MRS BULLETIN

Serving the International Materials Research Community

A Publication of the Materials Research Society

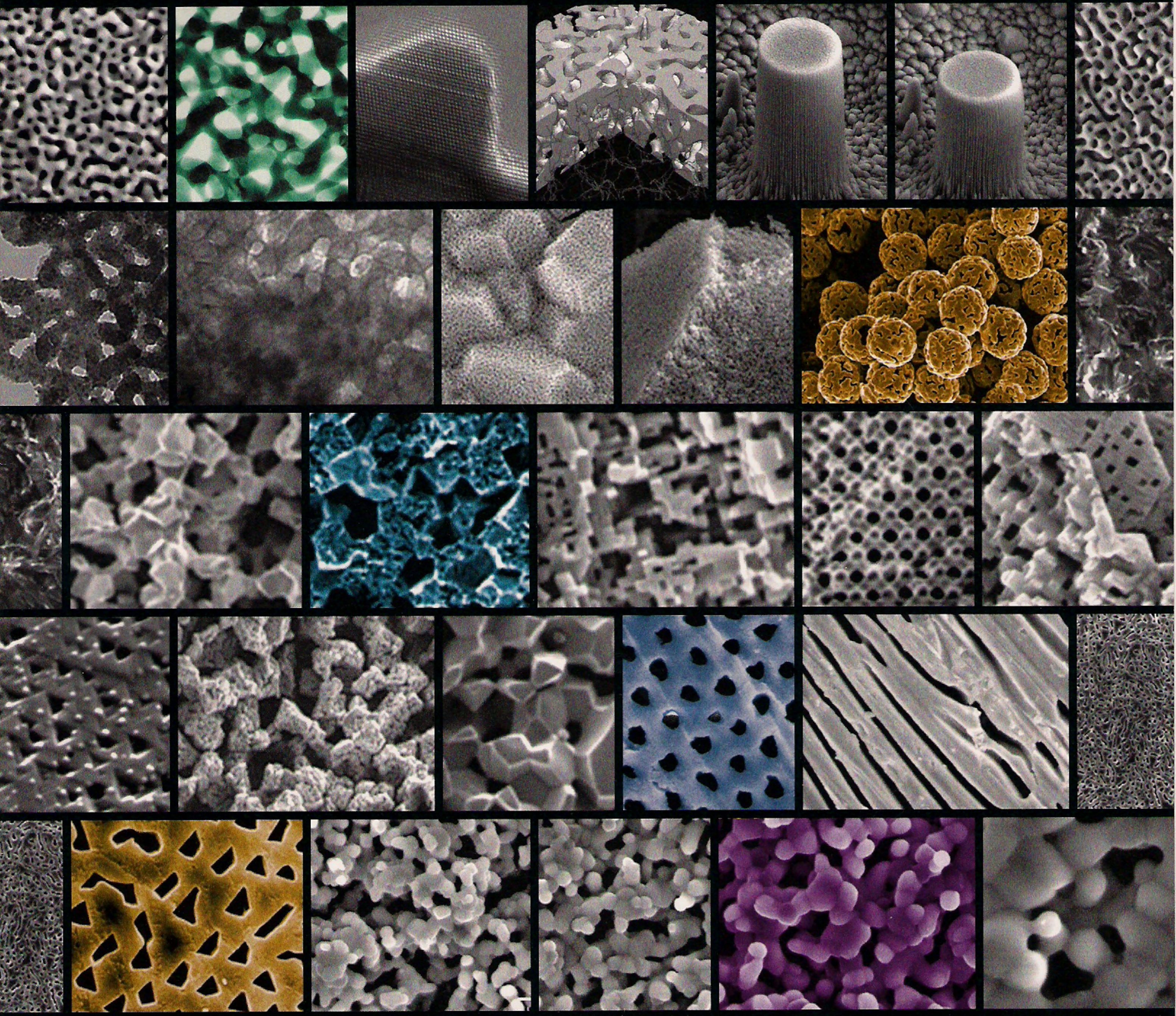
August 2009, Volume 34, No. 8

MEMBER OF INTERNATIONAL UNION OF MATERIALS RESEARCH SOCIETIES

Also in this Issue:

Materials at 200 mph: Making NASCAR Faster and Safer

Hard Materials with Tunable Porosity



Materials at 200 mph: Making NASCAR Faster and Safer

Diandra Leslie-Pelecky

The following article is based on the Symposium X: Frontiers of Materials Research presentation given by Diandra Leslie-Pelecky of the University of Texas at Dallas. The presentation was delivered on December 1, 2008 at the Materials Research Society Fall Meeting in Boston.

