. The market defined levels for high and low temperature ranges are typically based on expected operating temperatures of the device. For example, interior systems are tested to a lower peak temperature than those for engine control simply due to the operating environment. Safety systems such as radar start to blur the lines because they may or may not be located in harsh areas. Also, the duration or length of the accelerated tests have been increased for safety systems due to their critical nature.

Table 3. Thermal cycle test conditions

	Test condition	Duration (cycles) requirements				
		Powertrain	Body	ADAS	Chassis & Safety	Infotainment
Temperature cycling	-40 / 150 °C	2000		2000	2000	
	-40 / 125 °C		2000	3000	3000	1000
	-40 / 105 °C					1500

To simulate the environments of automotive electronics, accelerated tests are used specific to functioning electronics. They include thermal cycling and sensitivity to moisture.

Test procedures

For this experimentation each material change was tested separately to understand its full performance improvement or lack thereof. For a production build, it is recommended to test the parts both separately and as a full construction to understand the improvements that can be realized for a specific application. To test the various levels of the PCBA, automotive industry methods were used. All reflow processes were held to the IPC J-Std reflow profile which is considered a more aggressive profile due to the long soak zone and high peak temperature. For all testing, a peak temp of 250°C was used. Thermal cycling was tested against an aggressive thermal cycling profile of -40°C to 160°C, with 10 min dwell, for 2000 cycles.

Surface finish effect on insertion loss

To understand insertion loss differences between surface finishes, the microstrip differential phase length method was used. Microstrip test vehicles created from a leading PTFE substrate material specifically used for 77GHz radar designs, were fabricated in a production environment. The strips were processed in pairs measuring 50.8 and 203.2 mm (2' and 8") length each having a width of 0.75". For ease of handling the 5-mil thick PTFE based material was adhered to an FR4 backing layer for rigidity. The test vehicles were plated with the following production available surface finishes; high temperature organic solderability preservative (OSP), immersion silver (Imm Ag) and immersion tin (Imm Sn). Each finish was coated to both a thin and thick level following technical datasheet process parameters and conditions. This was chosen to illustrate any effect of oxidation due to coating porosity for the OSP and immersion silver, or any influence of the immersion tin intermetallic compound growth. In addition to the microstrips, specific thickness coupons were added for separate thickness measurements based on the requirements for each surface finish. These included strip and UV absorption of the OSP, and coulometric reduction of the tin, to determine pure tin versus intermetallic compounds which may have formed under conditioning.

Factors

- Surface finish: organic solderability preservative, immersion silver, immersion tin
- Coating thickness:
  - OSP 0.2 and 0.6 microns
  - immersion silver 0.15 and 0.25 microns
  - immersion tin 1.0 and 1.3 microns
- Conditioning: two reflow exposures with 250°C peak temperature

Responses

- Plated thickness: ultra violet visible absorption, x-ray fluorescence and electrochemical reduction
- Growth of tin IMC – coulometric reduction analysis
- Appearance before and after conditioning – visible
- Insertion loss

After coating of the surface finishes, the thickness was determined on thickness test coupons using a UV dissolution method for the OSP, x-ray fluorescence for the silver and coulometric reduction for tin.

Table 4. Plating process cycles

OSP	Imm Ag	Imm Sn
Cleaner	Cleaner	Cleaner
Rinse	Rinse	Rinse
Microetch persulfate based	Microetch persulfate based	Microetch persulfate based
Rinse	Rinse	Rinse
Precoat	Predip	Predip
OSP coating	Immersion silver	Immersion tin
Rinse	Rinse	Rinse
Dry	Dry	Rinse aid
		Dry

Microstrip parts and additional thickness coupons were sent to the Rogers Corporation research facility for insertion loss measurements before and after 2 exposures to a reflow profile with peak temperature at 250°C in a 7-zone convection reflow oven.

Insertion loss measurements were taken for each circuit across a wide range of frequencies on a Keysight model #N5251A. The insertion loss data was gathered as coated and after two exposures to the reflow oven. Samples were then returned for post reflow thickness measurements and appearance observation.

Solder alloy effect on solder joint integrity

As previously mentioned, the initial investigation of an alternate alloy to SAC in the early 2000s was to improve solder joint reliability for high temperature applications. Though radar systems are not considered to have the highest operating temperature in a vehicle, they are tested to extreme peak operating conditions to effectively stress the solder alloy and distinguish its performance characteristics.

