Interconnect and Packaging Techniques for System Integration of High Power Assemblies that Improve Assembly Efficiency and Design Flexibility

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Abstract

Growth in electrification and power conversion is driving a large need for electrical efficiency and improved cost models that in theory can be gained through the design consolidation of secondary assemblies into complete single modules. To put this theory into practice, there must be a cost effective way to interconnect these subassemblies that is space efficient, easy to assemble, supports high power and is resilient to temperature cycles.

To integrate subassemblies cost effectively is to develop them so that they have interconnects between each subassembly that are an integral part of the subassembly itself and are not secondary add on or bolt on connector systems. Additionally these interconnects must be easily pluggable, to allow assembly methods that are manufacturing friendly, measureable and don't require secondary heating methods.

This paper will show how proven highly reliable interconnects like press-fit, IDC and wirebonds can be integrated into subassemblies along with capacitors, motors, DBC power substrates, thermal coolers, heats sinks, busbars and other subassemblies typically found in power assemblies, to create a cost effective design that provides flexibility in manufacturing assembly with measureable results.

Key words

Connectors, High Current, Power Modules, Power-Stack, Press-Fit, Solderless.

I. Introduction

Electrification is driving tremendous market growth in the power inversion and conversion market. Advancements in chip technology, like the drive from Silicon to GaN and SiC [1], are increasing overall power density that challenges the overall packaging configuration for better heat dissipation and lower inductance to support faster switching speeds. High power chips need to ideally connect to their subsystems with the lowest possible number of interconnects and short current paths to increase efficiency.

Present high power connections are made with nuts and bolts, large wire harnesses and soldering. These traditional methods are out-of-date with the advancements made in the development of power systems.

In order to take advantage of the chip advancements, the adoption of solderless interconnect systems, such as press-fit, insulation displacement connector (IDC) terminals, wire bond and direct weld methods, provides the most cost effective approach to next generation power module packaging.

When these solderless interconnect systems are integrated into the subsystems and the overall packaging of a power system, fewer connections are possible, shorter connections points are made, assembly methods become efficient and the power system can become one integrated package and a true efficient "power stack" assembly.

II. An Integrated Packaged Assembly

For power modules, the general industry standard for interconnection and assembly remains one of soldering. Solder methods introduce secondary heat issues and a propensity for bad joints, cold weld, assembly inefficiencies and connections that are non compliant to CTE mismatches. To accommodate the power handling requirements, methods of either bolting or welding harness connections are employed. These methods are assembly process intensive and result in larger overall assemblies with longer current paths and higher overall packaging inductance in the assembly. Multiple subassemblies involve interconnect systems between power circuits and their supporting control circuits such as link capacitors, bus bar/board systems and harness networks. These all add to the BOM cost, increase assembly complexity and grow the overall physical size of the power assembly.

The ideal approach to the packaging of a power system subassembly is to design and equip the subassemblies to be an integral part of the complete assembly. To do this it is necessary to equip them with features that allow them to fit within the total package. Here the ideal solutions are interconnects that are pluggable, can carry high current, have short current paths and are compliant to CTE mismatches.

The major step change is to reconsider the use of new developments in the established technology of 'press-fit' and IDC connections in the module packaging design. New developments in this interconnection methodology, when combined with wire bonding, allow for the development of "3D" assemblies with efficient power handling, good thermal dissipation and robust connections with smaller sub-assembly units that can have considerably reduced manufacturing costs. Fig.1 shows a layout for an assembly utilizing a housing with integrated press-fit leads and industry standard power lead couplings.