Abstract

Speed is the ultimate goal of racing, and materials are an increasingly important area of research for making race cars faster. The splitter, which produces front downforce, is made from Tegris, a polypropylene composite offering comparable stiffness and improved impact properties at significantly lower cost than alternative materials. Engine blocks must be cast iron, but careful control of microstructure using precision manufacturing methods produces a lighter engine block that generates more horsepower.

Speed and excitement must be balanced with safety, and materials are key players here, as well. Energy-dissipating foams in the car and the barriers surrounding the tracks allow drivers to walk away uninjured from accidents. Fire-resistant polymers protect drivers from high-temperature fuel fires, and technology transfer from the National Aeronautics and Space Administration (NASA) to the National Association for Stock Car Auto Racing (NASCAR) in the form of a low-temperature carbon monoxide catalyst filters the drivers' air.

Sports are an outstanding way of showing the public how materials science and engineering are relevant to their lives and interests. Materials science and engineering is just that much more exciting when it's traveling at two hundred miles an hour.

Introduction

The National Association for Stock Car Auto Racing (NASCAR) is "stock car" racing, in contrast to the open-wheel Formula One and Indy Car racing series. With a minimum weight of 1565 kg (3450 lbs), NASCAR stock cars are about twice as heavy as open-wheel cars. Their 5.87 L (358 in^3) engines produce 6.3+ MW (850+ horsepower), allowing the cars to reach speeds of more than 329 kph (200 mph).

NASCAR has a challenging role as a sanctioning body: developing rules that promote competitive racing while keeping costs in check and—most importantly—ensuring safety. Races initially featured literal "stock" cars; however, speed increased rapidly. Qualifying speeds at Daytona International Speedway (Figure 1), for example, rose from 225 kph (140 mph) in the late 1950s to 312 kph (194 mph) in 1970, making safety modifications necessary.

Building the Car

Eventually, it became easier (and safer) to make race cars that look like stock cars than it was to turn stock cars into race cars. In 2001, NASCAR started to design a new car, initially called the "Car of Tomorrow." The new car was motivated by three considerations: improving competition, lowering costs for owners, and improving safety. The new car (shown in Figure 2) was introduced in 2007 and ran its first full season in 2008.

The cars, which are built largely by hand, start with a mild steel (1018 or similar) tube-frame chassis. Titanium alloys or carbon-fiber composites would provide better strength-to-weight ratios; however, the higher cost led NASCAR to limit chassis materials to "magnetic steel." Each finished chassis is inspected at the NASCAR R&D Center using digitizing arms and then certified with 10 strategically placed radio frequency identification tags that are used to confirm the chassis identification at the racetrack.

The car's body is surprisingly thin, with a minimum thickness of 24 gauge (about a half millimeter). The roof, hood, and decklid (trunk) are stamped, but the rest of the car is shaped by hand using an English wheel, a metalworking tool that resembles two rolling pins, one on top of the other. Sheet metal is compressed between the two wheels, forming the body panels. Drawing quality aluminum killed (DQAK) steel provides the formability necessary for the intricate curves. A giant template grid fits over the car to check that the body conforms to NASCAR rules.

Cars are painted or (more and more frequently) "wrapped." Wrapping is essentially wallpapering a car with a polymer film onto which a design has been printed. A grid of micron-scale holes allow air to escape from under the plastic as it is applied to the car.