An active and passively monitored test vehicle was used for the solder joint integrity evaluation. The active test vehicle included 15 BGA84 components daisy chained for in-situ resistance measurements throughout the thermal cycle conditions. The second test vehicle consisted of passive components such as 1206 and 0805 resistors for shear strength testing measurements at defined intervals. Shear strength testing is a commonly accepted indicator of solder joint reliability, as it relies on the assumption that mechanical reduction of a solder joint over thermo-mechanical aging leads to failure of the electronic circuit. For this work, the same surface finishes used for insertion loss were also tested in conjunction with the solder alloys. Only the upper thickness levels were used to reduce the test size. It should be noted that this work only includes a portion of the fully executed solderability testing. More information can be shared upon request.

Factors

- Surface finish:
  - organic solderability preservative (OSP) 0.6 microns
  - immersion silver 0.25microns
  - immersion tin 1.3 microns
- Solder alloy: SAC305 and Innolot
- Reflow profile: 250°C peak temperature
- Thermal cycle conditions: -40 to 160°C with 10-minute dwell times at the extremes
- Conditioning prior to shear testing: 0, 1000 and 2000 thermal cycles -40 to 160°C

Responses

- Electrical resistance in excess of 20% of initial resistance for 5 consecutive readings as per IPC 9701 A
- Shear strength (kg)

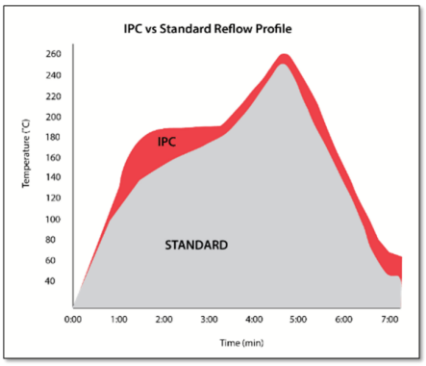

Figure 4. Comparison of standard reflow profile with soak zone to IPC profile with straight ramp

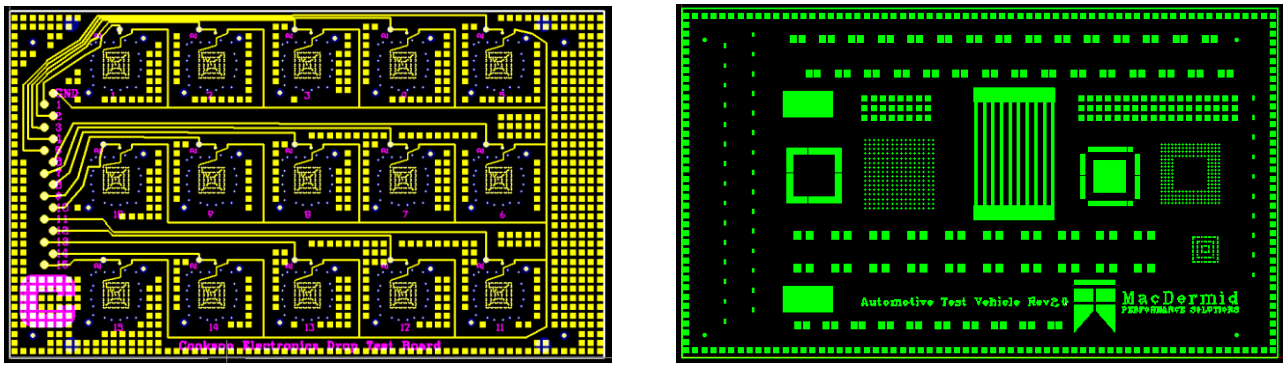

Figure 5 (a and b). Thermal cycle test coupon containing BGAs b) Automotive Test Vehicle for shear strength evaluation

In total, 15 components per test vehicle and 3 test vehicles (figure 5a) per condition were measured. Including three surface finishes in the evaluation resulted in a total of 540 measurements taken. The BGA designs were arranged in a daisy chain to allow for in-situ measurements. Failures was identified as a condition where electrical resistance of the device increased in excess of 20% of initial resistance for 5 consecutive readings as per IPC 9701 A.

Shear strength was analyzed before and after 1000 and 2000 thermal cycles. Shear testing was executed on the 1206 resistor for the "automotive test vehicle" shown in figure 5b. Parts were tested for high speed shear (1000microns/sec) evaluation at 0, 1000, and 2000 cycles to estimate the effect of thermal cycling on solder joint strength. The test vehicle is an 8-layer board which includes multiple BGAs, LGA, MLF and resistors for evaluation.

