New power modules improve surface-mount manufacturability

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Plug-in Power Products

Introduction

The latest generation of Texas Instruments (TI) board-mounted power modules utilizes a pin interconnect technology that improves surface-mount manufacturability. These modules are produced as a double-sided surface-mount (DSSMT) subassembly, yielding a case-less construction with subcomponents located on both sides of the printed circuit board (PCB). Products produced in the DSSMT outline use the latest high-efficiency topologies and magnetic-component packaging. This provides customers with a high-efficiency, ready-to-use switching power module in a compact, space-saving package. Both nonisolated point-of-load (POL) switching regulators and the isolated dc/dc converter modules are being produced in the DSSMT outline.

TI's plug-in power product line offers power modules in both through-hole and surface-mount packages. The surface-mount modules produced in the DSSMT outline use a solid copper interconnect with an integral solder ball for their attachment to a host PCB. This attachment method is designed to be more reliable than other surface-mount interconnects, which translates to improved manufacturability for customers that employ high-volume, surface-mount manufacturing methods.

Component coplanarity

In the electronics industry, the term "coplanarity" means the maximum distance that the physical contact points of a surface-mount device (SMD) can be from its seating plane. When placed on a flat surface, an SMD will rest on its three lowest points. This defines the seating plane of the device. The number given for coplanarity defines the maximum gap that can exist from the underside of any pin to the PCB to which it is being soldered. This measurement is unilateral.

The traditional requirement for a reliable solder joint is that each pin of an SMD make contact with the solder paste covering its respective solder pad. Solder paste is deposited on the host PCB with a solder stencil and squeegee. The thickness of the solder stencil determines the thickness of the solder deposited. The thicker the solder paste, the more likely it is that the SMD pin will make contact with the solder. During reflow, the surface tension properties of liquid solder cause the solder to wet between the pin and pad. The solder bridges any physical gap between them to form a fillet. Figure 1 shows a cross section of an acceptable solder joint.[1] If the measured coplanarity of the pins is too great for the amount of solder deposited, some pins may not make contact with the solder paste. In this situation the liquid solder simply forms a pool on the PCB pad. It does not wet to bridge the gap between the pin and pad, resulting in an electrical open circuit. Figure 2 shows how an excessive gap between the component lead and solder pad prevents the formation of a solder fillet. In this case the finished assembly must be either reworked or rejected, with a corresponding impact to manufacturing yield and cost. A thicker solder stencil can be used to deposit more solder. This will accommodate parts with a higher coplanarity variance but will cause problems with smaller components that have fine lead pitches. Excessive solder on the pads of small parts can result in adjacent pins being bridged and shorted. The additional volume of solder also increases the risk of solder debris being formed during reflow.

One commonly used thickness for a solder stencil is 0.006 in. (0,015 mm). This thickness generally provides a sufficient amount of solder to ensure that the pins of the components make contact with the PCB solder paste. This dimension is consistent with the coplanarity of SMD packages that limit the maximum distance of any pin from the

Figure 1. Acceptable SMT solder joint

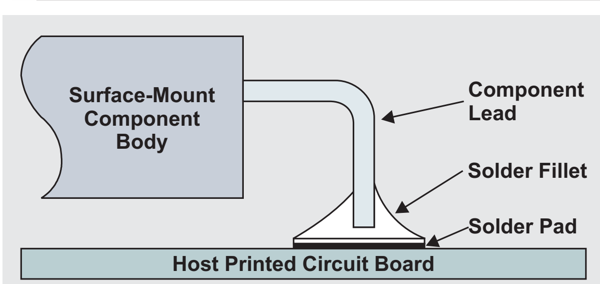


Figure 2. Excessive gap prevents fillet formation

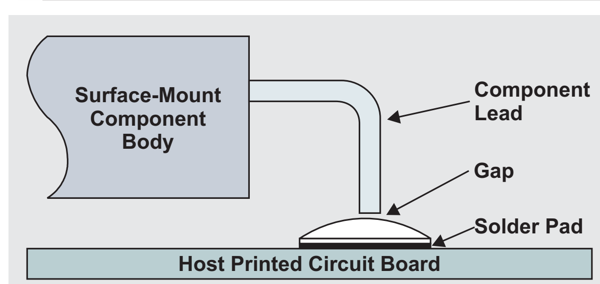
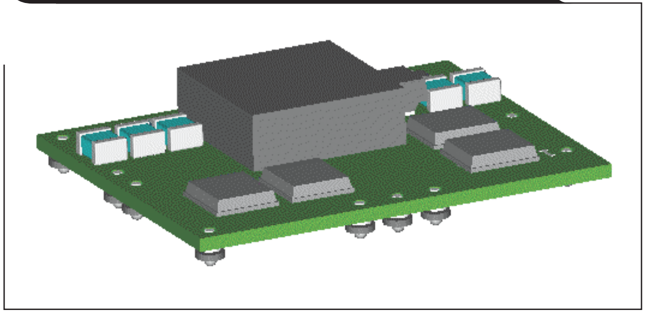