Materials for Speed

Splitting the Air

A car's grip is proportional to the force pushing its tires into the track. That force comes from the car's weight plus aerodynamic forces, the latter of which scale with the speed squared. All but two of the 38 races each season require only left-hand turns. In response, the old car had evolved into a kidney-bean shape: Its body was offset to the left, and the left-side fenders

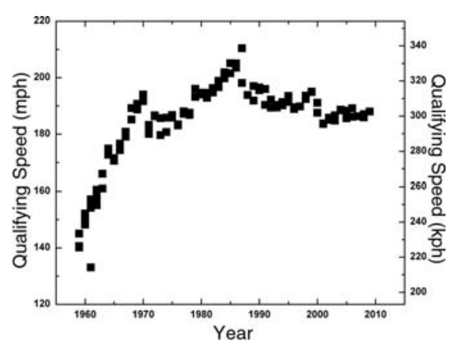


Figure 1. Qualifying speeds at Daytona International Speedway 1959–2009. The two cusps in 1970 and 1989 correspond to the implementation of restrictor plates, which limit engine power by reducing airflow to the engine.

were broader than the right-side fenders so that when weight shifted to the right in left-hand turns, the greater aerodyanmic downforce would keep the left-side wheels in contact with the track.

In the new car, the front valance was replaced by a splitter, and the rear spoiler (a flat metal blade standing up on the end of the trunk) was replaced by an inverted wing. Aerodynamic adjustability shifted from the body, which cannot be changed easily, to the front splitter and the rear wing, which can be adjusted at the track. The new body is much more symmetric and the new rules leave little room for shape modifications.

The front splitter produces downforce by literally splitting the air. Air above the splitter has a higher pressure than air passing below. After trying everything from wood to carbon-fiber composites, the NASCAR R&D Center settled on Tegris, a composite product with the necessary combination of strength and stiffness.

Tegris is a polypropylene composite that starts with a tape yarn consisting of an inner, highly oriented crystalline layer and an outer amorphous layer with a lower melting temperature. The tape yarn is woven into a fabric, and sheets of fabric are pressed together under moderate temperature (138°C–160°C) and pressures from 1380–2760 N/m^2. The outer layer (~15 vol%) melts to form the matrix, while the inner layer provides the mechanical properties.

Tegris does not have a brittle failure mode—it delaminates, so it does not leave sharp pieces for other cars to run over. Consistent with NASCAR's efforts to reduce costs for owners, Tegris offers comparable stiffness and improved impact properties at significantly lower costs than alternative materials such as carbon-fiber composites.

NASCAR uses Tegris primarily as a sheet product, but Tegris has potential applications in other areas. The new car's static center of gravity is 2–3 inches (5.0–7.6 cm) higher than in the old car, so more weight shifts on braking, accelerating, and turning. Teams try to reduce the weight of components such as dashboards to lower the center of gravity. The formability of Tegris makes it an ideal candidate for these applications, as well as for lower-speed use. For example, a Tegris kayak[1] weighs in at only 16 kg, and 3 kg of that is the seat.

Engines

NASCAR uses carbureted pushrod engines that reach temperatures of 1200°C in each of its eight cylinders. Engine blocks are required to be cast iron, but not all cast iron is made equal.

Despite advantageous thermal properties, gray cast iron (>95 wt% iron with 2.1–4 wt% C and 1–3 wt% Si) is brittle due to stress concentration at the edges of the graphite flakes that form during processing (Figure 3a). Ductile iron, in which magnesium is added to produce round graphite structures, is less brittle but has lower thermal conductivity. As shown in Figure 3b, Mg additions in the narrow

