

Clamping of High Power RF Transistors and RFICs in Over-Molded Plastic Packages

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INTRODUCTION

This application note provides Freescale Semiconductor customers with a guide for mounting high power RF transistors and integrated circuits in Over-Molded Plastic (OMP) packages by clamping down the RF power device in the Power Amplifier (PA) housing. Each PA design has its own unique characteristics. Similarly, each manufacturing operation also has its own process capabilities and variations. Therefore, each design and assembly may require some fine-tuning. The intent of this application note is to provide customers with the information necessary to derive the best possible process that is most suitable for their design and the assembly process that is most compatible with their manufacturing operation.

The RF Power devices are generally assembled into the PA assembly by either a solder reflow process (including surface mounting) or a bolt-down process through an opening in the Printed Circuit Board (PCB). Soldering the devices provides a very good thermal and electrical grounding due to the high conductivity interface of a solder joint, which results in improved RF performance. The PA is also less susceptible to oscillation type damage when it is properly grounded. Better thermal grounding also results in lower junction temperature and higher reliability. For customers who rely on bolting the RF power devices in the housing, there is usually some degradation in performance as well as stability and reliability. This is primarily due to variation in source impedance from one installation to another as well as poor interface resistance. As a result, the PA industry has seen a steady shift away from bolt-down to solder reflow mounting.

However, some customers still prefer bolting down RF Power devices. This application note provides guidelines for those customers who would like to improve the performance of their PAs using the bolt-down type process.

This application note describes the methodology to design an injection molded clamp that clamps the device body only. The leads are soldered to the PCB. Freescale's testing of a properly designed clamp showed an improvement in the area of contact between the device source contact and the aluminum chassis in which the PA is housed. This improved thermal and electrical grounding increased the performance of OMP devices in the PA assembly.

Based on the guidelines presented here, customers should be able to develop a manufacturable assembly process that can do the following:

- Design a clamp that will fit into their assembly.
- Provide a good thermal ground to conduct the dissipated heat efficiently from the high power RF device to the system sink.
- Provide a good electrical ground to provide a stable RF performance over the life of the power transistor.
- Maintain the package integrity during the assembly and in the field.
- Design a system where reflowed and clamped devices will not compromise solder joint reliability.

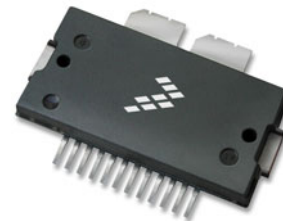


Figure 1. Typical RF Power Device in an Over-Molded Plastic (OMP) Package Suitable for Clamp-Down Assembly Operation

The TO-270WB device shown in Figure 1 is designed to be reflowed into a cavity with the source contact soldered to a pallet or coin and the leads soldered to the PCB. The method described here is applicable to all OMP devices where the source contact is not soldered but is held in physical contact by the clamping force.

POSSIBLE ASSEMBLY PROCESS FLOW

The general process described here results in a clamp design in which the body of the device is clamped to the next level assembly housing with some interface between the source contact of the RF device and the housing. The leads on the gate and the drain sides are soldered to the PCB. Two process flows can be used to accomplish this.

The simplest approach is to reflow all of the components except the RF Power devices on the PCB. The PCB is then bolted into the housing. The RF device is then placed on the PCB and clamped in place using a process similar to bolting the RF device down. The clamp is an injection molded plastic component with an opening for two screws. The clamp is bolted down on top of the device body using two #4-40 (or M3) screws, flat washers, and lock washers. The normal tightening torque for the screws is 5 in-lb. for #4-40 screws (0.6 N-m for M3 screws). After the device is clamped in place, the leads are hand-soldered to pre-tinned land areas on the PCB. This approach is referred to as “reflow, clamp, and solder.”

An alternative method is to reflow the RF Power device on the PCB with the rest of the components. After the PCB is reflowed, the PCB is bolted down into the housing and the RF Power device is clamped in a process similar to that described above. This method is useful for multi-lead devices for which the leads are difficult to solder by hand. However, the clamping operation and the tolerance stack-up among the PCB thickness, housing cavity depth, and the device seating plane height can cause mechanical stress on the solder joint, possibly resulting in early failure of the solder joint during thermal cycling in the field. This approach is referred to as “reflow and clamp.”

For improved solder joint reliability, Freescale recommends using the reflow, clamp, and solder process. If this is not feasible, particularly for multi-lead parts, this application note will provide guidelines to improve the solder joint reliability. Figure 2 shows an example of the resulting assembly.

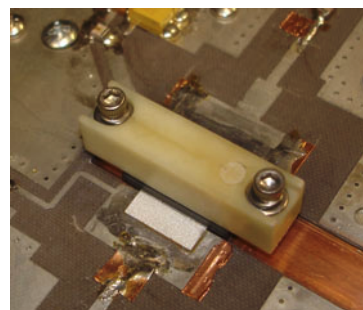


Figure 2. Typical Example of OM-780-2 Device Soldered to a PCB and Clamped to an Aluminum Plate

DESIGN OF CLAMP

In designing a proper clamping mechanism, Freescale considered the following criteria. The clamp should be made from electrically non-conductive materials, such as organic polymers with reinforcements rather than made from conductive metals. The use of a conductive metal clamp will create a ground plane above the device, which would affect the PA performance. In most cases this is not desirable, but if a customer's design wants to include a ground plane on the top of the device, there is nothing inherently wrong about using conductive metals. The clamp design should (a) provide adequate stiffness to withstand the required clamping force; (b) use injection moldable material for low-cost, high-volume manufacturing; (c) provide high temperature ($\sim 150^{\circ}\text{C}$) survivability for long duration; (d) provide high stiffness at elevated temperatures ($\sim 100^{\circ}\text{C}$); (e) improve electrical and thermal ground contact for the RF device; and (f) be low cost.