Figure 3. DSSMT power-module assembly



seating plane to no more than 0.004 in. (0,01 mm). For large, complex components such as power semiconductors, magnetic components, and power modules, the package coplanarity is often higher. These parts require a larger solder pad and a thicker layer of solder paste to ensure that they are soldered.

While it is always possible to dispense more solder paste to a select few pads on the host PCB, it complicates the soldering process. A thicker solder stencil can be used, but steps must then be made to reduce the amount of solder deposited onto pads that do not require it. The stencil thickness can be "stepped down" or the apertures (openings) reduced. There are issues with both approaches. The disadvantage with step-down stencils is that they are more expensive and are impractical to implement on a few pads of a densely populated PCB. The reduced-aperture option has to be applied to a large number of solder pads and often requires trial and error to determine a workable aperture pattern. Because of the issues associated with these techniques, original-equipment and contract manufacturers are reluctant to employ them. The expectation is that all components should comply with coplanarity limits that are compatible with a 0.006-in. (0,015-mm) solder stencil thickness. From the industry's standpoint, this simplifies the design of the solder stencil and minimizes the cost.

Power-module construction

Due to their size and construction, the surface-mount packages of power modules are challenged to meet the same coplanarity as smaller surface-mount components. Power components tend to have larger PCB footprints with thicker, longer pins, located on a wider pitch. These characteristics make it more difficult to manufacture power components to the same coplanarity tolerances as small semiconductor ICs. It is not unusual for power-module packages to specify a maximum pin distance from the seating plane of 0.006 in. (0,015 mm) or greater.

Power modules are usually constructed from a sub-assembly PCB. The leads or pins can be either part of a lead-frame or independently attached to the PCB. Depending on the construction, the module may include a plastic or metal case or may even be covered by an exterior molding. The pins can be either solid (rolled or stamped) or flat. The pins elevate the module, giving clearance underneath the body, and provide a foot that can be soldered onto a pad of the host PCB.

As the industry pushes toward higher levels of integration, power modules produced in the DSSMT outline are being well received. The case-less construction allows components to be placed on both sides of the module's PCB (see Figure 3). This results in a more compact module with a correspondingly higher power density. The DSSMT modules use solid pins mounted directly beneath the module. This provides mechanical support as well as an electrical connection to the host PCB.

Factors affecting DSSMT module coplanarity

The three principal factors that affect the coplanarity of DSSMT power modules are dimensional variations in pin length, warping of the module PCB, and soldering variations.

Compared to flat pins, which must be cropped and formed, solid pins are relatively thick and short. This makes them more robust and less susceptible to misalignment through handling. They are manufactured to a pre-defined length with modern machine tools, a process that results in a consistent product with tight tolerance limits.

The DSSMT package outline places the module PCB in control of the mechanical integrity of the package. This includes the physical alignment of its pins, both lateral and axial. The PCB material is a laminate and subject to manufacturing variations, including warping. Over the dimensions of a semiconductor IC or even a large discrete component, the effects of warping are minimal compared to those of a power module, which can measure up to 3 in. (75 mm) along one side.

Pins with integral solder ball

The solid pins used on TI's DSSMT power modules incorporate a solder ball on the end that interfaces with the host PCB. The solder ball can comprise regular tin/lead (63 Sn/37 Pb) solder or high-temperature tin/silver/copper solder. DSSMT modules manufactured with these interconnects have improved solder-reflow capability. Most significant is their ability to automatically compensate for coplanarity differences between the module and the host PCB.