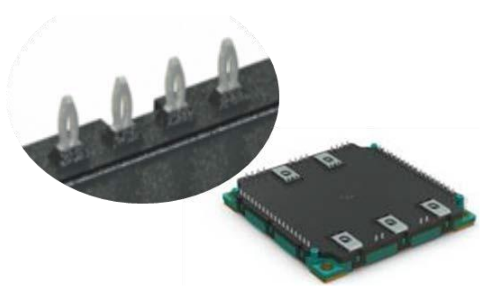

Fig.1 A typical power module utilizing press-fit

Standardizing interconnect types and integrating them into the package housing simplifies the process methods by enabling the assembly to be built within the overall package. It is now the challenge to design all subassemblies to be integrated within the overall package and in a sense make them integrateable units. The design process needs to consider all possible ways to integrate the press-fit options in order to eliminate cables, bolts and other specialty connector systems and reduce current paths. The use of these connector systems also allows for redundancy with little to no extra costs and reduces overall assembly size and weight.

III. Press-fit Technology in Power Connections

A. Basic performance and connection

Press-fit interconnections come in a wide variety of options and have a wide range of interconnection advantages however the "eye of the needle" (EON) type has been one of the preferred choices for robust and harsh environments [2] as they meet vibration and temperature profiles beyond 150^{o}C. EON types are repeatable connections that make direct contact with the PCB, rather than through solder, so there is no risk of voids or solder volume variables to affect the reliability of the joint. These types of Press-fit are now available in a range of sizes and in various alloy options that support high current. They are flexible with high retention and exhibit low contact resistance through all environmental conditions [3]. This enables a cost effective, process friendly system that can be easily measured and monitored throughout the assembly process.

However, particularly in a power assembly, the ability of the assembly to dissipate heat is one of the largest factors contributing to a connection's current carrying capacity.

B. Current carrying capacity

It was once thought that solderless connection technologies carried less current than a soldered joint, but the new generation of high normal force press-fit connections allow direct contact with plated through holes in the PCB. This enables a much better heat transfer and use of high performance alloys with conductivities of up to 80% IACS, achieving high current densities.

Conductivity ability has three key factors when using press-fit technology; size, material selection and thermal dissipation. At a certain size or cross section of a high force solderless connection, thermal dissipation becomes more of a factor in the ability for any connection to carry current.

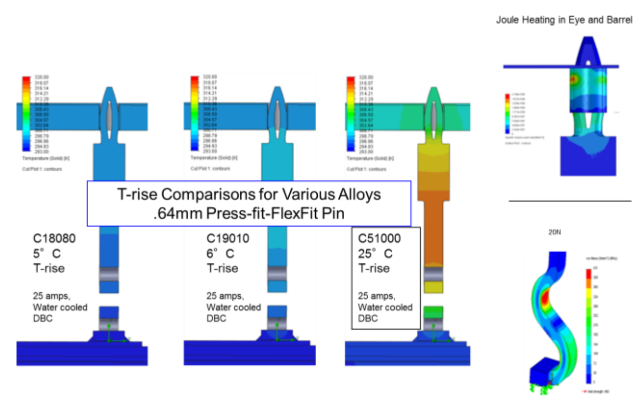

Fig. 2 Thermal analysis model of alloy performance

In the simulation shown in Fig.2 the model uses data for a typical copper flexible press-fit terminal that is SMT soldered to a DBC. Three copper alloys were compared: 15% IACS (C51000), 40% IACS (C19010) and 80% IACS (C18080). There is clearly a large difference in temperature rise from the 15% IACS to the 40% IACS material, but hardly any difference between the 40% to 80% IACS. Since the 80% IACS material has a limited supply chain, limited availability and is more expensive, the engineering decision is to choose the 40% IACS as this will not degrade performance and will yield a better commercial cost and availability.

For verification of the simulated analysis current carrying comparison tests were completed using a setup of PCB test coupons designed to take a range of press-fit sizes. All the test coupons had 3.5 mm wide, 3 oz copper traces, top and bottom and 1 oz copper plated through holes, spaced 7.5 mm apart. The current flow across (through) two adjacent connections was measured, along with the temperature at the joint. Measurements were done on various cross sections and materials.

