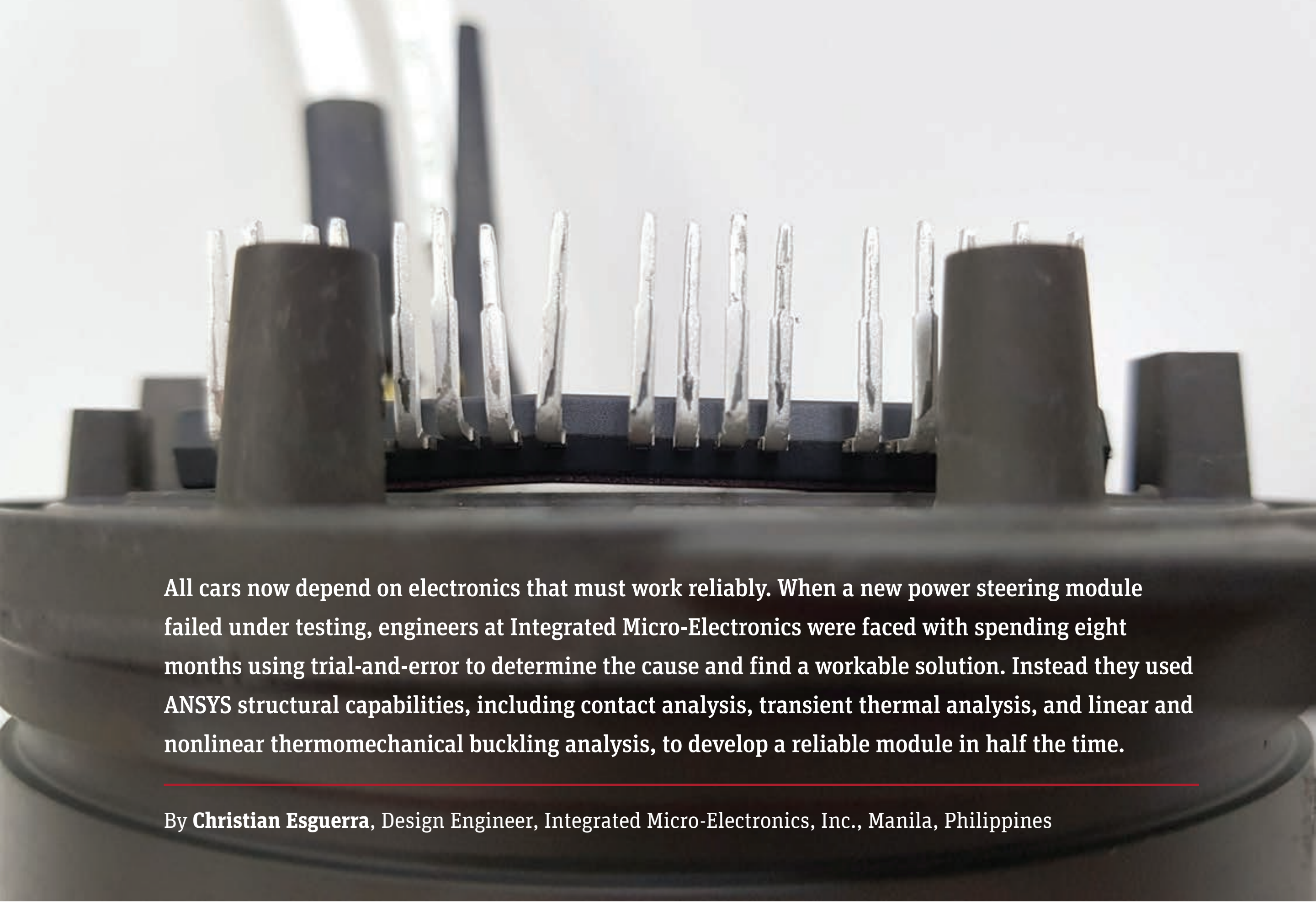
Breaking Story on an Automotive Power Module



All cars now depend on electronics that must work reliably. When a new power steering module failed under testing, engineers at Integrated Micro-Electronics were faced with spending eight months using trial-and-error to determine the cause and find a workable solution. Instead they used ANSYS structural capabilities, including contact analysis, transient thermal analysis, and linear and nonlinear thermomechanical buckling analysis, to develop a reliable module in half the time.