Figure 4. Detailed view of a Solderball Pin

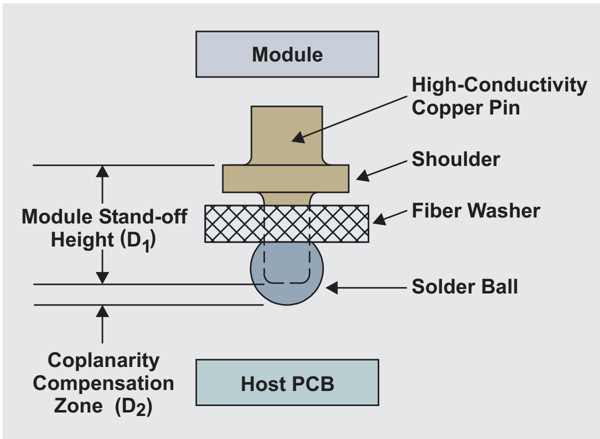


Figure 4 shows a detailed view of a single Solderball Pin™. The high-conductivity solid copper pin incorporates an integral contact or shoulder. The top of the pin is formed into a barrel, which locates within a plated through hole on the module PCB. The shoulder provides a contact area for the copper landing pad on the underside of the module. The lower part of the pin extends through a small fiber washer into a ball of solder. When the module is placed on the host PCB, the solder-ball end of the pins is placed into the same thickness of solder paste as other components. The module is then processed in a normal reflow operation. The main purpose of the fiber washer is to prevent liquid solder from wicking up the pin. The washer retains the solder around the butt joint formed between the pin and the pad on the host PCB. This ensures that there is sufficient solder to form a solder fillet when standard paste levels are used.

Coplanarity compensation

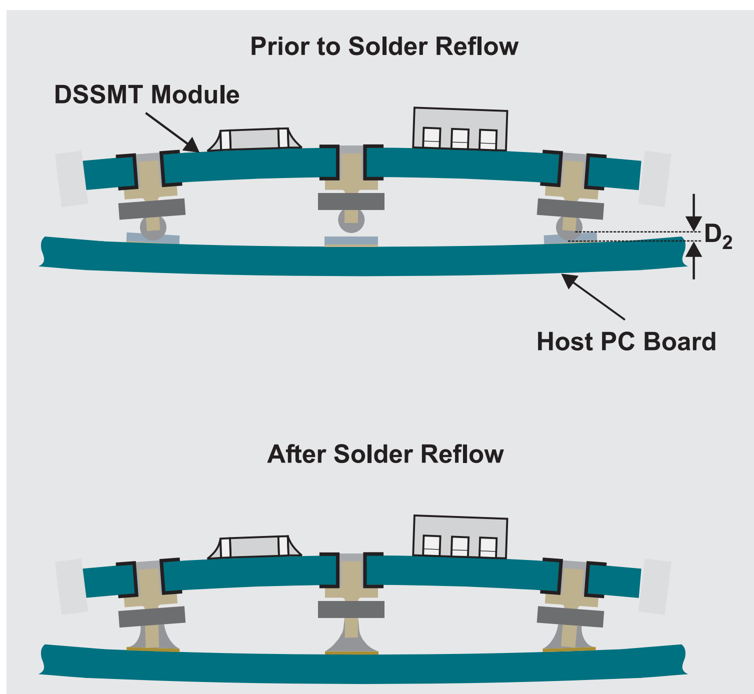
When a standard solder-paste stencil is used, the solder ball adds two important attributes that allow a higher coplanarity variance to exist between the module and host PCB. First, it provides an additional source of solder; and second, it allows the subassembly to drop slightly when the solder becomes liquid during reflow. This drop occurs when the weight of the module overcomes the buoyancy of the molten solder. The amount of drop is equal to the distance that the solder ball extends beyond the end of the pin (within the ball). This is the dimension D_2 in Figure 4, known as the coplanarity compensation zone.[2]

The dimension D_2 corresponds to the additional amount of coplanarity adjustment. The extent of this adjustment is such that the solder ball end of the pin does not have to make physical contact with the solder paste prior to reflow. The seating plane of the module need only bring each solder ball to within a distance of less than D_2 of the solder paste. Figure 5 demonstrates how the coplanarity compensation zone works when a DSSMT module is passed through a standard solder-reflow process. For the purposes of this illustration, the coplanarity variance between the module and the host PCB has been exaggerated.

Prior to reflow, the solder balls of only the two outer pins are shown making contact with the solder paste on the host PCB. The solder ball of the center pin is raised above the paste due to the warping of the boards. The gap created by the raised pin is not a problem as long as it is less than the distance D_2. This is the distance that the lowest pins are raised above the host PCB pads by the solder balls. During reflow, the solder balls become liquid, allowing the module to drop by this distance. The solder ball of the center pin is then able to make contact with the solder paste. Once contact is made, the solder from the ball and paste coalesce to form a fillet. A typical module may have a dozen or more discrete connections, several of which could be raised off the host PCB pads. The joints of these connections would all be brought into compliance as a result of the module sinking toward the host PCB during the solder-reflow process.