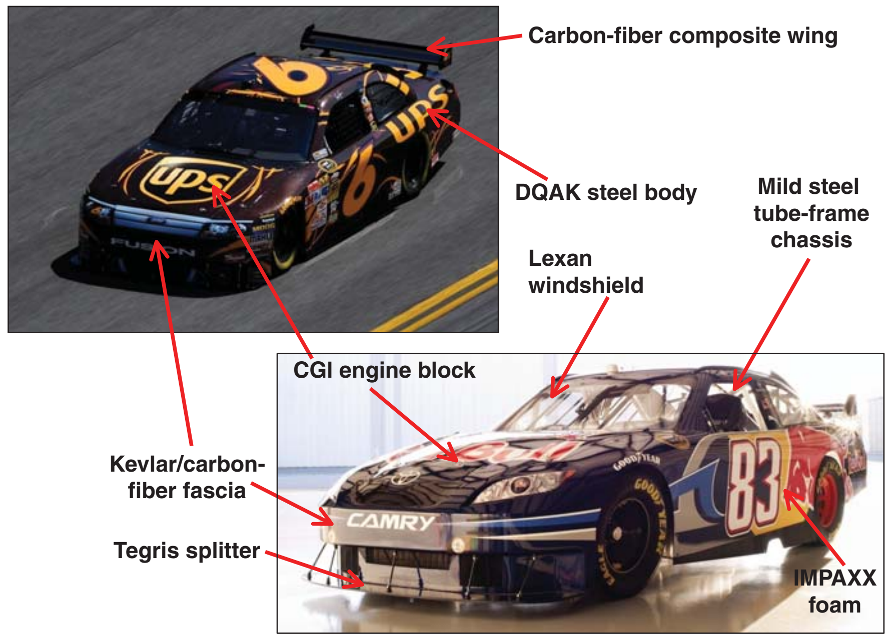


Figure 2. Race cars from Roush Fenway Racing (top) and Red Bull Racing (bottom) show a few of the places where advanced materials are used to improve speed and increase safety. Images courtesy of Getty Images (top) and Thomas Hoeffgen (bottom). CGI, compacted graphite iron; DQAK, drawing quality aluminum killed.

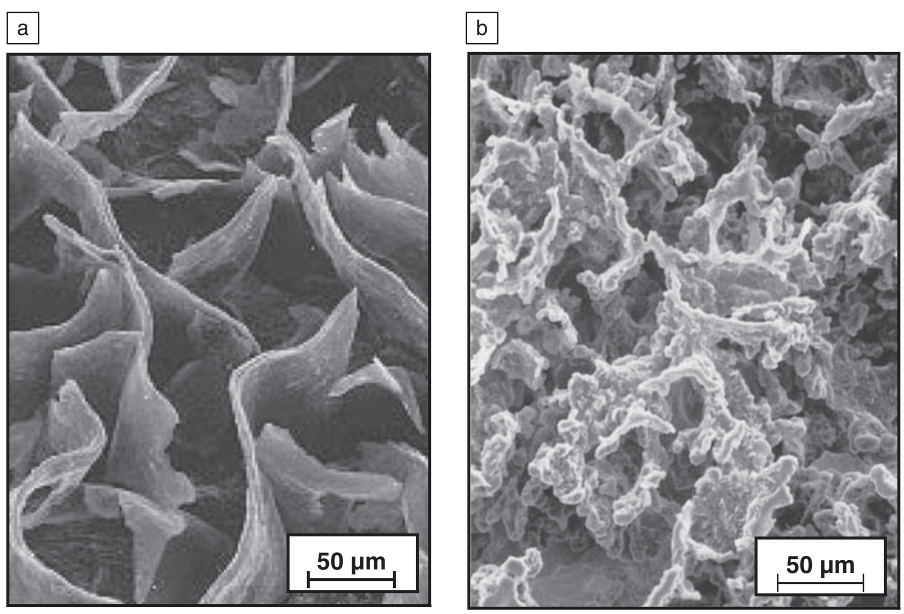


Figure 3. Deep-etched scanning electron microscope photos comparing (a) gray cast iron with (b) compacted graphite iron, which is less brittle and stronger. Images courtesy of SinterCast.

range of 0.007 wt% to 0.015 wt% change the graphite from flakes into rounded, interlocking coral-like structures.[2] This compacted graphite iron (CGI) has at least 75% higher tensile strength, 35% higher stiffness, and double the fatigure strength of gray cast iron. Although CGI has been known since the late 1940s, the need to control Mg additions precisely (a drop of just 0.001 wt% Mg can cause a 25% reduction in tensile strength) precluded use in large-scale production until computer controls became accurate enough to maintain the required Mg concentration.[3]

In addition to weight savings (10–30% on engine blocks), CGI blocks have less cylinder bore distortion as the block heats, which means tighter sealing, higher cylinder pressures, and, ultimately, more horsepower.[4] About 80% of all NASCAR teams use CGI engine blocks. All of Audi's commerical V-diesel engines rely on CGI cylinder blocks, and Ford is the global leader in CGI, with five engines on the road and two more to be launched in the next year.