Material choice for enhanced thermal management from the die

As device complexity increases and motor vehicles are asked to do more, the subsequent increased processing power leads to increased heat generated [15]. Removal of this heat from the die within the IC substrate will promote improved performance of the package and extended life. Standard ICs use materials that remove 2-10W/m-K, today greater thermal transfer is a necessity. For advanced safety systems such as the MMICs used on the radar designs, the desire is greater than 10W/m-K. It is common to use a thermally conductive adhesive for heat transfer from die to leadframe. A new thermal conductive adhesive is available which can be used with metal or substrate attachment. The material combines micron silver flake, thermoset resins and diluents to form the die connection. An improvement over conventional die attach materials, this leading-edge technology provides higher thermal transfer. It can be used as a replacement for solder in the die attach which is another avenue to remove lead containing materials in the electronic build. The technology also promotes lower resistance or less loss when compared to solder, enhancing the electrical performance.

To prove the performance of this material, thermal conductivity was measured at 175°C for a 60-minute exposure. Laser flash equipment was used to measure the thermal conductivity of the die attach material. The effective thermal conductivity (K-eff) is typically measured in a multi-layer format, this enables the analyst to understand all factors of contact resistances at the interfacing surfaces [16]. A plastic BGA measuring 7mm x7mm was used to test the performance of the thermally conductive epoxy in comparison to the conventional material. In a production environment, the material was ink jetted in an "x" pattern on the substrate followed by die placement. The epoxy was cured at 175°C for 1 hour. The die was then wire bonded and the package was completed with final encapsulation. Parts were analyzed by x-ray for any evidence of delamination after MSL 3 preconditioning.

Results

Surface finish effect on insertion loss

In agreement with previous work executed by Rogers Corporation, the OSP and immersion silver resulted in the same insertion loss as the bare copper control [17] when analyzing from 0 to 80GHz. The graphs for both finishes overlay regardless of coating thickness or reflow conditioning. Immersion tin had the greatest loss compared to the bare copper control and as the frequency increased, the delta between the two became greater. Tin also showed a significant difference when comparing as plated to post reflow conditioning.

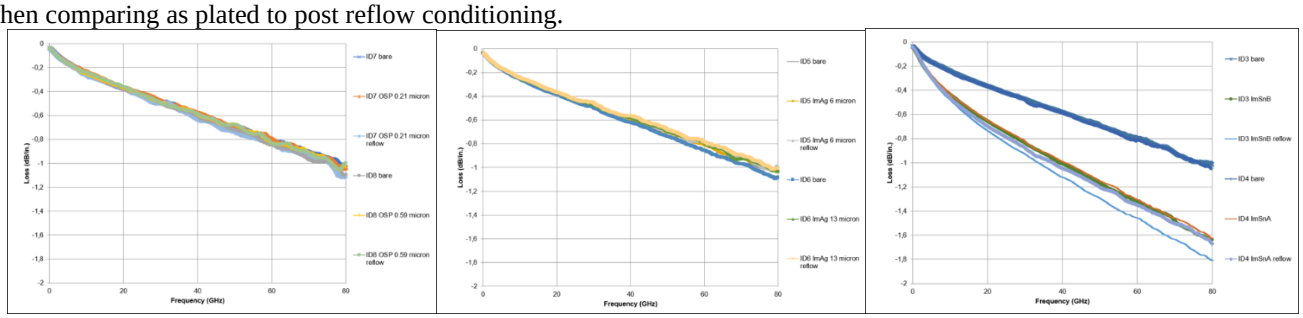

Figure 6 (a, b and c). Insertion loss of OSP, Imm Ag and Imm Sn at two thickness levels and with and without reflow

When focusing on the 77GHz measurement, the insertion loss comparison between finishes becomes clearer as shown in Table 5. The tin insertion loss is about 0.2dB/in greater than the bare copper, OSP and immersion silver. This might not be a concern for lower frequencies, but it becomes a concern for systems operating at higher frequencies. In addition, the thicker tin deposit has greater losses after reflow conditioning.