The dimension D_2 is a key parameter. The pin manufacturer characterizes this dimension as 0.0127 in. (0,32 mm) nominal, with a standard deviation of 0.0013 in. (0,033 mm). This suggests that the manufacturer's process can easily meet a minimum of 0.008 in. (0,2 mm).

Figure 5. Behavior of DSSMT module during reflow



The amount of coplanarity compensation offered by the dimension D_2 adds to that provided by the thickness of the solder paste on the host PCB. The sum total of these dimensions represents the maximum gap that can exist between the end of a pin and its PCB pad to form a fillet. If the minimum dimension for D_2 is 0.008 in. (0,2 mm), and the recommended solder paste thickness is 0.006 in. (0,15 mm), then the combination can accommodate for a minimum of 0.014 in. (0,36 mm).

DSSMT module coplanarity variance

Generally the coplanarity variance of an SMD can be evaluated by measuring the distance of each contact point from its seating plane. With a solder ball covering the pin ends, the contact point cannot be directly inspected. It is only during reflow that the module settles onto its seating plane. Applying heat to remove the solder to permit inspection is impractical. This would disturb the pin and affect the measurement. For this reason the coplanarity is best assessed by a review of the manufacturing process, along with empirical measurements on manufactured parts.

The three principal factors that affect the DSSMT module coplanarity are: the dimensional tolerance of the copper pin length, warp in the module PCB during solder reflow, and soldering variations of the pin/module joint. Each of these factors can be assessed for its impact on the module's coplanarity variance.

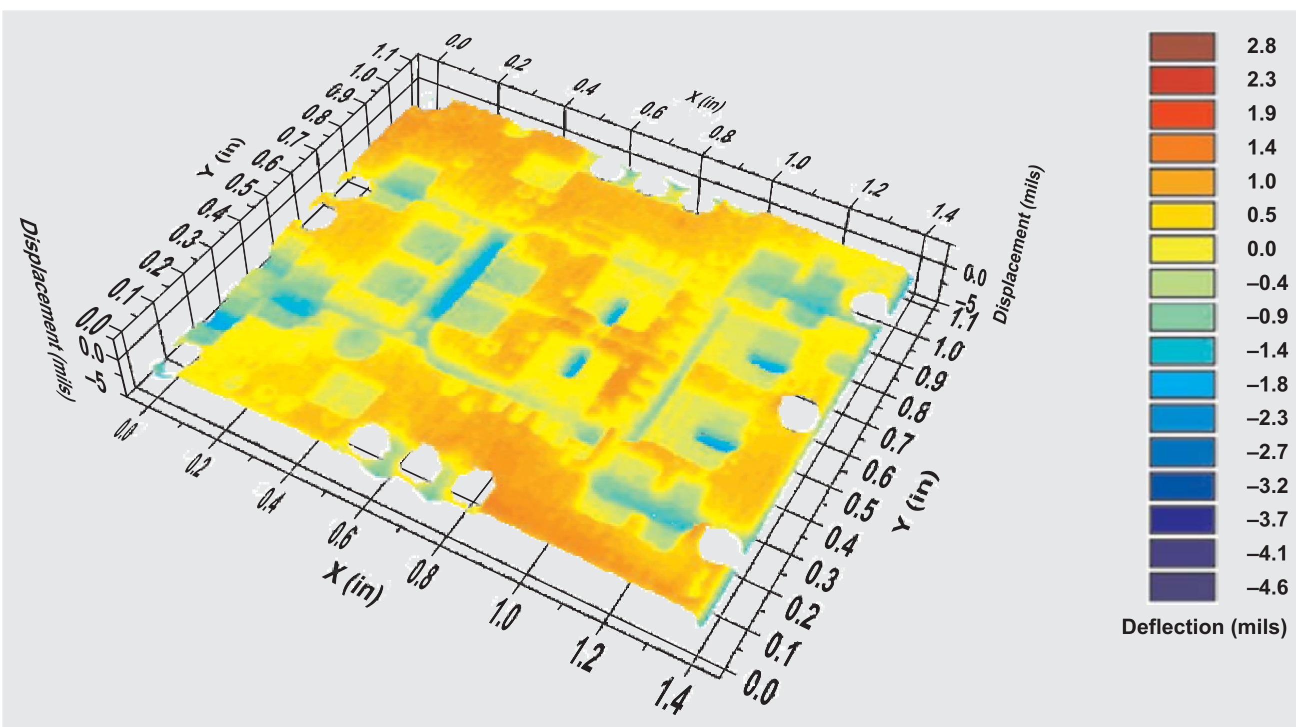
The first factor, variation in pin length, has a direct effect on coplanarity. The pin length is dimension D_1 in Figure 4, the distance from the top of the shoulder to the pin end (within the solder ball). Statistical process control (SPC) obtained from the pin manufacturer gives this dimension as 0.065 in. (1,65 mm). The standard deviation is σ = 0.00056 in. (0,014 mm). If 3σ is used, the variance of the pin will be ±0.0017 in. (±0,043 mm).