After reviewing many conceptual designs and considering the initial concavity of roughly $0.001''$ (0.025 mm) for the package, a simple design was proposed as shown in Figure 3. This part can be easily injection molded and be low cost. If the proper material is selected, it will provide high temperature stiffness and stability. This material must provide the proper elevated temperature performance stability, be able to transfer the clamping load correctly, and must generate the largest contact area possible at the source contact.

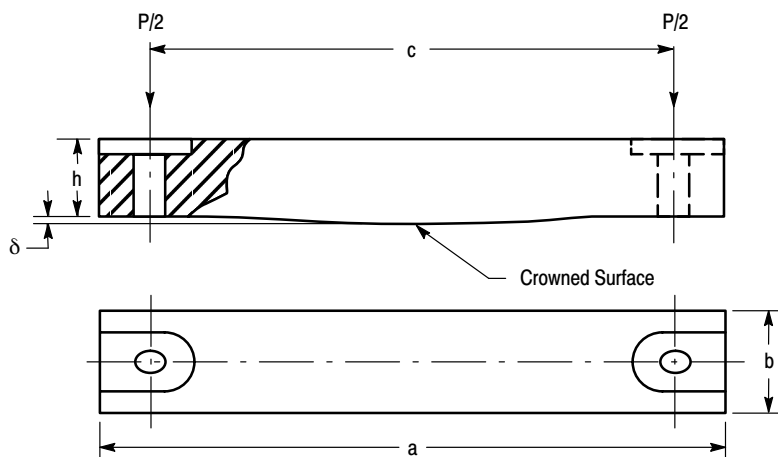


Figure 3. Proposed Design of the Clamp

Note that the contact surface is crowned in Figure 3. Two dimensions that are critical for the clamp design are clamp thickness (or height) “h” and crown height “ δ ”. The width “b” is determined by the width of the package. An extensive structural simulation was conducted to determine these two dimensions for the clamp design and selection of materials.

The 2D contact models were constructed for this simulation. A typical finite element model is shown in Figure 4. The design clamping force (generated by two bolts under 5 in.-lb. of torque) was set to be 450 lbf. (2000 N). The design parameters were: (a) the deflection of the clamp must be less than δ ; (b) the contact area at the package heat sink contact surface must be as large as possible with sufficient pressure distribution; and (c) the clamp height “h” must be less than 0.375 in. (10 mm) due to head room availability in the PA module.

Freescale initially included eight different materials in the evaluation. The materials selected for simulation were aluminum, G-10, Polyamide-imide (PAI), Liquid Crystal Polymer (LCP), Poly-phenylene Sulfide (PPS), Poly-phthalamide (PPA), Poly-ether-ether-ketone (PEEK), and polyamide. All of the polymers have high stiffness at an elevated temperature of 100°C due to the high level of glass fiber reinforcement. Two of the polymers (G-10 and PAI) are machinable material. Our goal is to select injection molded material, but machinable polymers are useful to conduct preliminary evaluation without making an investment in injection mold tooling. Aluminum can be machined for small volume and can also be die cast for large volume manufacturing. Preliminary tests using pressure paper revealed that 0.25” (6.0 mm) thick aluminum provides good contact at the source contact. Thus, aluminum was used as a baseline for comparison.