Coatings

To limit cost, NASCAR specifies materials for almost every part on the car. For example, engine valves may be titanium alloys but not more expensive titanium aluminides. Thin-film coatings not only broaden the range of possible mechanical properties but also are especially useful when different areas of a single part require different properties.

Adding tetra-ethyl lead to gasoline was primarily to prevent "pinging"–autoigniting the air-fuel mixture prior to the spark. Lead gasoline additives fouled catalytic converters and created concern over health and environmental safety, which led the United States to eliminate leaded gasoline. Auto-ignition can be addressed by increasing gasoline octane, but lead also protects against valve seat recession (wearing down of the valve seats). An engine valve operating at 9500 rpm hits its valve seat 79 times each second. $BeCu_{25}$ is used for intake valve seats due to its high strength; however, the high temperatures of the exhaust valve require $BeCu_3$ or Moldstar 90 (a Be-free Cu), which have greater thermal conductivity.

The valve seat recession issue was addressed by coating the valve head seat angle (the part that mates with the valve seat) with diamond-like carbon (DLC) or chromium nitride. DLC transforms to graphite at high temperatures, so its use in the exhaust valve is limited, and metallic hard coatings must be used.

Most valves have more than one type of coating. DLC or CrN coatings on the valve tips prevent lash cap wear. Valve stems (which pass through bronze valve guides) are highly polished to allow smaller tolerances, and then they are coated with low-friction molybdenum-based alloys, such as molybdenum disulfide. Valve-stem coatings include some surface porosity (<2.0%) to minimize stress and promote oil retention. Physical vapor deposition or plasma-assisted chemical vapor deposition techniques commonly are used, although some coatings are plasma sprayed. Typical coating thicknesses range from 1 to 5 μm, depending on the coating and the part.

Coatings are not limited to valves, as shown in Figure 4. It is hard to find two contacting metallic pieces in which at least one member of the pair is not coated. Multilayered metal-containing DLC coatings are applied to parts that sustain high impacts, such as gears. Piston rings are coated with titanium or chromium nitrides or metal-containing DLC to decrease friction while maintaining a tight seal. A nickel-silicon-carbide coating is used on cylinders or cylinder linings. Even fasteners in the engine are coated to facilitate tearing down the engine, which happens after every race.

Safety

Making Tracks SAFER

During a qualifying run at Texas Motor Speedway in April 2008, Michael McDowell's No. 00 Toyota Camry lost grip in turn one and veered suddenly into the outer wall. The impact spun the car around, causing it to hit the wall again, followed by barrel rolls down the 24-degree banked turn.[5] Within minutes of coming to rest at the bottom of the track, McDowell climbed out of the car and waved to the crowd before making the mandatory trip to the infield care center. One factor that allowed McDowell to be out on the racetrack (in a backup car) the very next day was the SAFER (steel and foam energy reducing) barrier created by Dean Sicking and his team at the Midwest Roadside Safety Facility at the University of Nebraska–Lincoln.

Figure 4. Most valves have different coatings on different parts. Decreasing friction is critical on the stem, while wear resistance is the primary concern for the head. The photo also shows valve spring retainers, valve locks, and piston wrist pins, all of which are also coated. Images courtesy of Xceldyne and CV Products.

The first racetrack barriers were concrete walls, sometimes augmented by stacks of tires or plastic barrels filled with water or sand. The formula for impulse tells us there are two ways to decrease the force of an accident: decrease your speed (antithetical to racing) or increase the time over which contact occurs. The idea of "soft walls" seems obvious, but their implementation poses challenges. Foam-lined walls, for example, can "catch" the cars, stopping them suddenly, or sending them back into the paths of other cars.