To evaluate the second factor, PCB warp, a shadow moiré test system was used to study samples of the module's PCB under reflow temperature conditions. This test is an optical technique that gives a precise measurement of out-of-plane displacements. It was conducted on PCB samples of TI's larger DSSMT modules, the PTH12030WAS. This product measures 1.37 in. × 1.12 in. (34,8 mm × 28,45 mm). The deflection of the PCB was mapped with color 3D plots at various temperatures, from 25°C up to 260°C ambient.

Figure 6 shows the plot from one of the samples at 260°C. The vertical displacement is given in mils (0.001 in.). The results of this testing[3] revealed that none of the PCB samples saw a deflection greater than 0.003 in. (0,1 mm) at reflow temperature. This maximum deflection was recorded in the areas around the pin landing pads, at the opposite corners of the PCB. PCB deflection was also reduced as the ambient temperature was raised from 25°C, and was lowest at reflow temperatures. This is notable, as it is during reflow that the module establishes its seating plane.

The third factor that can affect coplanarity, soldering variances of the pin/module joint, is primarily caused by the pin's tendency to float on its landing pad. This is known as axial float. It can cause the pin to drop slightly

Figure 6. Shadow moiré 3D plot at 260°C



due to its shoulder not being completely flush with the underside of the PCB. Figure 7 is a cross section of a DSSMT module, taken through the pin/module joint. It shows the shoulders of the pins to be almost flush with the module's PCB surface, indicating that pin float is well controlled during the manufacturing process. This variance is considered negligible compared to the other parameters examined; and it promises to be even less significant if the module is exposed to a high-temperature, lead-free reflow process. The pin is attached to the module with high-temperature tin/silver (96.5 Sn/3.5 Ag) solder. At high-temperature reflow, this joint will also reflow, and any pins standing proud (due to axial float) will be reseated by the weight of the module. However, for the purposes of this assessment, we'll assume a token variance of 0.001 in. (0,025 mm) for this parameter.

Of the three principal factors that affect module coplanarity, pin length is the largest contributor. This is because it has a twofold (2×) effect on the gap that can exist beneath a pin and the module's seating plane. Consider that the seating plane of the module might be established by three pins close to their maximum variance in length. A gap of 2× this variance will then exist beneath each pin that is close to its minimum variance.

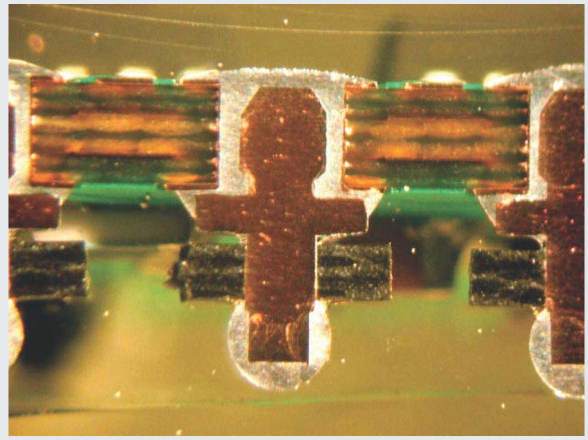
Table 1 summarizes the three major factors that affect module coplanarity. The results suggest that the module could contribute as much as 0.0074 in. (0,188 mm) in coplanarity variance with respect to its seating plane.