It is known that immersion tin thickness changes with heat exposure which is not a characteristic for OSP or immersion silver. Pure tin was measured on the same coulmetric equipment to determine thickness change after the two reflow conditions. Three readings per sample were taken to calculate an average. The sample initially coated with 1.0 micron of pure tin averaged 0.2 microns remaining which results in an estimated intermetallic compound (IMC) layer of 0.8 microns. The samples plated to 1.3 microns had 0.35 remaining pure tin and an estimated IMC layer of 0.95 microns. The changes in insertion loss could be attributed to the greater amount of IMC compound. Additional work will be done to get a more precise answer for why the tin performance is different with reflow conditioning.

Table 5. Insertion loss measurements at 77GHz

OSP	As coated (dB/in)	2x reflow (dB/in)
OSP 0.2 microns	-1.00	-1.05
OSP 0.6 microns	-1.03	-1.02
Imm Ag 0.15 microns	-0.99	-1.01
Imm Ag 0.33 microns	-0.99	-0.99
Imm Sn 1.0 micron	-1.57	-1.60
Imm Sn 1.3 microns	-1.60	-1.77

Only the thin OSP coating displayed a change in appearance after reflow exposure. It can be described as a slight darkening with more iridescence. Even with the slight change in appearance, there was no detriment to insertion loss. Immersion silver did not experience any appearance change and no change in insertion loss was observed. The immersion tin also did not display any visible appearance change but the change in insertion performance was observed over the range of frequencies tested. Proper choice of surface finish is important at 77GHz frequencies.

Solder alloy effect on solder joint integrity

The strongest factor found to influence thermal cycle resistance was the type of solder alloy selected. For all surface finishes tested, the Innolot alloy exhibited the highest resistance to cracking and thus lowest propensity to change in electrical resistance over continual thermal cycles by outperforming the SAC305 baseline by over 25% on average. The -40/160ºC was specifically chosen to effectively evaluate the creep resistant properties of the solder alloys. Given predictive modeling, lower temperature extremes would result in higher cycles to failure. Additionally, given the failure criteria as defined by IPC 9701 A, a change in resistance of greater than 20% does not indicate the resultant device is no longer electrically functioning.

The interaction and resulting Weibull plots suggest minimal variation in between the finishes with immersion tin exhibiting the highest propensity to change in resistance. Results suggest the amount of free Sn affects the failure rate due to continual exposure to higher temperature ranges. Further investigation of these results will be examined in future work.

The immersion silver and Cu OSP surface finish resulted in 63.2% of the parts tested passing resistance readings above 1750 cycles as illustrated by the Weibull plots for the Innolot alloy on the challenging thermal cycle profile described above.