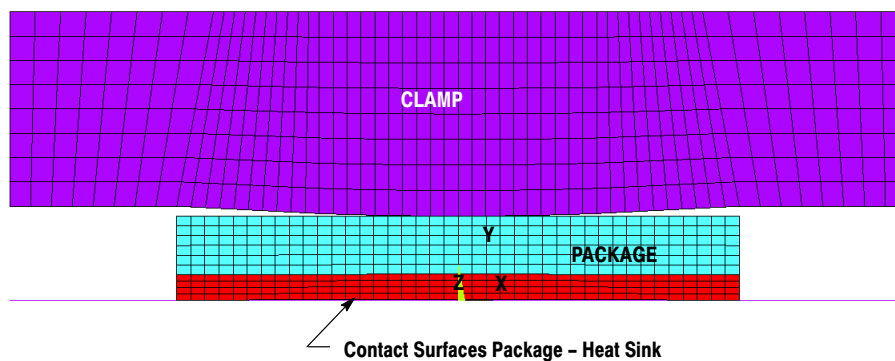


Figure 4. A Typical 2D Contact Model for Clamp Simulation

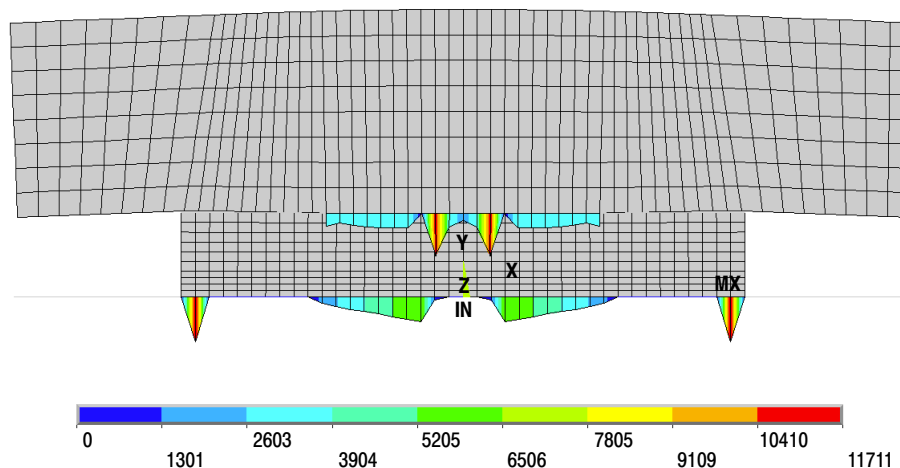


Figure 5. Typical Contact Pressure at Source Contact

The drawing for the clamp selected for the TO-270WB/TO-272WB packages is shown in Figure A-1 in Appendix A. The drawing for the clamp selected for the TO-270WBL and OM-780 package is shown in Figure A-2 in Appendix A.

The simulation results identified three materials — LCP, PPA, and Polyamide — where the deflection of the clamp was less than 0.005" (0.13 mm) and provided good contact pressure as shown in Figure 5. To further evaluate the material, a one-cavity injection mold tool was made based on the final geometry of the clamp. Several hundred pieces from each of the three materials were molded and used for material testing and electrical evaluation. Two sets of material property tests were conducted on these samples: (a) a four-point bend test at room temperature and at an elevated temperature of 100°C, and (b) a creep test under a constant deflection at an elevated temperature of 100°C. Special attention was given to the behavior of the clamp samples under elevated temperature, which simulates the actual operating condition of RF Power devices in the field. The test fixture for four-point and three-point bend tests for the material characterization is shown in Figure 6.

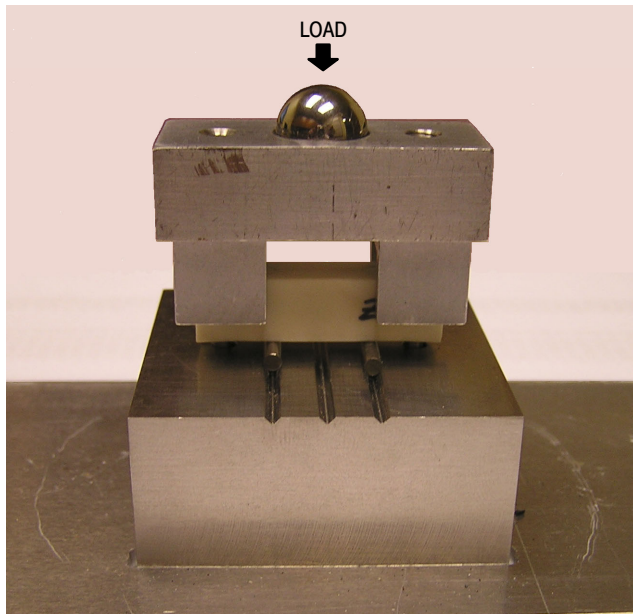


Figure 6. Material Testing Fixture

The bend tests were conducted at room temperature and at 100°C. The sample size was four samples for each material. The load was increased from 0 to 700 lbf. (3.114 kN), and a load-deflection curve was plotted for each material. The slope of the load-deflection curve provided the stiffness. This test was used to determine the stiffness at room temperature and at elevated temperature. The LCP material was selected with two different levels of glass reinforcement, while PPA and polyamide were selected with one level of reinforcement. The LCP material showed the largest drop between room temperature stiffness and elevated temperature stiffness.

For the creep test, the sample size was three samples for each material. An initial load of 500 lbf. (2.224 kN) was applied to a sample, and the deflection of the sample was kept constant. The parameter of interest during creep test was load relaxation over a fixed time duration at an elevated temperature of 100°C, which is critical to the effectiveness of a clamp. The indentation generated by the supporting pins in a four-point bend test at an elevated temperature of 100°C would offset the deflection and introduce load relaxation errors in the creep test. To avoid this error, a rigid flat plate under the crowned surface of the clamp was used as a support instead of the two pins. This made it a type of three-point bend test fixture. The sample and test fixture were all enclosed in a thermal chamber with the temperature of the sample kept at a constant temperature of 100°C. The time duration was set for about 18 hours. The force was recorded during the creep test, and force versus time was plotted to determine relaxation. The PPA material showed the largest relaxation of the force, followed by LCP. The polyamide material showed the smallest force relaxation at an elevated temperature. In all cases, most of the relaxation occurred over the first five to six hours of testing. After that, the load was observed to be fairly constant.

