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Analysis in Action: Reducing Time to Market in Electronic Packaging

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Companies getting products to market faster than others generally capture greater market share. Time-to-market is especially critical in the highly competitive electronics and semiconductor market, where product designs, pricing, and distribution strategies see some of the most rapid and revolutionary changes of any manufacturing industry.

As a major player in this market, Motorola initiated a corporate-wide cycle-time reduction program in 1992 to address these time-to-market issues. The ambitious goal of the initiative is to reduce cycle times ten-fold by 1997 by refining the product development process, working collaboratively in project teams, and harnessing the latest technology.

The initiative has been implemented successfully throughout Motorola's Semiconductor Product Sector, which manufactures over 40,000 products ranging from components supporting pagers and cellular telephones to discrete consumer and automotive applications. As part of this business, the Hybrid Power Modules Operation in Phoenix, Arizona, designs and manufactures power modules for improving electric motor operating efficiency in numerous industrial applications, commercial products, and electric vehicles.

In the development of packaging for these modules, ANSYS® finite element analysis (FEA) software from ANSYS, Inc. in Houston, Pennsylvania, is used as an essential tool by mechanical engineers working collaboratively with other members of the project team. Not regarded as merely a spot solution for isolated problems, ANSYS is a critical element of an integrated product development strategy where design concepts, product configuration, and production methods are continually analyzed and refined. This coordinated approach lowers costs, improves quality, and shortens development times compared to "build-and-bust" methods that rely heavily on expensive and time-consuming prototype testing.

Metrics used to measure the effectiveness of the initiative so far indicate that the Hybrid Power Modules Operation (as well as Motorola corporate-wide) is on target with its goals for reducing cycle times. The ten-fold reduction in cycle time is not necessarily expected on every project. Rather, the important power is that all individuals and groups continuously strive to improve and aim for that goal. In this respect, the program has been a resounding success by any measure.

Meeting the Engineering Challenge

Rated up to 1,200 Amps/1,200 Volts for one of the largest motor-control applications, hybrid power modules consist of insulated gate bipolar transistors (IGBT) and free-wheeling diodes configured in various arrangements on a baseplate made of either copper or newer metal matrix composite (MMC) materials produced from silicon carbide and aluminum.

Packaging these modules to operate flawlessly for years in these demanding applications is an engineering challenge. Semiconductors in the compact enclosed modules must resist damaging heat build-up while withstanding an array of structural loads with wide ambient temperature swings.

To meet stringent and often conflicting design requirements while reducing product development times, mechanical engineers use technology tools such as ANSYS. Specific types of finite-element analyses performed with the software in the development of the modules include: thermal studies on steady and un-steady (transient) heat dissipation, coupled-field analysis (thermal/electric) to balance voltage drop and temperature, time-independent plasticity analysis to determine optimum lead-forming geometry, viscoplastic analysis to study fatigue in soldered joints, linear elastic stress analysis to determine effects of applied loads, and dynamic analysis to determine natural frequencies and normal modes of vibration. Engineers will also use magnetic analysis to determine transient capacitance and inductance of components.

Using ANSYS in this manner to continually refine module packaging throughout the design process, mechanical engineers work collaboratively with members from other areas of the operation, including electrical engineers who design the circuitry and manufacturing personnel who coordinate production activities. Customers are also brought into the product development process to provide valuable input on product specifications and requirements, while suppliers play a key role in integrating their parts into the final product.

In this manner, the product is developed collaboratively, with various areas working together on the project from concept through production to jointly develop a manufacturable product that meets customer demands and gets to market as quickly as possible.

The industry's first integrated intelligent power module by Motorola.

Figure 1

The power module's process induced displacement plot of the subassembly.

Best Practices at World-Class Manufacturers

One of the first phases of the cycle-time reduction initiative was examining ways in which world-class companies successfully shorten product development time. Various methods were investigated and benchmarked for large-scale manufacturing enterprises in a range of industries. A list of "Ten Best Practices for Product Development" was then compiled to guide the Motorola groups and operations in reducing their individual cycle times.