The polyethylene energy dissipating system (PEDS) was installed at the Indianapolis Motor Speedway in 1998. The PEDS was composed of five-foot long sections of overlapping high density polyethylene (HDPE) plates separated from the outer walls by ~40 cm diameter HDPE cylinders. In principle, when a car hits the PEDS, the cylinders should deform, and the smooth HDPE front should not snag the car. The cylinders should rebound back to their original shape. In their first race test, the PEDS shattered, flinging debris across the track; however, despite a very hard hit, the driver walked away from the accident with nothing more than a concussion.

Tony George, owner of the Indy Racing League, got Sicking's group involved in 1998 on safety barriers, and NASCAR joined the effort in 2002. Many tracks host Indy car and stock car races. Since the car masses differ by a factor of two, the barrier must function over a range of energies. Sicking recommended an outer wall of hollow square steel tubes (about 20 cm on a side), which have sufficient flexibility but will not scatter debris on the track upon impact. The HDPE cylinders were replaced by pyramidal foam wedges (Figure 5). Owens Corning Foamular 150—an extruded polystyrene foam used for building insulation—absorbs energy and allows the outer wall to move. The construction directs the car along the barrier and not back into traffic.

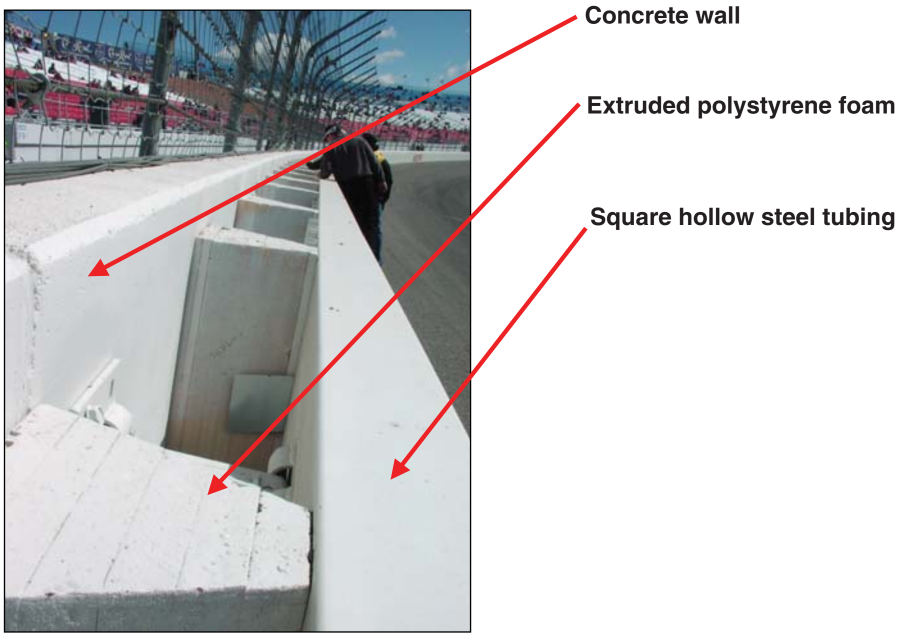


Figure 5. The SAFER (steel and foam energy reducing) barrier features hollow square steel tubing on the side closest to the cars and extruded polystyrene foam trapezoids that compress between the steel and the concrete wall when hit. Photo by Robert Hilborn.

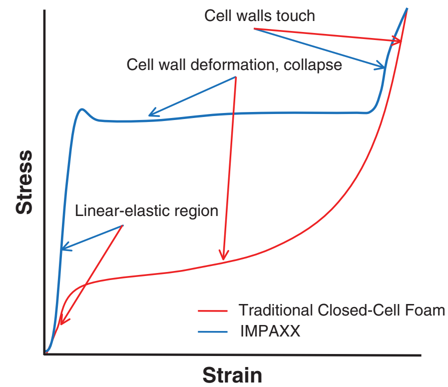


Figure 6. Schematic illustration of the engineering stress-strain relationship for a standard closed-cell foam (red) and IMPAXX (blue) foam showing that IMPAXX absorbs significantly more energy than traditional closed-cell foam.[7]