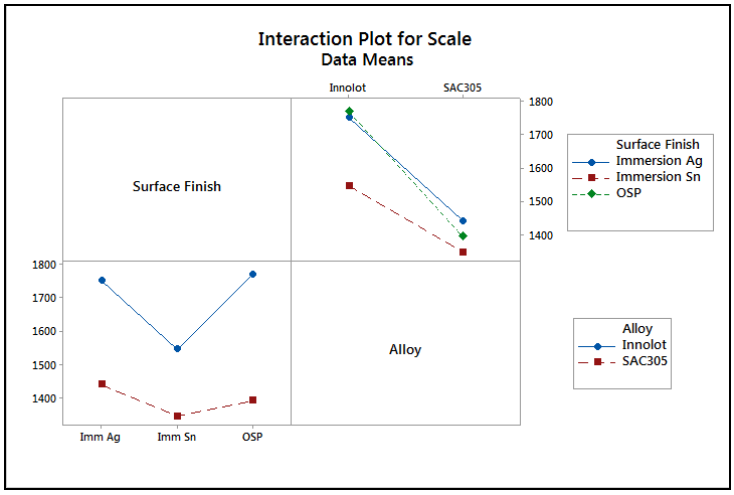

Figure 7. Interaction plots for thermal cycle testing

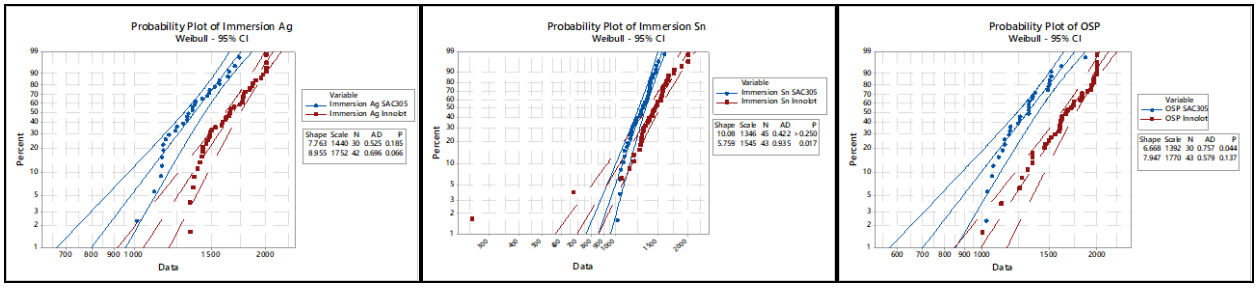

Figure 8. Weibull plots for thermal cycle testing

The passive component test vehicle results aligned with the results seen on the actively monitored BGA devices. As expected from the sum of squares calculation, shear strength of both alloys was affected most by the number of temperature cycles. However, the Innolot solder alloy exhibited the lowest rate of shear strength reduction over 2000 thermal cycles relative to the SAC305 baseline. The results indicate that the design of the Innolot alloy is more resistant to mechanical reduction over the number of temperature cycles. Similar to the active device test vehicle, shear strength was found to be consistent across each of the surface finishes evaluated. In each of the instances, a Tin rich Cu6Sn5 intermetallic is formed. Ultimately, regardless of alloy or surface finish, the largest rate of reduction in shear strength occurs between 0 and 1000 thermal cycles with the Innolot alloy maintaining a significantly higher shear strength over 2000 cycles relative to SAC305.

