Reinventing the Wheel? No, Just the Tire

Sumitomo Rubber engineers use Abaqus FEA for material simulation to improve rolling resistance and vehicle fuel economy

The U.S. auto industry has been abuzz about CAFE (corporate average fuel economy) standards since aggressive targets were recently set for the fleet: 34.1 mpg by 2016, increasing to 54.5 mpg by 2025. Regulations in the EU, Japan, and China—higher than the U.S.—are also set to increase sharply by 2020.

The new numbers shift fuel-efficiency initiatives into the fast lane for engineering design teams at car makers and suppliers worldwide. Performance capabilities—such as advanced injection, combustion and exhaust systems, lightweight materials, and aerodynamic enhancements—are a major focus. And so are tires.

Roughly two-thirds of the oil consumed in the U.S. serves to power the country's 250-million-vehicle fleet. Of that total, about 20 percent is dedicated to simply overcoming the friction of tires rolling on pavement. Rolling resistance (RR), as this property is called, is dependent on two major factors: tire design—which includes size, structure, and material makeup; and operating conditions, encompassing inflation pressure, vehicle load, ambient temperature, rotating speed, and alignment.

Tire makers have already improved rolling resistance by 25 to 30 percent over the last 20 years. Still, further advances are needed to achieve the new fuel-economy rules. But engineers generally agree that advances in RR can cut fuel consumption by an additional 3 percent. Improving tires, as compared with other automotive systems, is considered to be a relatively low-investment way to enhance automotive fuel efficiency.

Simulation helps examine rolling resistance

Over the years, engineers at Sumitomo Rubber Industries in Kobe, Japan, have played their part in RR-improvement studies. Efforts led by their simulation team have advanced both the structure and material makeup of tires. But the urgency of their redesign efforts has been upped by future standards, as well as an existing 2010 agreement among tire manufacturers to introduce a graded tire-performance labeling system.

If squeezing better performance out of rubber tires were simply a matter of minimizing friction, the engineering challenge would be easier to solve. But performance is also a function of safety, accomplished by making the tire grip the road, especially in wet conditions. From a design point of view, "wet grip" (as it's known), is the functional opposite of RR. So the design challenge becomes one of tradeoffs: how to minimize friction for better RR versus how to maximize grip to keep drivers safe. The secret to balancing these two opposing physical principles lies in the rubber.

"The performance of a tire depends on the characteristics of various compounds and the complicated relationships between structures at the micro- and nano-levels," says Naito Masato, assistant manager in Sumitomo's Material Department.

Rubber tires consist of an intricate mix of polymers, fillers, and cross-linkers. Polymers, known for their softness and elasticity, form the dominant matrix and are structured in strands of molecular-sized beads that can number in the hundreds of thousands. Silica and carbon—the fillers—serve as reinforcing agents and are added for strength and to improve wear. Dispersed through the matrix, fillers form bonds with the polymers (through intermediary coupling agents, or functional groups, in the polymer molecule). This makes the material more rigid. The spacing of

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the silica in the polymer matrix and the position of the bonding between the two materials inhibits the wasteful deformation and heat generation responsible for the tire's rolling resistance. "We have a long history of simulating tires," says Masato. "But until recently, it was not easy to examine these relationships in greater detail to further improve our material designs."

For more than 15 years, Sumitomo engineers have been using Abaqus finite element analysis (FEA)—which is part of the Dassault Systèmes **3D**EXPERIENCE technology portfolio under the SIMULIA brand—to conduct tire simulations (Figure 1). "We chose Abaqus because it can handle large-scale simulations and has the capabilities to analyze the large, nonlinear material deformations of rubber," says Masato. "The software is highly accurate and has a variety of all-purpose material models that are easy to calibrate."

New simulation methods look deeper into the rubber

Early material simulations were instrumental in helping Sumitomo engineers improve tire performance. But with market pressure rising, new techniques were needed to understand the complex material behavior that occurs when the rubber meets the road.

For this purpose, the team developed a multiscale simulation methodology—called 4D NANO DESIGN—which looked at tire materials at increasing depths of magnification. At the first level, FEA predicts micrometer-scale (1/1,000 mm) deformation of the rubber, including the exact location of the energy loss in the material. A molecular dynamic (MD) simulation, next analyzes the three-dimensional arrangement of silica particles and the bonding between the polymer and silica at the nanometer scale (1/1,000,000 mm). A molecular orbital (MO) simulation at the sub-nanometer level (1/10,000,000 mm) then examines the reactivity (or electronic and energy status) of the materials. "The material behavior of rubber tires could not previously be simulated with this degree of accuracy," says Masato.