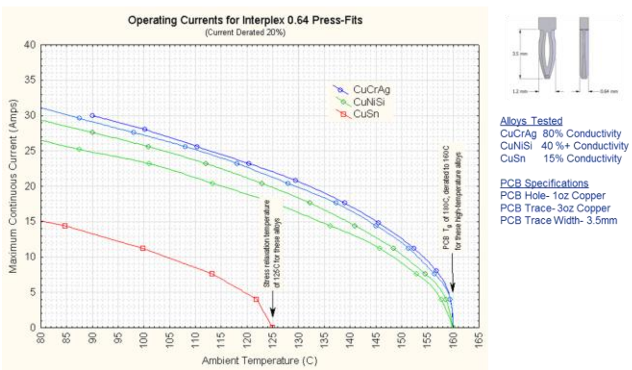

Fig. 3 Press-fit connection current carrying capacity

The results shown in Fig. 3, for a 0.64 mm thick EON connection,\ clearly show the effect of temperature on current carrying capacity as well as the effect of material choice. Similar results were achieved for connections with 0.8 mm and 1.2 mm thick materials and these also indicated the limitations of using the 15% IACS CuSn alloy materials. Overall, the results verified those achieved in the simulated analysis in that the CuNiSi 40% IACS materials perform sufficiently well to justify their selection as preferred materials.

C. Mechanical performance

Press-fit solderless interconnects have been used in a variety of applications for over 40 years and many have been redesigned for increased normal force to give better retention while still being compatible with IEC press-fit standards. These redesigns have mostly been driven by the automotive industry where operational temperatures reach up to 175°C with on engine vibration profiles with a maximum acceleration of up to 20G [4]. As shown in Fig.4, the connection retention force of a 0.8 mm EON press-fit is well within the region of 80-100 N for normal operational environments.

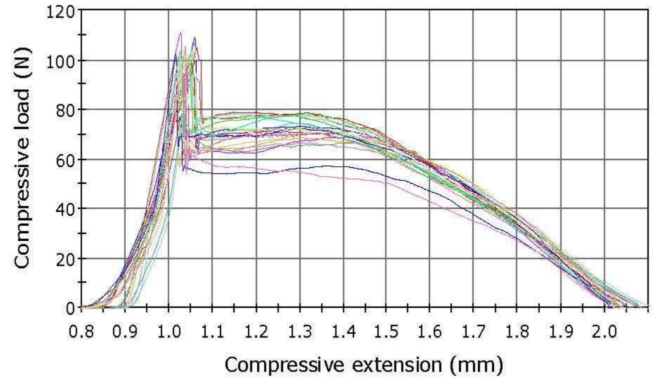

Fig.4 – 0.80 mm press-fit retention force curves

The latest developments of EON press-fits come in a variety of sizes, use high performance materials, have high temperature compatibility and high normal force with stable contact resistance of typically under 0.5mΩ for the product life. In fact, as shown in Table 1, following test of parts under the vibration profile aforementioned, with a temperature range of -40 °C to +150 °C, the average contact resistance remained well below 0.2mΩ. These characteristics make such high force contacts very compatible for high power applications.

Table 1. Test Group - Vibration in Temperature

	Final Contact Resistance mΩ			
Gauge	0.64mm		0.80mm	
Sample#	min hole	max hole	min hole	max hole
1	0.14	0.17	0.08	0.11
2	0.15	0.19	0.07	0.13
3	0.14	0.15	0.09	0.12
4	0.12	0.17	0.10	0.13
5	0.13	0.17	0.12	0.14
6	0.14	0.18	0.10	0.13
7	0.16	0.17	0.10	0.15
8	0.16	0.19	0.12	0.14
9	0.16	0.20	0.12	0.12
10	0.15	0.17	0.11	0.11
Min	0.12	0.15	0.07	0.11
Max	0.16	0.2	0.12	0.15
AVG	0.145	0.176	0.101	0.128
Std.Dev	0.01	0.01	0.02	0.01

D. Copper 'bus-bar' connection performance

Copper bus systems are one of the key parts of new power assemblies as they enable high current transmission with low losses and provide a level of heat transfer. Connecting to the bus-bar systems has, up to now, been a difficult process that could involve soldering, quick disconnect harness systems, bolting, welding and other similar cumbersome connection systems. These are typically process and assembly intensive, which add cost and require physical space, making overall assemblies larger and creating longer distances between connection points. The combination of these factors results in longer current paths that can increase parasitic and mutual inductance, reducing the efficiencies of overall power assemblies.