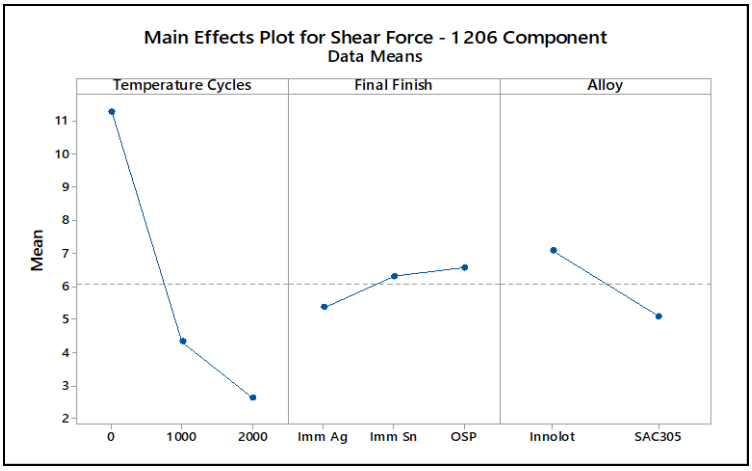

Figure 9. Main effects plot for shear strength

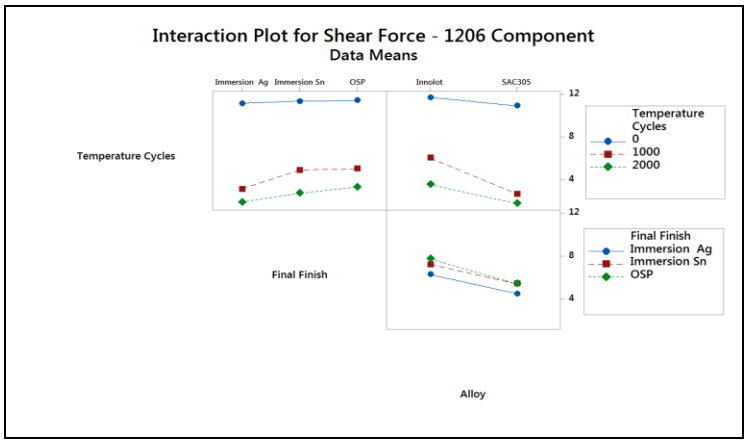

Figure 10. Interaction plots for shear strength

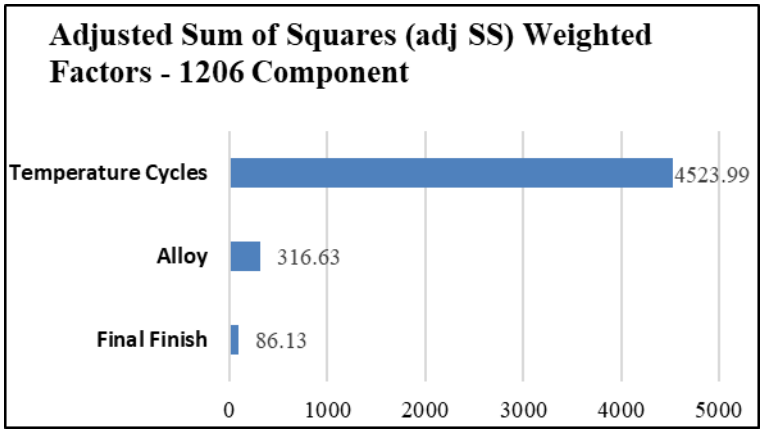

Figure 11. Sum of squares for shear strength

Thermal management of die

Bulk conductivity does not accurately predict the thermal resistance of a package. It does not consider interfacial resistance between the die and the adhesive. The previously developed "effective" conductivity test resulted in a dramatic improvement from the high silver and hybrid silver adhesives. When compared to a conventional epoxy die attach, the hybrid silver sinter material showed was almost 3 times greater at 14W/m-K compared to 5W/m-K. As this was demonstrated on a bare silicon die, another advantage is realized compared to leaded solder materials and eutectic gold-tin. It does not require back side metallization.

A PBGA measuring 7mm x7mm was used to test MSL resistance at 260°C. Parts were checked by x-ray for delamination after preconditioning to MSL 3 exposure. No evidence of delamination or voiding were observed. The new adhesive does not pose a threat to the required epoxy mold adhesion.

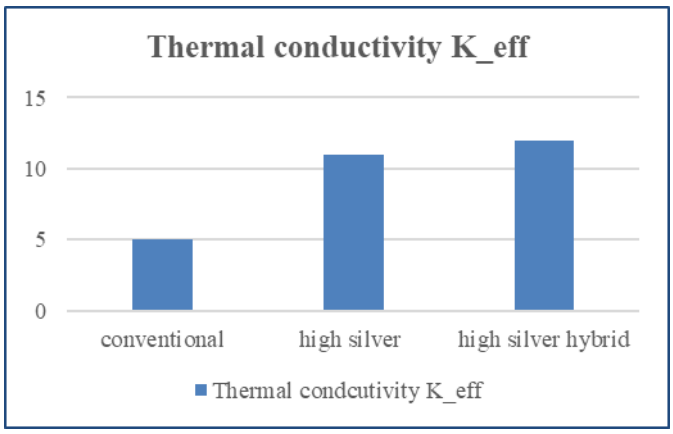

Figure 12. Effective conductivity comparison W/mK

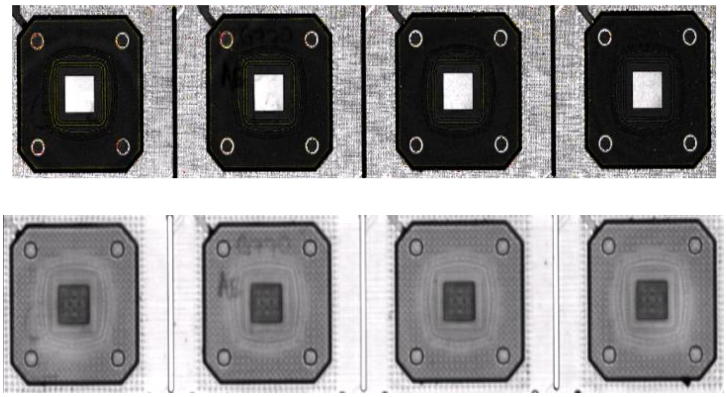

Figure 13. X-ray images to determine adhesion loss

Conclusions

Significant advances are happening in the automotive space to deliver greater safety to passengers and pedestrians around the vehicle. These enhanced safety requirements utilize specialized technologies with enhanced requirements to achieve success. AS this research demonstrates it is imperative that the proper surface finish be chosen for high frequency applications. Enhanced solder alloys such as Innolot are a requirement to withstand the aggressive thermal cycle conditions required for advanced safety. Innolot in this testing shows a dramatic increase in thermal cycle resistance with superior shear strength. Lastly, the hybrid silver sintering adhesive will also extend product life by improving the thermal transfer away from the die.

Each of these materials provides improvements over the incumbent but could realize even greater improvement when used together in one design. It is critical to test individual material changes as well as those combined in the final design build for a complete understanding of end use life and performance.

Acknowledgements

This work was a group effort, I'd like to extend a my appreciation to all those involved including the MacDermid Alpha circuitry, assembly and semiconductors groups, the Rogers' team and my marketing team for all their help.

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