Based on the room temperature stiffness, elevated temperature stiffness, and elevated temperature stiffness relaxation test results, Celstran® PA66-GF60-02-US polyamide 66 with 60% long glass fiber reinforcement and heat stabilized material from Ticona was selected as the material of choice for further experiments. Customers can follow this type of testing to determine the suitability of materials not included in this study.

To confirm that the clamp design and material selected were able to improve the contact region at the source contact, a pressure paper test was conducted. Pressure paper is a two-element set with a donor paper layer containing ink-filled micro-bubbles and a secondary receiver paper available to indicate the higher pressure contact areas. The two paper mat surfaces are put in contact with each other and used as an interface pad. The paper used in the test had the pressure range of 70 psi to 350 psi (483 kPa to 2414 kPa). Five devices in TO-272WB packages were selected for evaluation. In one test, these five devices were bolted on a flat surface, and then the test was repeated with the devices being clamped on the same surface. Figure 7 shows the pressure paper imprint for the five devices. The images on the left side are for devices bolted on a flat machined aluminum plate. The images on the right side are for the same devices clamped on the same flat machined aluminum plate. As the images clearly show, the clamping of the devices creates the contact area in the center of the package. When the devices are bolted down, the contact region is typically near the bolt-head region. When the same devices are clamped with the recommended clamp, the contact region shifts to the center of the device, and the contact area is significantly larger. This results in lowering the source impedance for the device, which improves the device's RF performance and stability. The increased contact area also reduces the thermal interface resistance and lowers the junction temperature.

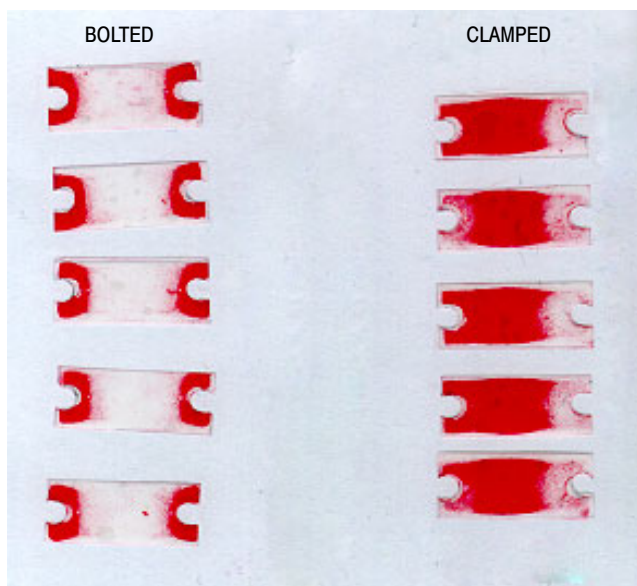


Figure 7. Pressure Paper Test Results for Five TO-272WB Packages with #4-40 Screws at a Mounting Torque of 4.0 in-lb

IMPACT OF CLAMPING ON THE DEVICE PERFORMANCE

In addition to the clamp testing, another important criterion is mounting influence on RF performance. To validate the mounting influence on the device performance, two RF power discrete devices (MRF6V2300N/NB and MRF6S19100N/NB) and two RF IC devices (MW7IC2240N/NB and MW7IC18100N/NB) were selected to cover a broad spectrum of device technologies, frequency and power ranges. Clamps made from three materials under evaluation were selected for device performance characterization. Device characterizations were performed to measure key RF performance parameters, such as gain, efficiency, linearity, etc., under three conditions: post-production test set-up, bolt-down, and clamp-down. In addition, RF drive down testing was performed to calculate the P1dB values for the three different clamp materials. In all the cases, the clamped devices showed improvement in the RF performance over bolted devices. The results demonstrated that all three materials had sufficient stiffness at room temperature to provide performance improvement for clamped over bolted devices.

In addition to the pressure paper test and RF performance parameter measurement, one more test was performed to check the impact of source impedance on the device performance. Fifteen MRF6S19100NB devices were tested in two-tone measurements with 100 KHz tone spacing and highly backed-off power conditions. Figure 8 shows IMD3 at lower (-L) and upper (-U) frequencies, and at 30 Watts of output power. The typical P1dB value for these devices is around about 120 Watts. The devices were tested in two conditions: bolted in the test fixture and clamped in the test fixture. As Figure 8 illustrates, the IMD3-L value dropped by approximately 4 dBc, and IMD3-U dropped by approximately

1 dBc. This indicates a lower common source impedance and better grounding with devices clamped compared to devices bolted into the same test fixture.