To get to smaller, more compact and more efficient power stack systems, the use of press-fits connected directly to copper bus bars and boards assemblies is being explored. By directly using high force EON contacts for making the high current connections, it expected that a power assembly will benefit greatly in terms of reduction of size and assembly costs.

The slow adoption of this approach was based on the misconception that over time and with higher temperatures, creep of the copper bus bar would weaken the interconnect and degrade overall performance.

In approaching this interconnect solution there are three elements to be addressed: hole specification and details, redundant connections and mechanical strain relief. A number of test coupons have been developed to study these elements. The bus bar and holes used were a variety of sizes and were also tin plated. Several test holes were created through a range that was just above and below the standard tolerance window for the press-fit part. The test was setup with a 0.80 mm press-fit gauge part with 4 press-fit eyes per coupon and the copper bus used was 1.6 mm in thickness as shown in Fig.5.

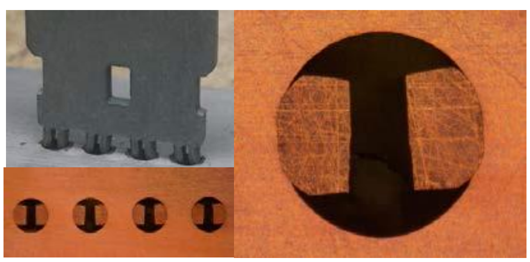

Fig.5 Interplex bus-bar test coupon detail

The device under test was exposed to an elevated temperature of 150 ^{o}C for 6 months to allow for accelerated creep of the copper bus to occur. Normal forces of the press-fit test coupon were evaluated before and after the temperature soak. Several readings were taken through the temperature soak cycle out to 4500 hours. The press-fit interconnect maintained resiliency throughout the cycle and final normal forces were still well within an acceptable range for a good functioning power interconnect (Fig.6).

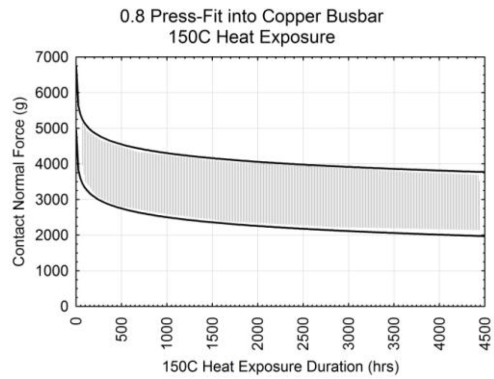

Fig.6 Thermal ageing - busbar connection contact force

Even though these results verified the functionality of the high force press-fit connection was well maintained through the creep of the copper busbar, additional test variations are being defined for more aggressive environments. The results suggest that high force and high power solderless interconnects can be realized for a variety of bus bar connections. This has opened up the design window for more EON solderless interconnect designs to be developed to carry more current per interconnect while still maintaining good normal forces for a good power connection system.

IV. INTEGRATING PRESS-FIT INTO POWER ASSEMBLIES.

The present methods for packaging and interconnecting components and subassemblies used for power conversion assemblies are a deterrent to the efficiencies that can be gained from the advancing power densities offered by the introduction of GaN and SiC chip platforms. Solder, bolting, harnesses, wire bonding, and secondary component assemblies all result in hot spots, long current paths, high inductance and inconsistent assembly methods.