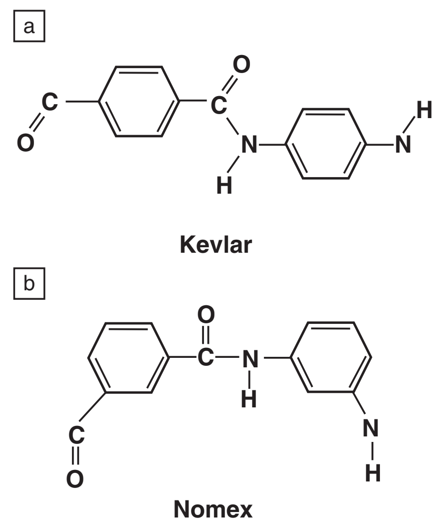


Figure 7. (a) Kevlar and (b) Nomex molecules share the same atoms, but the straight Kevlar molecules allow greater alignment, giving Kevlar high strength. The kink in Nomex precludes alignment, so Nomex is not as strong as Kevlar; however, Kevlar starts to decompose between 427°C and 482°C, whereas Nomex carbonizes instead of burning, melting, or decomposing.

Energy-absorbing foam is also found inside the car. Dow Automotive's IMPAXX foam is sandwiched between the outsides of the chassis bars and the car's body on both sides. A 90-mil (2.3-mm) steel plate in the driver's side door and a piece of Tegris in the right-side door prevent sharp objects from getting into the driver's cockpit.

IMPAXX is a closed-cell extruded polystyrene foam. The isolated pores of closed-cell foams make them more rigid than open-cell foams, which have a percolative path of pores through which gas can escape when the foam is compressed. Most closed-cell foams obey Hooke's law to about 5% strain. Higher strain deforms the cell walls (at nearly constant stress) until they touch, at which point the engineering stress-strain curve rises sharply,[6] as shown in Figure 6. IMPAXX's ability to absorb large amounts of energy is due to the foam's specific cell-wall architecture, which can withstand large applied forces before buckling.[7] The combination of energy dissipation in the track and in the car greatly minimizes the impact drivers feel in accidents.

Driver Gear

Jeff Gordon's No. 24 car is sponsored by DuPont, which means that materials occasionally are not just *in* the car—they are *on* the car. Nomex and Kevlar have both been featured on the rear panel of Gordon's car. Kevlar reinforces the front and rear carbon-fiber-composite fascia, while Nomex provides fire protection.

Nomex (poly-meta-phenylene terephthalamide) and Kevlar (poly-para-phenylene terephthalamide) are sibling aramids (aromatic polyamides), with Kevlar being the *para* form and Nomex the *meta* form. The monomers consist of the same atoms in the same order (Figure 7); however, Kevlar forms very straight chains due to steric hindrance, whereas Nomex has a kink. This makes Kevlar (a highly crystalline fiber that hydrogen bonds) extremely strong, but strength is not the top priority in case of fire.

NASCAR requires fire suits to protect the driver from a 982°C (1800°F) flame for five seconds. Kevlar starts to decompose between 427°C and 482°C. Nomex is not nearly as strong as Kevlar; however, it does not decompose when heated. Instead, the outer layer of the Nomex fiber forms a "char"—a carbon layer that surrounds the fiber and prevents it from being used as fuel.[8]

Chapman Industries' CarbonX is a polyacrylonitrile polymer that is heated to high temperatures during processing. Essentially, the char is created ahead of time. CarbonX will not ignite or burn, even when exposed to 1400°C for two minutes. Because it is essentially pre-burned, CarbonX currently comes only in dark colors. Since fire suits are part personal protective apparatus and part billboard, most drivers wear Nomex firesuits, with either Nomex or CarbonX underwear.