- **Total Cycle-Time Reduction.** Processes for developing, manufacturing, and distributing products must be continuously improved to remain competitive in getting products to market as quickly as possible.
- **New Product Development Process.** The entire process for designing and ensuring manufacturability of the highest quality new products must be streamlined for maximum speed and efficiency.
- **New Products Driver.** Customer needs, demands, innovations, and expectations must come first in deciding what new products will be developed.
- **Engineering Metrics.** Methods must be established for measuring the effectiveness of meeting the needs of both internal and external customers.
- **Robust Design and Training.** Push the whole technology platform to the edge to make sure the way we design products uses up-to-date methods.
- **Engineering Tools.** Be proactive in using the most up-to-date technology, equipment, and software for the development of robust products.
- **Electronic Networks and Interfaces.** Access, exchange, communicate, and utilize information quickly through available sources such as computer networks and the Internet, e.g. World Wide Web.
- **Empowerment and Customer Visits.** Designers are empowered to seek customer input so everyone is involved in product development.
- **Research Labs and Technology Sharing.** The technology created in groups such as research labs should be shared throughout the company and disseminated industry-wide.
- **Reuse and Career Recognition.** Projects should first consider utilizing previous processes without reinventing the wheel each time. Individual accomplishments should be rewarded and recognized.

Choosing Technology Tools

With technology as one of the primary focus areas in the initiative, Motorola has invested aggressively in hardware and software for design automation, analysis, simulation, and data exchange. If groups can demonstrate that a tool will help improve speed in performing tasks, then there are really no barriers to acquiring and installing that technology.

In the Hybrid Power Modules Operation, a variety of software is employed for electronic circuit development, including device simulation packages for modeling semiconductor components, schematic capture software for circuit design, and printed circuit board layout packages for arranging and interconnecting components. Packaging design utilizes mechanical engineering software including 3D computer-aided design (CAD) for establishing the geometry of the modules and FEA for analyzing the structural integrity of the components. The ANSYS program was selected as the solver of choice for FEA work.

All software in the operation runs on networked Hewlett-Packard 9000 Series 735 workstations with 125-MHz processors. These machines were selected after extensive benchmarks of CPU speed and careful evaluation of vendor support and software availability/release. Although lower-priced machines were available, the levels of complex modeling, analysis, and simulation required in the Hybrid Power Modules Operation demand the high-end performance and power provided by these workstations. Running this on slower, less capable machines just doesn't make sense from a technical or a business standpoint.

At Motorola, selection of hardware and software is based on consensus of end users rather than dictums handed down from management. As a result, tools are purchased based on functionality and usefulness rather than cost alone. To facilitate the selection process and encourage sharing of information about such tools, Motorola instituted what it calls "Centers of Excellence." Each center is subdivided into areas of known disciplines, such as the Thermal Center of Excellence, Mechanics Center for Excellence (MCOE), etc. Twice yearly, a gathering of hundreds of representatives all from Motorola meet at the company's Advanced Manufacturing Technology (AMT) Symposium and exchange information.

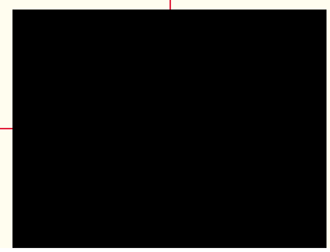
The MCOE provides an excellent forum for engineers to share their base of experience company-wide. Through these meetings, users learn from other groups about their application of FEA and in turn share information about what they're doing. Of particular interest are reasons the Hybrid Power Modules Operation selected ANSYS.

Unlike other FEA solvers that rely on separate programs for building models and displaying results, ANSYS has useful pre- and post-processors integrated in the same software. This makes the entire analysis process much more efficient, especially when models must be changed based on results and multiple iterations must be performed. Also, ANSYS has excellent communication via product data management (PDM) links to CAD libraries of parts stored in Motorola databases. With this type of electronic interconnection, mechanical engineers have access to previously created part designs, thus saving time compared to developing geometries from scratch.

In addition to the comparatively routine use of FEA in the group for thermal, structural, and vibration analysis, ANSYS was selected for high-end functionality in areas such as coupled-field (also called "multiphysics") analyses, which allow users to study two or more different interacting variables/disciplines, such as thermal-electric and structural-electric (or piezoelectric). ANSYS does this through elements containing all the necessary degrees of freedom and handles the field coupling by calculating the appropriate element matrices. With the direct method of coupled-field analysis, ANSYS performs these analyses simultaneously and saves considerable time, not only because the analysis is completed quicker but due to the fact that file manipulation is eliminated.