Three primary areas of press-fit interconnect are advancing to address these shortcomings:

A. Direct lead termination from Power circuits by lead frames and/or terminals

This interconnection approach offers large cross sectional area terminations that are well suited for increased power, and can be equipped with press-fit technology, offering reduced mutual inductance compared to a multiple wire bond approach. An example of this is the use of Press-fit leads on a subassembly/Component Lead Frame, such as an integrated package with a solderless connection system (Fig.7). Here the subassembly circuit board, usually Direct Bond Copper (DBC), can be built up prior to being assembled to the leadframe. Typically the DBC is bonded to the leadframe with wirebond type interconnections. Alternatively, the ideal solution is to develop a direct bond approach by redesigning the connector parts to have tab connections that can replace the wirebonds.

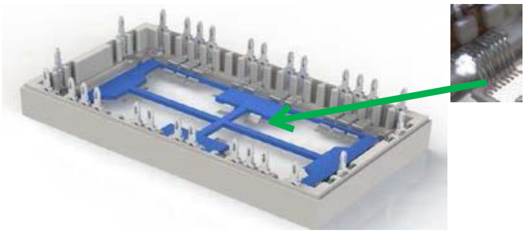

Fig.7 A lead-framed sub assembly

B. Integration of high force press-fit connections within the subassemblies themselves.

When equipping power link capacitors, motors, bus bars and other components (or subassemblies) with press-fit technology, the separate subassemblies can be made pluggable and can be easily integrated as part of the assembly, reducing overall assembly size and becoming more electrically efficient. A typical example is the need for the use of Link Capacitors in power assemblies. By equipping these capacitors with integrated press-fit leads (Fig.8) they can be supplied as ready to assemble components for fitting directly to a bussing or PCB system without welding, soldering or bolting.

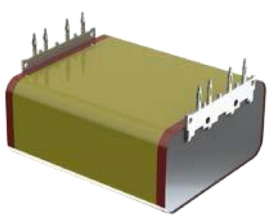

Fig. 8 A press-fit terminated power link capacitor

C. High force solderless connections to bus bars, circuit cards and motors.

The use of high force solderless interconnects eliminates bolts, welding and harness assemblies, thereby shortening current paths. This also offers a permanent connection system that maintains resiliency through thermal cycling while providing efficient high current paths. An example of this is the use of Press-Fit with IDC on Motor (winding) Terminals.

With the advancements in the power generation and conversion market, more rugged and high performance motor systems are being developed. Such systems utilize larger wires and have insulation systems that are typically thicker and multilayered to maintain dielectric properties and long term reliability whilst operating at a higher operational temperature for the life of the motor. A typical method for terminating from the motor wire is through IDC that cut through the insulation and make electrical contact to the bare wire in one assembly operation. Historically, IDC technology worked well for lower performing motor windings but was limited to lower currents and thinner insulations. Newer IDC connection systems now being developed utilize the technology available with high force press-fits and apply this to the motor winding termination (Fig 9).

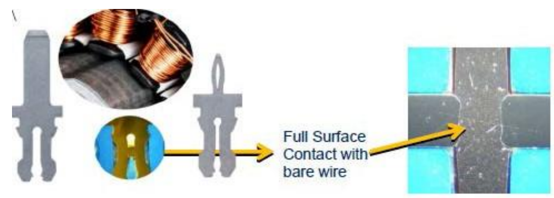

Fig.9 IDC and EON press-fits for motor terminations

These newer designs separate out the insulation cutting features from the electrical contact features while also maintaining a high normal force throughout the life of the product. Since materials utilized are common for both IDC and press-fits, the two technologies can be combined to make direct connections to the motors if needed.

In most Power Assembly products, wirebond terminations are used, often in conjunction with press-fit as detailed in section A) above. To reduce cost and impove efficiencies, ways of replacing such wirebonds with direct connections are being developed.