Fire is an obvious danger, but carbon monoxide is colorless and odorless. Stock cars have neither mufflers nor catalytic converters, as high engine throughput is essential for high horsepower. Efforts to minimimize CO exposure were stepped up in 2002 at the urging of drivers. At that time, the National Aeronautics and Space Administration (NASA) was preparing to launch a CO_2 laser as part of a Laser Atmospheric Wind Sounder satellite. Given the difficulty of regular CO_2 delivery to space, a catalyst was needed to convert CO output by the laser back to CO_2. Space is cold, however, and known catalysts needed heat to work. NASA invented a plantinized tin oxide catalyst that worked to –26°C. Then the solid-state laser was invented. There was no need for the new catalyst in space, but it turned out to be the perfect solution for NASCAR drivers.[9,10] Air passes through a series of filters, catalysts (including the NASA catalyst), and a cool box before entering the driver's helmet. The tubes entering the helmet sometimes are visible in in-car shots during races. NASA and NASCAR also collaborated in the mid-1990s to develop thermal blankets made from spun ceramic and glass materials that reduce the heat in the driver's cockpit by up to 10°C.

The Future

The National Association for Stock Car Auto Racing (NASCAR) is a technological enigma. While the cars themselves are relatively low-tech, an ever-expanding array of advanced technology (e.g., finite element analysis, computational fluid dynamics, and wind tunnels) is used behind the scenes to increase speed and improve safety. Many of the materials used in NASCAR are finding their ways into passenger cars, whether they be compacted graphite iron (CGI) engine blocks that reduce weight and save fuel, advanced coatings that decrease frictional losses in the engine, or foams that dissipate energy in collisions.

Sports are a great way to show the public how materials science and engineering impact their lives. An estimated 75 million people in the United States are NASCAR fans, watching races at tracks from California to Florida and New Hampshire to Phoenix. Like most sports fans, NASCAR fans are passionate about their interest, which means they are willing to go the extra mile to understand why their driver is (or is not) winning races. Materials are ubiquitous. It is hard to find places where they are not important. Materials moving at 322 kph (200 mph) open new avenues for us to share our work with the public.

Acknowledgments

Thank you to Jeff Bulmer of IonBond, Steve Dawson of SinterCast, Heather Hayes of Milliken & Co., NASCAR historian Buz McKim, Andy Randolph of Earnhardt Childress Racing Engines, Joe Rogers of Xceldyne & CV Products, and Marie Winkler-Sink of Dow Automotive for their assistance with research and helpful comments on the manuscript.

References

1. www.nativewatercraft.com/ult_12_tegris.cfm.
2. S. Dawson, *106th AFS Casting Congress*, Kansas City, KS, 4–7 May 2002.
3. S. Dawson, T. Schroeder, "AFS Transactions," (Paper 04-047, American Foundry Society, 2005).
4. R.J. Warrick, G.G. Ellis, C.C. Grupke, A.R. Khamseh, T.H. McLachlan, C. Gerkits, SAE Paper 1999-01-0325, International Congress and Exposition, Society of Automotive Engineers, Detroit, MI, 1–4 March 1999.
5. B. Halford, *Chem. Eng. News* **87**, 12 (2009).
6. S.K. Maiti, *Acta Metall*. **32**, 1963 (1984).
7. G. Slik, G. Vogel, V. Chawda, *Proceedings of the 5th LS-DYNA Forum* (2006).
8. S. Villar-Rodil, J.I. Paredes, A. Martinez-Alonso, J.M.D. Tascon, *Chem. Mater*. **13**, 4297 (2001).
9. NASA Technical Brief, "From NASA to NASCAR: Space-Age Technology Finds Its Way into Auto Racing" (2008).
10. NASA Technology Innovation, *Partnership Helps Virginia Company Grow, Racers Breathe Better* **12**, 20 (2005).

Diandra L. Leslie-Pelecky *is a professor of physics at the University of Texas at Dallas. After earning her PhD degree in condensed matter physics at Michigan State University, she joined the faculty at the University of Nebraska—Lincoln before starting her current position in 2008. In addition to research in the biomedical applications of magnetic nanoparticles, Leslie-Pelecky engages the public in science and engineering through K–12 schools, public outreach, and authoring* The Physics of NASCAR. *More information about materials and motorsports can be found at www.stockcarscience.com. Leslie-Pelecky can be reached at the Department of Physics, The University of Texas at Dallas, 800 W. Campbell Rd., EC 36, Richardson, TX 75080, USA; tel. 972-883-4631; fax 972-883-2848; and-mail diandra2@utdallas.edu.*