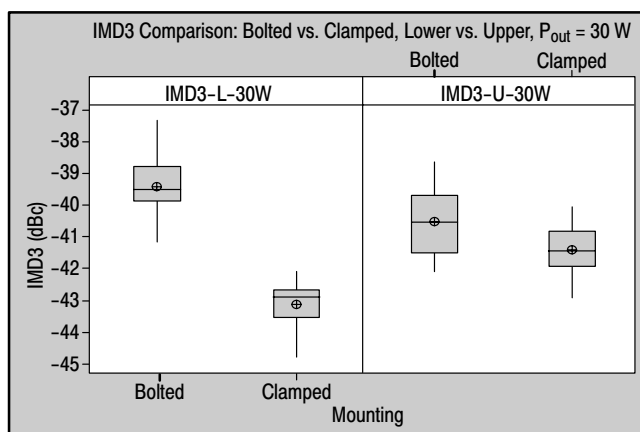


Figure 8. IMD3 Comparison for Bolted versus Clamped MRF6S19100NB Devices using a Celstran® Clamp and Bare Interface

The data presented in Figure 8 is for a bare interface creating a direct contact between the back side of the device and the test fixture ground plane. To check for the influence of various interface materials, the same test was rerun on five parts with the following different interface materials: bolted with a bare interface; clamped with a bare interface; and clamped with copper foil, indium foil, liquid solder, solder foil, PGS®, T-GON®, and a thermal grease interface. PGS® and T-GON® are thermally and electrically conductive graphite interface pads. Solder (SnAgCu), copper and indium foils are thermally and electrically conductive metal foils. Thermal grease is a silicone based compound that is thermally conductive, and liquid solder is a metal alloy that is liquid at room temperature. Figure 9 shows the values of IMD3-L at 30 Watts of output power for MRF6S19100NB devices. The IMD3-L values for clamped devices with all interface conditions are between 2 and 4 dBc lower than the same devices bolted down. Similarly, the IMD3-U values for clamped devices with all interface conditions are approximately 1 dBc lower than for those of bolted conditions.

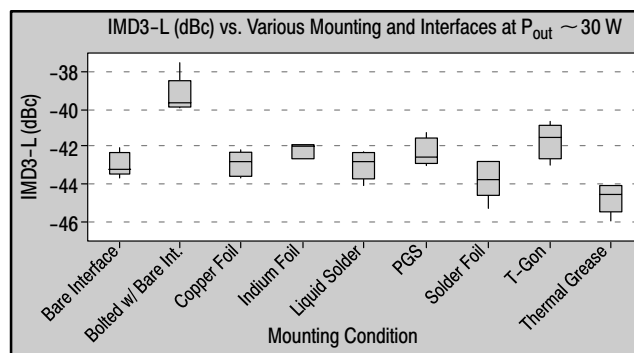


Figure 9. IMD3-L Comparison for Bolted versus Clamped MRF6S19100NB Devices using a Celstran® Clamp and Various Interface Materials

Based on the device performance results shown here, it can be stated that all three materials selected in the evaluation — LCP, PPA and Polyamide — provide sufficient stiffness at room temperature that the device performance is improved over just bolting down the device. Since the material property characterization showed that the LCP and PPA material has much more load relaxation over time at 100°C compared to polyamide (Celstran®) material. Celstran® was selected as the material of choice to conduct environmental testing.

Environmental Testing of the Clamps

In the previous sections, the methods used to create the clamp design and material selection were described. Tests were run to prove that a properly designed clamp can provide a good contact interface at the back side source contact surface and improve RF performance over a bolt-down application. To demonstrate that clamping is a viable option, however, Freescale needed to demonstrate that clamps can survive a Base Transceiver Station (BTS) environment. For that purpose, clamped MRF6S19100N/NB devices were put through four types of reliability tests: RF-High Temperature Operating Life (RF-HTOL), DC-HTOL, High Humidity High Temperature (H3T), and Temperature Cycling (TC).

For RF-HTOL testing, sixteen devices were powered in CW condition under an N-CDMA signal and the RF output of ~30 Watts. In this test, the junction was maintained at 200°C for 1,008 hours of continuous operation. The clamps were recorded to have a maximum temperature in the range of 130°C to 140°C. To maintain the devices at constant 200°C, the pallets were provided with cartridge heaters. The heat dissipated from the device operating under this condition will not be able to maintain the case temperature high enough for the junction to reach 200°C.

For DC-HTOL testing, thirty devices were powered in direct current (DC). The clamped devices were placed in a 175°C chamber where the junction temperature would reach 200°C. In this test, the clamps would reach the same temperature as the chamber temperature. The test duration for DC-HTOL testing was also 1,008 hours. In the H3T test, twenty clamped and non-biased devices were put into 85°C and 85% Relative Humidity (RH) environment for 1,008 hours.

For the TC test, twenty MRF6S19100N devices were clamped into an aluminum plate, as shown in Figure 10. In addition, fifteen parts were placed in the same chamber as freestanding devices. The temperature cycling range was from 125°C to -40°C, with a 15 minute dwell time at each temperature. The devices were put through 1,000 temperature cycles.

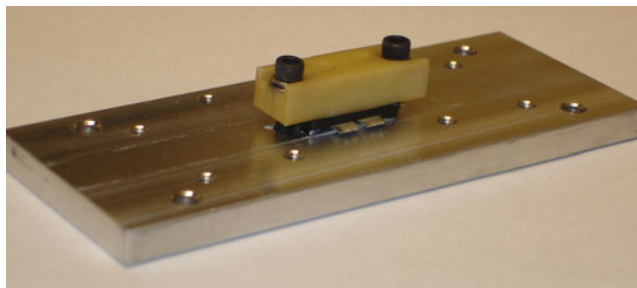


Figure 10. Typical Temperature Cycling Test Sample

Because the contact surface of the clamp is crowned, a non-contact laser profilometer was used to characterize the shape of the crowned surface before and after the environmental tests. Figure 11 shows the difference in the height of the crown before and after the environmental tests. For controls, additional clamps were used for surface measurements only. The non-tested system control clamps are identified as the Virgin data set in Figure 11.