The 1200 volt non-punchthrough (NPT) insulated gate bipolar transistor silicon.

Figure 2



The localized electric field density from the module power lead coupled-field analysis.

The Broad Scope of FEA in Electronic Packaging

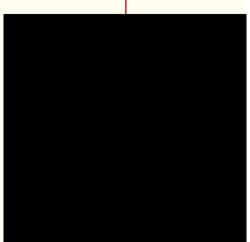
Mechanical engineers in the Hybrid Power Modules Operation use the ANSYS program for a wide range of tasks in developing packaging configurations for the semiconductor devices. In typical semiconductor packaging design, layout of components is done first and the configuration studied with thermal analyses to define and optimize the temperature distribution inside the module. Next, leads are configured to finalize module circuitry and thermal-electric analyses are performed to balance voltage drop and temperature. Also, time-independent plasticity analyses are used to study lead deflection induced during assembly and production. Viscoplastic analyses are then employed to verify the strength of solder joints. Finally, linear elastic structural analyses and dynamic analyses are performed to check for package integrity. Plans are to also use magnetic analyses (Emag®) to determine electrical parasitics, such as transient capacitance and inductance.

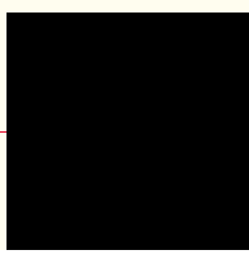
- **Thermal.** Since heat is the mortal enemy of electronic devices/circuits, thermal analysis is used most often in electronic packaging to arrange components in the least space without overheating them. To determine the temperature distribution inside the module, the analysis takes into consideration the amount of power contributed by each component and heat dissipation via conduction, convection, and radiation.

- **Thermal-Electric.** This coupled-field analysis simultaneously studies both electrical parameters and component heating to determine, for example, temperature rise and voltage drop in current conductors, such as power and signal leads. Performing these analyses at the same time saves considerable time over the previous indirect approach requiring two separate runs that were time-consuming and required numerous file manipulation operations.
- **Time-Independent Plasticity.** A common problem in semiconductor assemblies is when copper parts such as leads deform under loads (during production or as a result of heat during operation); the material acts nonlinearly so that stress is not proportional to strain. Characterized by the permanent straining that occurs in a material once a defined level of stress is reached, ANSYS takes this into account using kinematic hardening, isotropic hardening, anisotropy, Drucker-Prager, or user specific procedures.
- **Viscoplasticity.** Used extensively in the Hybrid Power Modules Operation for evaluating the integrity of solder joints, the viscoplastic analysis capabilities of ANSYS are based on the Anand model (from MIT Professor Lallit Anand) for representing high-temperature rate-dependent metal forming/deformation, where materials undergo large displacements with irreversible straining over time. These high-end analyses replaced previous prototype testing methods, saving considerable time and expense during the development process.
- **Structural.** This type of analysis is used to determine displacements, stresses, strains, and forces in a component as a result of an applied load. In electronic packaging design, structural analyses predict stress on components and assemblies, such as circuit boards, leads, and silicon devices.
- **Dynamic/Modal.** Power modules often undergo forced vibration from the electric motors, industrial machinery, or vehicles on which they are mounted. Transient dynamic analyses are used to determine the response of a component under the action of a specified time-dependent load. Modal analyses are used to determine a component's (or assembly's) mode shape and natural frequency.
- **Magnetics.** The Hybrid Power Modules Operation is currently evaluating ANSYS/Emag for the evaluation of electrical parasitics, such as inductance.

Motorola's 1200V/1200A high-powered IGBT module incorporates paralleled emitter and collector power leads.

Figure 3





Steady state thermal results of Motorola's single switch module using NPT silicon technology.

Analysis In Action

A good example of the time and cost savings of FEA is in the use of viscoplastic analysis to study solder joints. In many electronic applications, solder is the weak link, since it is above half its melting point at room temperature. This characteristic of solder results in creep processes dominating its deformation kinetics. This irreversible straining that occurs over time manifests itself as fatigue cracking, disrupting the thermal/electrical performance of the module.