For the FEA micrometer-scale analysis, the team needed to create a finite element model (FEM) that accurately reproduced the 3D structure of the rubber, including the distribution and exact location of filler through the polymer matrix. This was done by collecting sophisticated test data: dynamic testing provided details of polymer behavior; transmission electron microscopy (TEM) and X-ray scattering were used to reveal 2D micrometer-to nanometer-scale structural details; and transmission electron micro tomography helped map the 3D structure.

Because the computational challenges were formidable, Abaqus Standard's newly introduced iterative solver was employed in a high-performance computing environment to simulate the response of the microstructure. The FEA results showed that the highest heat (the cause of rolling resistance) was generated where the filler particles contacted each other (Figure 2).

Guided by the FEA results, a molecular dynamics simulation (using COGNAC, a specialized soft-material software that is part of OCTA) evaluated filler dispersion techniques and calculated polymer formulations with evenly distributed filler (which would lead to improved RR). The engineering team then worked with the development manager to ensure that the suggested materials fit within accepted manufacturing protocols and costs. This process helped avoid laborious trial-and-error polymer synthesis-and-testing cycles. The MO simulation examined the reactivity of the chosen materials and further optimized the rubber structure.

Benefits of multiscale simulation

Sumitomo's new 4D NANO DESIGN technology allows the company to look into tire performance in totally novel ways. "We can now predict tire performance at the micro- and nano-levels. This can't be done using physical testing," says Masato. "Simulation has shortened our product development cycles and made our process more efficient."

Tires designed using these new methods are already on the road. And more improvements are likely on the way. "We anticipate that our new process will make a significant contribution to the more effective development of tires in the future," Masato adds.

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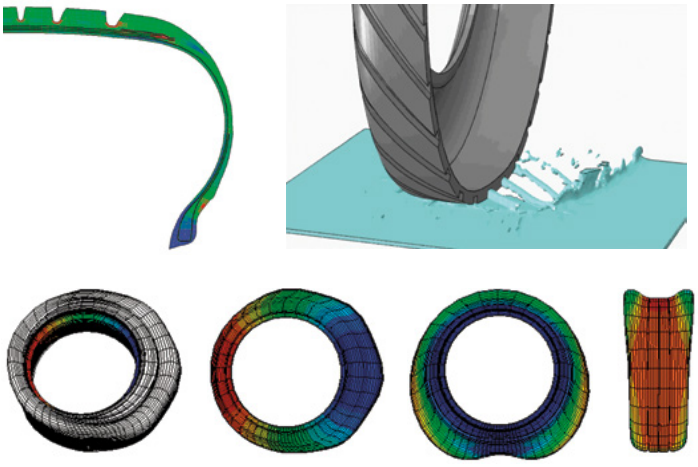

Figure 1. In earlier research, Sumitomo engineers used Abaqus to conduct tire simulations such as rolling resistance (top left, contour section of tire), hydroplaning and mode analysis (bottom, four views).

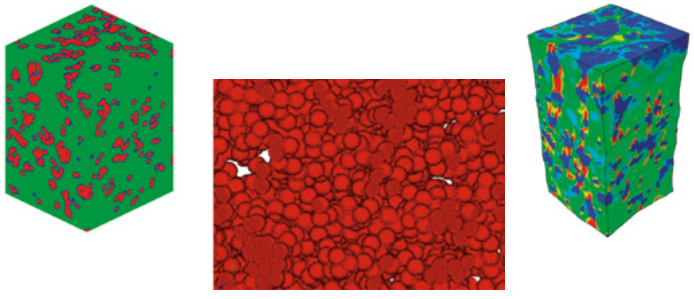

Figure 2. Using Abaqus FEA, a 459×712×489 nanometer block of rubber (far left) was modeled with 10 million hexahedral elements, which separately considered polymer (green) and filler (red) and accounted for both nonlinear viscoelasticity and elasticity characteristics while simulating tensile deformations. An enlarged view of the filler alone is shown (middle). In the strain distribution (far right), the rubber was deformed and where polymer was sandwiched between unevenly dispersed filler there was evidence of large strains (red), indicating the generation of heat, which increases rolling resistance.