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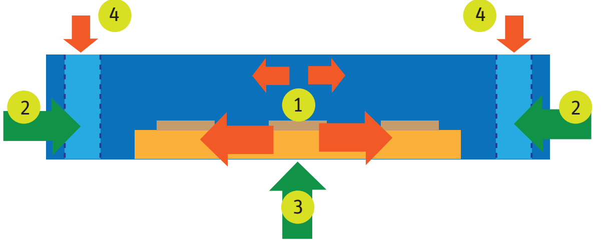
The power module is an electronic component in most modern automobiles. It contains inverters that convert low-voltage direct current power from the battery to high-voltage alternating current to drive the electric motor that steers the vehicle. This process generates heat that must be removed to avoid exceeding the junction temperature of the inverters. Most electronic power modules must pass reverse polarity testing to ensure against mishaps during installation of a new battery, reconnection of the original battery after repairs, or a jump-start. In the reverse battery test (RBT),



Forces during the reverse battery test:
1) expansion of substrate, 2) reaction forces exerted by bolts, 3) reaction to bolt preload and 4) bolt forces

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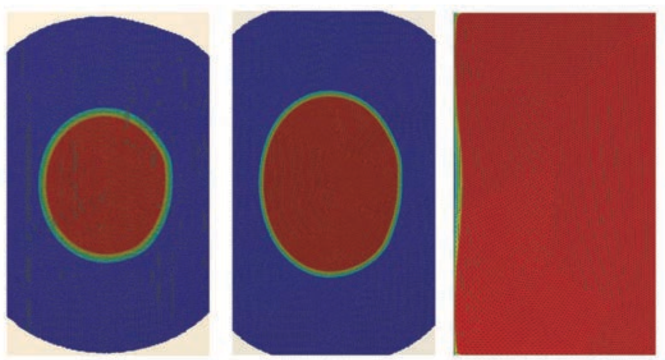
input polarity is reversed and the inverters behave like short circuits, drawing about 140 amps and generating much more heat than in normal operation.

Integrated Micro-Electronics (IMI) is the sixth largest provider of electronic manufacturing services to the global automotive industry and a major player in many other markets. The company’s engineers found that a power steering power module frequently cracked down the centerline of the epoxy molding compound (EMC) package and experienced solder remelting during the reverse battery test. With multiple design variables, a large design of experiments that would take up to eight months would have been required to diagnose and solve the problem. Instead, engineers used cross-platform, multiphysics analysis to understand what caused these problems and solved them in only four months.



Results of contact analysis simulation with red areas indicating sufficient contact pressure to enable thermal conduction with design parameters of (left) 200 μm warpage, 100 μm TIM thickness and 800 N bolt force; (center) 60 μm warpage, 500 μm TIM thickness and 800 N bolt force; and (right) 60 μm warpage, 500 μm TIM thickness and 1200 N bolt force

Reverse Battery Test

The power module contains nine metal oxide semiconductor field effect transistor (MOSFET) inverter chips that dissipate the bulk of the current. The direct bonded copper (DBC) substrate is made up of three layers consisting of, from the top down, copper, ceramic and copper. DBC combines the high thermal conductivity of copper and the low coefficient of thermal expansion of ceramic. However, the mismatch in coefficient of thermal expansion between copper and ceramic causes slight warpage, creating a concave shape on the bottom of the module that is expensive to eliminate. A screw and bolt on each side fastens the package to a heat sink that is part of the motor subframe. A thermal interface material (TIM) pad with high thermal conductivity provides electrical insulation between the substrate and the heat sink.

As the module heats up during the RBT, the whole package expands against the bolts and is subjected to in-plane compressive reaction forces. An upward force is generated on the module in response to the bolt preload. Heat softens the EMC, leaving just the DBC substrate to resist compressive forces exerted by the bolts. When the substrate can no longer resist, the package buckles upward. This much was clear at the beginning of the troubleshooting process. But with many different design variables to consider, IMI engineers faced a long and expensive process using the design of experiments method to guide the many physical experiments required to understand the impact of each design variable and solve the problem.