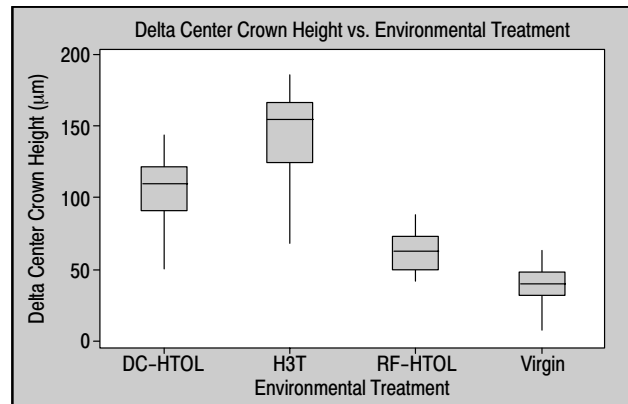


Figure 11. Change in Crown Height of Clamps during Environmental Tests

It should be noted that there is some shift in measurement of virgin clamp units between pre-environmental test and post-environmental test measurements. This is an indication of repeatability of the measurement. Compared to virgin clamp units, the clamps that were used for RF-HTOL testing (clamp temperature of ~140°C) showed ~30 micron average reduction in the crown height. The clamps used in the DC-HTOL test (clamp temperature of 180°C) showed ~80 micron average reduction in the crown height. The clamps in the H3T test (clamp temperature of 85°C with 85% RH) showed the height reduction of ~130 micron average reduction in the crown height. All of these reductions are significantly lower than the initial height of 0.3 mm (0.012").

Five of the clamps from each environmental test group were used to conduct a pressure paper test, and the contact surface was compared with five virgin clamps. Figure 12 shows the contact region for the same five parts with five virgin clamps and five clamps selected from the four environmental tests. The images show that even after the environmental exposure for extended time, the clamps retain their stiffness and provide the same type of contact at the source contact as the virgin clamps.

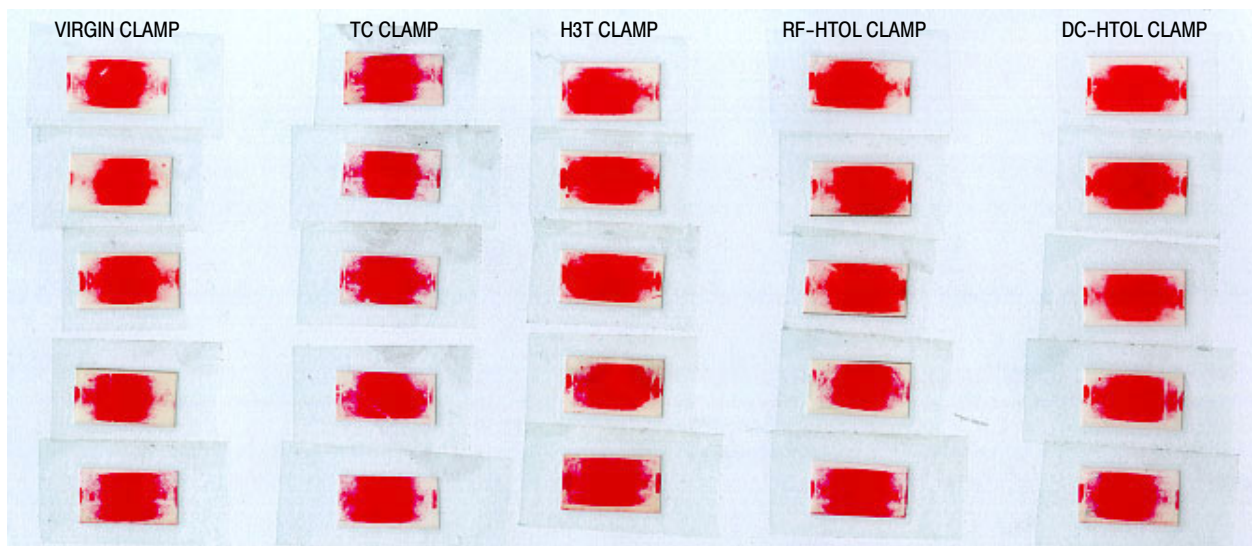


Figure 12. Contact Surface for Virgin Clamps and Clamps Used in the Environmental Tests

Ten additional clamps from three environmental test groups (DC-HTOL, RF-HTOL, and H3T) and ten virgin clamps were used to conduct RF testing under CW conditions. The RF testing included RF parameter measurements under CW conditions using MRF6S19100N devices, as well as RF drive down and the measurement of P1dB value. Figure 13 shows the P1dB values for the same ten parts with a different group of clamps. For comparison, the values of P1dB on the production test setup are also shown as control values. The P1dB values for the three environmental test groups are similar to the virgin clamps and slightly better than the production test fixture listed as Standard group in Figure 13. The RF performance parameters values are comparable for the three environmental groups and the virgin clamps. The gain values for all four clamped groups were between 14.3 and 14.9 dB. The efficiency values were between 49.3% and 51.5%. The IRL values were between -20 and -34 dB.