Viscoplastic analysis is an excellent tool for predicting solder joint failure under a range of conditions, however, most recently the analysis has been expanded for defining particular prefabrication geometry. In one recent project to design a 1,200 Amp/1,200 Volt module for a high-current industrial drives, for example, viscoplastic analysis predicted how much a 5-mm-thick copper baseplate would "bow" when its layers were soldered in place.

Ordinarily, making such a determination would require building and testing a set of physical prototypes: a process that generally takes over four months and costs nearly $250,000 for tooling and manufacturing. With ANSYS, only a single eight-hour analysis was required to predict baseplate distortion. This represented a huge time and costs savings and not only led to better solder reliability but also to an improved manufacturing process.

Continuous and Collaborative Product Development

While the Hybrid Power Modules Operation at Motorola has been hard at work determining how to reduce the time and cost of packaging semiconductors while maintaining high quality, many industry observers are trying to stick labels on approaches of this type. But none seems to fit exactly what we're doing here.

"Concurrent engineering" implies that everyone works on the project at the same time, which is not the case here because different people are involved at different phases of the program. "Integrated product development" is used as a marketing slogan by some vendors in referring to their particular software. "Virtual product development" doesn't really hit the mark either because it seems to emphasize doing all analysis up front in the early stages of design, somehow implying that no further analysis is needed after the conceptual work is completed.

The product development process in our operation is probably best described as continuous (on-going analysis is used throughout product development) and collaborative (everyone works together as a team in their areas of expertise and responsibility).

This common-sense approach allows for flexibility not only in changing and refining product design along the way but also in modifying the product design process itself when necessary. After all, the process should allow for continuous refinement and optimization of designs, and the same development process probably isn't best (or even workable) for all products. This allows the organization to adapt readily to changes ... fast changes caused by any number of factors, including customer change orders, cost-reduction ideas, suppliers who can't meet shipments, equipment breakdowns, bad weather, etc.

Teamwork involves close collaboration between many different groups. Within Motorola, mechanical engineers develop packaging by working closely with electrical engineers, with CAD and analysis data files exchanged routinely. To promote communication and cooperation, people from the manager to technicians work in the same sized cubicles, which are arranged so team members can talk to one another easily with out unnecessary (physical) barriers. This level playing field lets people interact more effectively than "hierarchical silo" organizational structures that isolate individuals and groups.

Engineers also work closely with manufacturing personnel throughout product development to quickly resolve design-for-assembly issues. This eliminates "we can't make that" and "if only you'd have" responses from production in organizations where designs are thrown over the wall to manufacturing at the end of product development.

In the Hybrid Power Modules Operation, engineering and manufacturing personnel work closely together and everyone is considered a valued member of the team with particular expertise and experience to contribute. Analysis capabilities for doing "what-if" studies are of considerable value in such an approach in evaluating everyone's ideas and suggestions. Analysis can also serve as a bridge connecting our operation with customers and suppliers, both of whom contribute valuable input during product development.

Motorola's high current module power substrate assembly.

Figure 4

The power module's total displacement after 24 hours creep shown in the viscoplastic analysis.

Customers are brought into the product development process early to provide valuable input on service requirements so engineers can gain a better understanding of the OEM's expectations, problems, and concerns. In this way, our operation moves beyond the role of a component maker to more of a solutions provider, forming closer relationships with customers and clearing the way for sustained business with them.

In many cases, information supplied by customers can be plugged directly into analyses to determine, for example, life expectancy of modules or power requirements. Also, valuable analysis techniques developed by working on a product are often passed back to their customers for use on other projects. For example, our work with viscoplasticity to study solder joint reliability was later transferred to a drives manufacturer customer for work they were doing with strain energy density.

Likewise, valuable product development information is exchanged with component suppliers. A results file from ANSYS is often sent to baseplate suppliers, for example, as a timely and accurate way of defining not only the geometry of the part but of creating the CNC input file to machine it.

In this way, analysis is not only a technology tool allowing our operation to solve tough engineering problems and optimize designs for specific products. Analysis as we use it forms the basis for continuously evaluating and refining our development process. And it provides a vehicle for working more closely with our customers and supplier business partners in getting better products to market faster.

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