The power board, typically DBC, is the core of an inverter assembly. It is typically a pure SMT ceramic based PCB, holding all the power components on one side as the reverse side is typically bonded to a heat sink or other thermal management to keep the temperature of the power switching components as low as possible. Both high and low power connections need to be made to the PCB and these connections must either be strong enough or flexible enough to withstand thermal cycling and CTE mismatches as the circuits power up. The typical choice for the connection to the PCB is wire bonding. Since within the subassembly/circuit itself, device-to-device connections are made by wirebonding, this process is continued to make connections to the outgoing leads as well. Wire bonds can be looped to create strain relief and multiple wire bonds can be made to connect the power circuits. Aluminum wire is typically used for power chip interconnects and also for the off board connections. Hence a similar Al wire bond pad on the connection lead is preferred. Since most connectors are a copper alloy material they require an Al inlay. Such materials that are compatible with high power press-fit technology are limited but are slowly becoming more available.

As technology moves to higher speeds and greater power density more multiple wirebonds will be needed to support the power output. This multiple parallel bond need will increase process time and risk an increase in mutual inductance within the circuit.

High switching speeds and more power density puts more demand on the connections from the power board. Fewer connection points with larger cross sections and shorter current paths will be necessary to sustain these higher demands so the preference would be to make a lead frame that can be directly attached to the DBC circuit, as in Fig.10. In this case, the direct contact to the power DBC is a better solution than wire bonding.

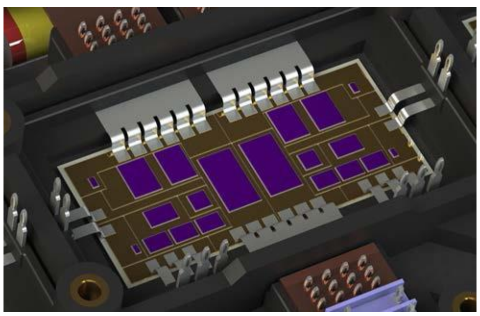

Fig.10 DBC attached directly to a press-fit leadframe

Creating leads or lead frames with larger cross sections with flexible SMT pads that can be directly bonded to the power board through welding or soldering greatly improves and sustains performance when terminating power DBCs. (Suitable high temperature “solder” bonding methods are now being enabled by developments such as sintered silver solders [5]).

On connecting to the control and bus circuits the high force connection systems like press-fit technology are already well suited to support this shift in technology. Also since high conductivity press-fit materials are already available and there is no specialty Al inlay material required for this type of connection system these solutions can be implemented today quite cost effectively.

V. Conclusion

Press-fit designs come in many formats like webs, formed, split beams etc., as well as EON. No one design can be stated as being better or worse, all have tradeoffs, but what is important is the performance to suit the any particular application. Test data availability is the ultimate verification.

In any overall packaging approach, the use of EON high force solderless connections is an effective solution for high current connections. Selection of CuNiSi, the 40% IACS material with the 0.63mm size parts as shown in Fig.3, enables currents in excess of 20 amps even at elevated temperatures. This type of EON will ideally suit many of the emerging low power applications that are required in small, compact modular packages.

Furthermore, on the development horizon newer designs of high force, resilient, pluggable interconnects are being engineered to take this connection approach to the next level of efficiency. The application of EON for busbar interconnects is an example of where the long term resilience, demonstrated by the results achieved in the long term 150^{o}C exposure tests, counters the effects of busbar material creep whilst maintaining excellent contact force to ensure a reliable joint methodology.

These test procedures detailed are targeted at ongoing advancements to carry more current per contact, maintain resiliency at high temperatures, be integrated directly into subassemblies and reduce current paths throughout the power assembly.

The data now available from these test processes is ensuring that solderless press-fit connection options can be modeled and tested to suit a wide range of applications. This is enabling new power products to be designed and developed for assembly with methods that are accurately monitored, highly repeatable and result in low contact force, flexible, cost effective high performance connection systems.

Acknowledgment

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