Simulating the Test

After considering the high cost and lead time involved in performing these physical experiments, engineers decided to simulate the RBT with ANSYS Mechanical software. As a first step, they needed to know the power dissipation through each of the nine MOSFETs, which are grouped as three transistors for each of the three alternating current (AC) phases. They performed an electrical simulation that showed that 80 percent of the current goes through the AC phase nearest the input. Approximately 15 percent was shared by the middle phase, and the farthest phase dissipated the final 5 percent.

IMI engineers then created an ANSYS Mechanical model of the substrate, package, TIM pad, heat sink (subframe) and bolts. They then applied preload to the bolts to predict the effective thermal contact area

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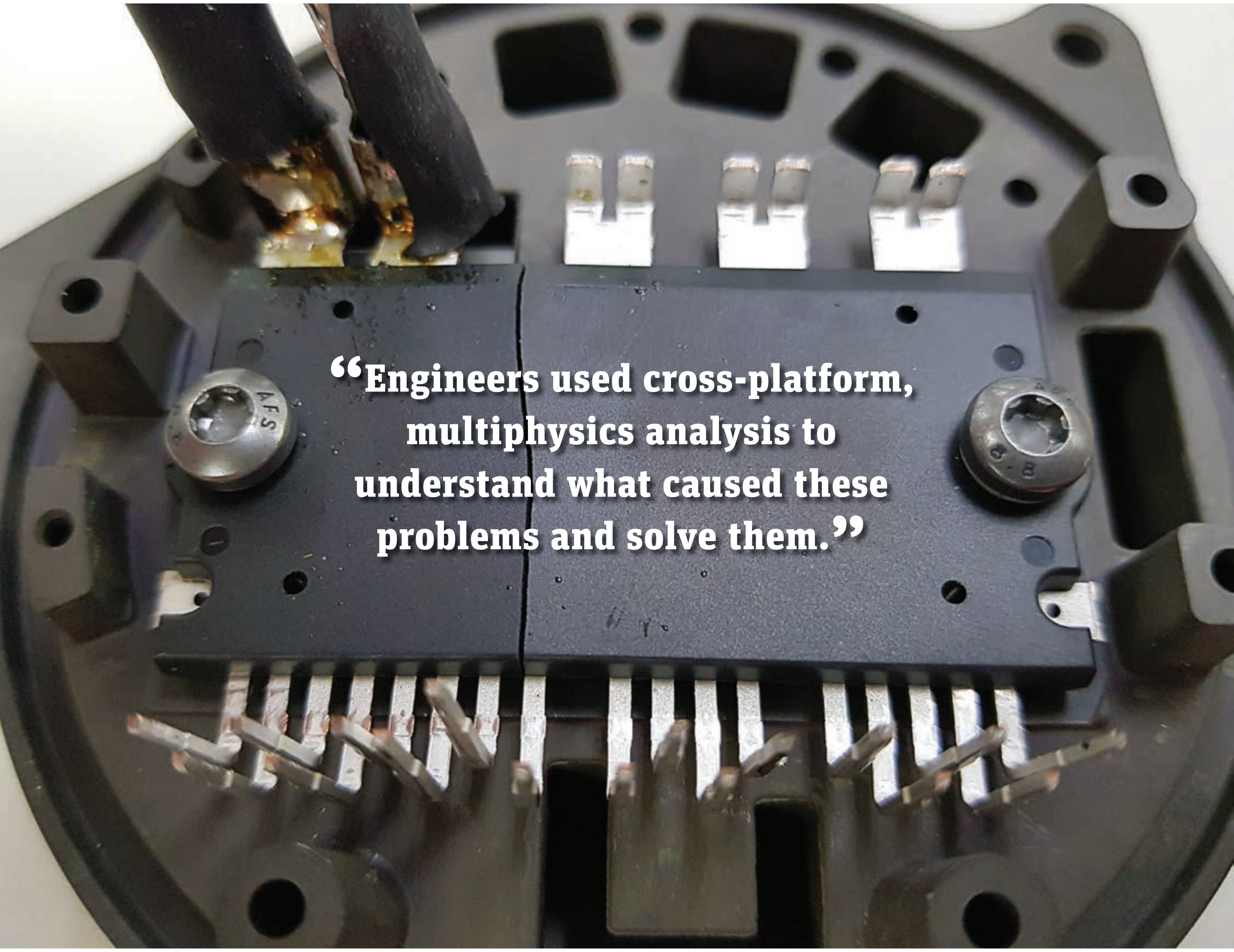

between the power module, the TIM and the heat sink. The contact area determines the amount of heat transferred to the heat sink, so it has an impact on the temperature of the module. Engineers ran a parametric analysis to determine the sensitivity of contact area to the bolt force, warpage of the package and thickness of the TIM. The contact area varied between 18.7 and 97.8 percent for the simulated cases. The results showed that contact area generally increases with decreasing module warpage, increasing bolt force and increasing TIM thickness. A high bolt force, thick TIM pad and small module warpage provided nearly 100 percent contact.