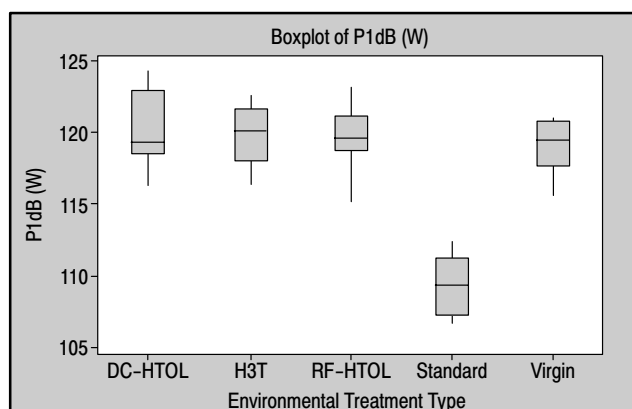


Figure 13. Comparison of P1dB Values for Ten Parts with Different Environmentally Treated Clamps as well as a Production Test Fixture

Based on the data presented here, we can state that the clamp design and the material selected are capable of meeting the performance and reliability requirements that are normally used for qualification by Freescale for its semiconductor devices.

Solder Joint Reliability of Soldered and Clamped Devices

As described earlier, there are two potential assembly process flows for clamped devices. One possible way is to reflow a PCB without the clamped RF power devices and then bolt the PCB into the housing. After the PCB is secured, the RF power device is mounted into the housing and the devices are clamped into place. After the device is secured, the device leads are soldered to the PCB land area. The PCB land area can be pre-tinned during the PCB reflow process. This process is referred to as "reflow, clamped, and solder." In this process, the solder joint of an RF power device has no additional mechanical load due to clamping, and the reliability of the solder joint is the same as a bolt-down RF power device assembled in similar process flow.

A second assembly process option is to reflow the RF power device with the rest of the components on the PCB. After reflow, as the PCB is bolted into the housing, the RF power device is clamped into the assembly. In this particular process flow, the RF device solder joints are mechanically stressed due to a mismatch in the stack-up tolerances. This process is referred to as "reflow and clamped". This is not a preferred method of assembly, but it may be the only possibility for devices that can not be hand-soldered. To prove the reliability of the solder joints when the clamped devices are reflowed first, special devices were built using TO-270WB-14 packages (Case 1618) in which alternate pins were shorted internally by wire bonding their posts to a common wire bond pad on the die. A special PCB (Figure 14) was designed so that when the special devices in TO-270WB-14 packages are soldered to this PCB, all the solder joints on the gate side are daisy-chained to create one continuous resistor. A four-point probe can be used to precisely measure the resistance of each daisy-chain. The

system is capable of measuring the resistance in micro-ohms. As the solder joint starts to crack, resistance will increase; if the solder joint fails, it will be recorded as an open joint.

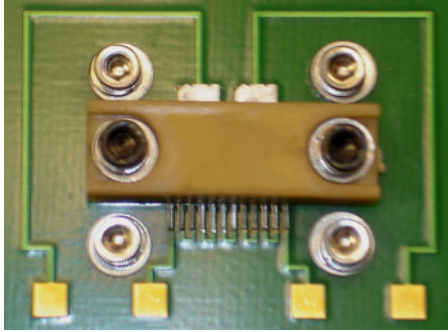


Figure 14. Solder Joint Reliability Test Sample with Daisy-Chained Solder Joint

The special devices in TO-270WB-14 packages were reflow soldered to an 0.030" thick FR-4 PCB with two sided metalization using SAC305 Pb-free solder paste. The paste was screen-printed using a 0.006" (0.15 mm) stainless steel stencil. After reflow, the PCB was bolted to a 0.25" (6.0 mm) thick aluminum plate. While securing the PCB, the devices were clamped using long #4-40 carbon steel screws with flat and lock washers. Each PCB had eight devices soldered to it, similar to the one shown in Figure 14. Two PCBs were assembled with 0.005" (0.125 mm) thick T-GON® 805 pads between the device bottom and the aluminum plate. Three other PCBs were assembled with thermal grease interface. The assemblies as well as one freestanding PCB were put in the temperature cycling between the range of 125°C to -40°C with 15 minutes of dwell time at each extreme temperature. These parts were thermal cycled to 1,000 cycles, and the resistances were measured at 0, 500, and 1,000 cycles.

Of the 24 devices in the group of three PCBs with thermal grease interface, one device was poorly soldered and indicated an unstable reading at time zero. Of the 16 devices

in the group with two PCBs with T-GON® interface pads, two devices were poorly soldered and indicated an unstable reading. Some failures occurred at 500 cycles in the group with thermal grease, and a few more failures occurred at 1,000 cycles. In the group with T-GON® interface pads, no failures occurred at either 500 cycles or at 1,000 cycles. Our hypothesis is that T-GON® pads are fairly soft and, therefore, will absorb tolerance mismatches in the stack-up without loading the solder joint. With a reduction in the mechanical stresses in the solder joint at assembly and during thermal cycling due to the softness of the T-GON® pads, the solder joints showed increased reliability.