Table 1. Module coplanarity variance to seating plane

DESCRIPTION	VARIANCE (in.)	MULTIPLIER	CONTRIBUTION (in.)
Pin length	0.0017	x2	0.0034
PCB warp	0.003	x1	0.003
Pin float	0.001	x1	0.001
		Total:	**0.0074**

To add confidence to this assessment, physical measurements were also made on sample lots of PTH12030WAS production parts before their assembly to a host PCB. In each case the amount of gap beneath the solder ball that was most elevated from the component's seating plane was measured. The results revealed that the maximum lift of a module pin averages 0.004 in. (0,1 mm), with a standard deviation of σ = 0.0018 in. (0,0457 mm). This suggests that the maximum process limit is 0.0094 in. (0,24 mm), assuming normal distribution. This compares to the calculated variance of 0.0074 in. (0,188 mm) for the pin ends. While the physical measurements give some insight into the assessed variances, they include the solder ball. The solder ball covers the pin ends, and its thickness also varies.* Therefore the spread of the physical measurement is expected to be higher.

Figure 7. Cross section of pin/module solder joint



Irrespective of whether the calculated or measured value represents the module's true coplanarity variance, the pin design provides up to 0.014 in. (0,36 mm) of coplanarity compensation. This is sufficient to ensure that all the module's interconnects form a satisfactory solder joint with the host PCB.

Qualification to IPC-9701

The reliability of the host board solder joints was evaluated with the procedure set forth in Reference 4. Thermal cycling qualification was carried out on 42 test modules designed to simulate the PTH12030WAS product. This is the full production sample size per IPC-9701. An additional 10 samples were used to verify the integrity of the joints after rework.

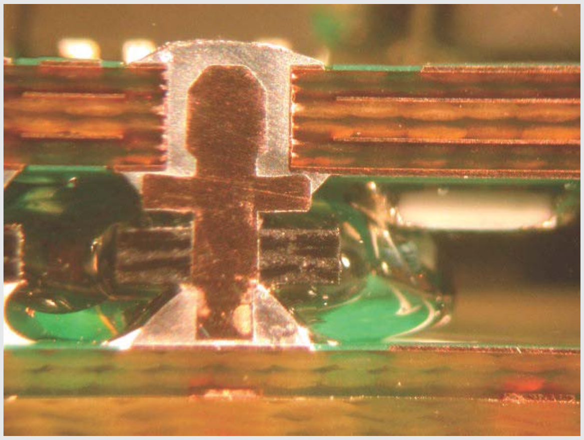
The PTH12030WAS is one of the larger DSSMT modules incorporating pin interconnects with an integral solder ball, specifically the regular tin/lead (63 Sn/37 Pb) version. The test modules were fabricated with the same manufacturing methods used to build the functional PTH12030WAS module. They were then attached to 7 larger host PCBs (6 per host PCB) with 0.006-in. (0,15-mm) tin/lead solder paste and 235°C maximum reflow temperature—the same solder/reflow limits recommended to customers. Both the test modules and the host PCBs were designed to allow the solder interconnects to be continuously monitored for electrical continuity.

With the prescribed test and monitoring methods, the 42 module PCBs were subjected to a total of 3500 thermal cycles over a temperature range of 0°C to 100°C. The results revealed zero failures.[5] Additional analysis was conducted on cross sections of parts that had been freshly soldered to a host PCB. These cross sections allowed the macro-inspection of the solder joints around the interconnect

*The solder ball thickness over the pin end has been characterized by the pin manufacturer as having a standard deviation of σ = 0.0013 in. (0,033 mm).

pins. There were no apparent defects. Figure 8 is an example of a cross section. It shows that the pin has established a generous solder fillet with the host PCB landing pad.

Figure 8. Cross section after reflow to host PCB



Conclusion

The latest power modules from TI are produced in a compact DSSMT package outline. The surface-mount-compatible versions of these packages use a solid cylindrical copper interconnect for their electrical connection with the customer's host PCB. These interconnects incorporate a solder ball at the end of the pin. The solder ball compensates for the coplanarity of a large module, allowing it to be assembled to the host board via a standard solder-paste stencil and a surface-mount solder-reflow process.

The amount of coplanarity compensation provided by these interconnects was compared against the variance that may be introduced by a large DSSMT module. The evaluation revealed a minimum compensation capability of 0.014 in. (0,356 mm) versus a potential total variance of 0.074 in. (0,188 mm). The analysis concluded that interconnects that incorporate a solder ball provide sufficient solder to compensate for the module's coplanarity variance. The integrity of the solder joints between the module and the host PCB were qualified to IPC-9701. The qualification tests that were performed showed good component-to-PCB solder-joint integrity. This translates to improved manufacturing yields and component reliability.

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