The next step was a transient thermal analysis with the electrical simulation providing the heat sources and the contact analysis determining the effective thermal contact between the module and the heat sink. Engineers ran another parametric analysis, using the same values of the same variables that were used in contact analysis. The results showed that generally the design parameters that produced higher contact areas also generated lower junction temperatures. In most of the simulated cases, the temperatures exceeded the solder reflow temperature. Only in cases with low warpage, thick TIM pads and high bolt forces could the module be expected to avoid solder remelting during the RBT.

Next, IMI engineers used the loads from the previous mechanical and thermomechanical analyses as prestress for a linear buckling analysis. They used the perturbed shape from linear buckling as a starting point for nonlinear buckling. The nonlinear buckling simulation accurately predicted the cracking

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"Simulation helped to *develop a solution* that did not increase manufacturing costs — in about *half the time* that would have been required using physical experiments alone."

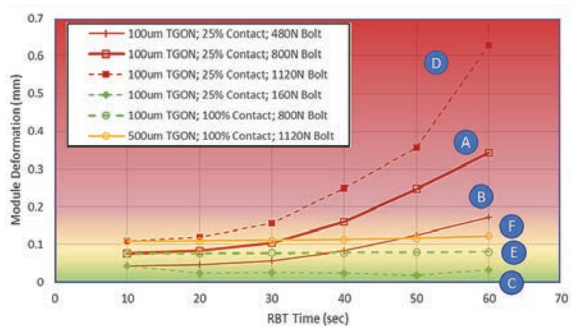
Setup of thermal contact deformation analysis for final design

seen in physical testing with the starting design parameters of 100 µm TIM pad thickness, 800 N bolt preload and 60 µm warpage. The simulation showed that buckling could be eliminated by reducing bolt force. But the transient thermal analysis showed that this would increase temperature to the point that solder remelting would occur. A hypothetical perfect package with zero warpage, 800 N bolt load and 100 µm thick pad would not buckle and would not remelt the solder. But this perfect package would require considerably higher manufacturing costs, which were unacceptable.

SOLVING THE PROBLEMS

Understanding the cause of the problems and their sensitivity to the relevant design variables, IMI engineers explored the idea of switching from a TIM pad to a TIM gel. The advantage of the TIM gel is that it maintains a greater contact area at lower bolt forces, enabling the bolt force to be reduced without causing solder remelting. The simulation showed that these changes would solve both the buckling and the solder remelting problems. Engineers built and tested a prototype, and the results matched the simulation.

Without simulation, it would likely have taken at least eight months to solve the problem, and the contract might have been lost. With simulation,



Nonlinear buckling analysis results with area colored red indicating cracking failure and area colored green indicating no cracking. Case C has little deformation but fails due to solder remelting. Case E has little deformation and a low temperature but could not be produced with the existing manufacturing process. Case F provides acceptable levels of deformation and temperature, but with no margin of safety, so even small levels of manufacturing variation could cause failures.

Integrated Micro-Electronics engineers quickly diagnosed the two problems of solder remelting and module cracking, and determined sensitivity to the relevant design variables. Simulation helped engineers to develop a solution that did not increase manufacturing costs — in about half the time that would have been required using physical experiments alone.

		Tj @ RBT 60s (°C)		
DBC Warpage (µm)	TGON Thickness (µm)	Bolt Force (N) 480	800	1120
200	100	318.0	302.1	281.0
	300	311.4	289.6	271.6
	500	312.8	277.3	248.0
120	100	310.7	289.7	265.1
	300	300.2	265.6	235.5
	500	305.4	259.9	223.1
60	100	277.4	254.5	225.0
	300	290.5	220.5	184.7
	500	310.4	214.9	176.5

Transient thermal analysis results with red indicating solder remelting will occur, green indicating solder remelting will not occur and yellow indicating borderline results