CONCLUSION

Based on the information provided here, the customer should be able to:

- Design a proper clamp that will provide improved contact at the source contact over a bolt-down assembly.
- Select material that will withstand the environmental requirements.
- Improve RF performance over bolt-down devices.
- Design a clamp that will fit into their assembly.
- Provide a good thermal ground to conduct the dissipated heat efficiently from the high power RF device to the system sink.
- Provide a good electrical ground to provide a stable RF performance over the life of the power transistor.
- Maintain the package integrity during the assembly and in the field.
- Design a system where reflowed and clamped devices will not compromise solder joint reliability.

A clamp design that meets these requirements for TO-270 and TO-270WB packages is shown as Figure A-1 in Appendix A. Similarly a clamp design for TO-270WBL and OM-780 packages is shown as Figure A-2 in Appendix A. Tests conducted have shown that the Celstran® PA66-GF60-02-US polyamide 66 with 60% long glass fiber can survive extended use at 200°C junction temperature and will survive extended thermal cycling. The solder joint reliability can be improved by the use of a soft interface pad such as T-GON® 805 to absorb tolerance mismatches in the assembly and reduce the stresses on the solder joint.

Appendix A. Typical Clamp Design

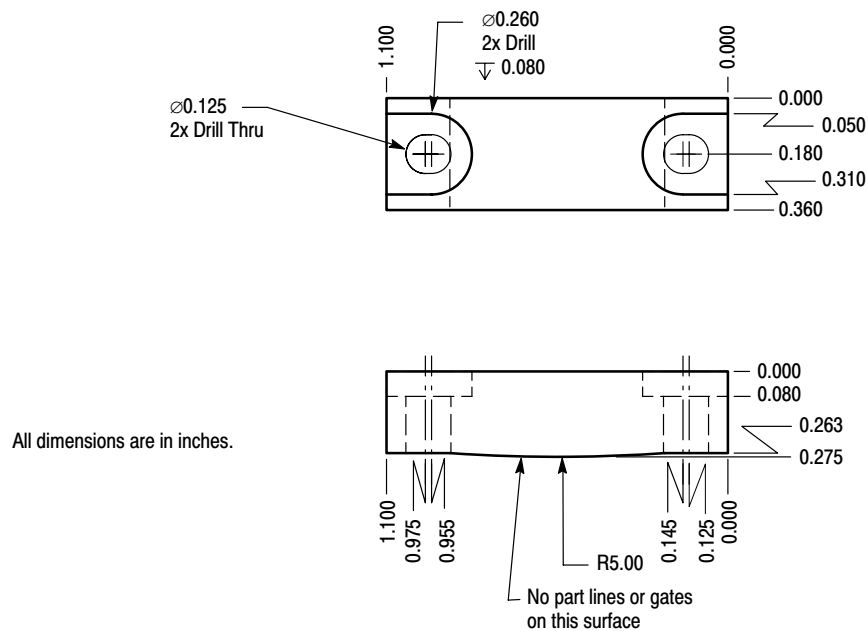


Figure A-1. Clamp Design for TO-270, TO-272, TO-270WB and TO-272WB Packages

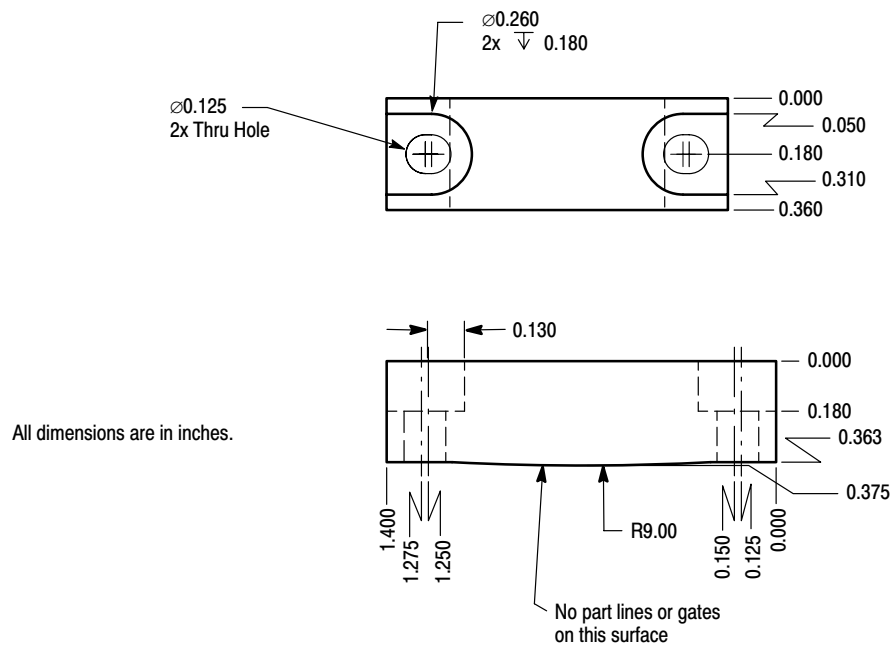


Figure A-2. Clamp Design for TO-270WBL and OM-780 Packages

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