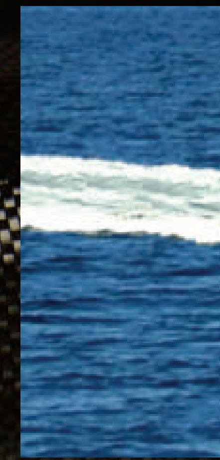
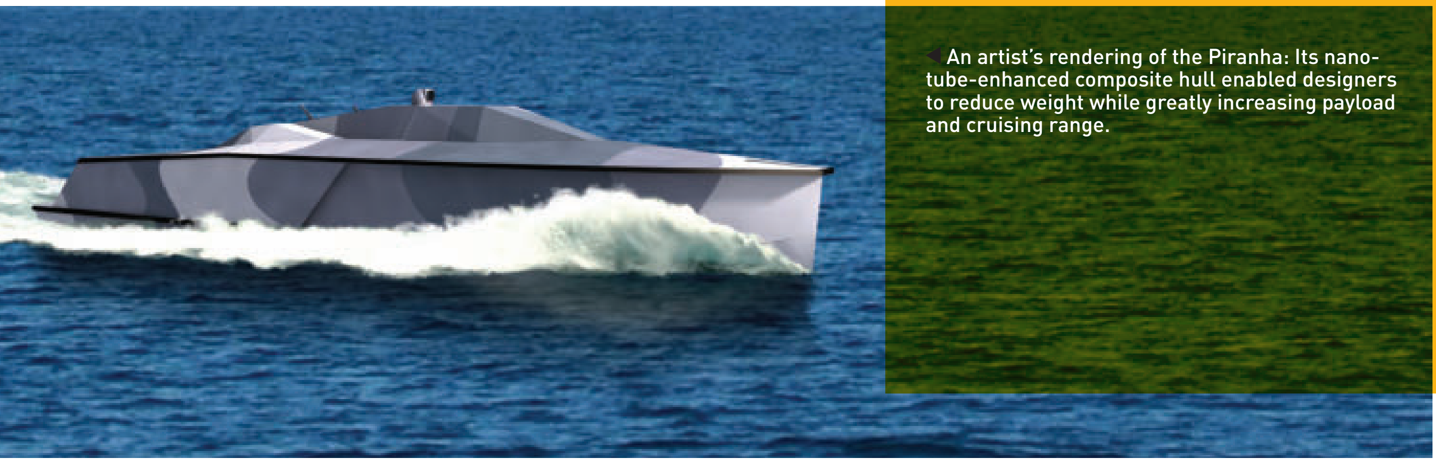


+positive reinforcement

Carbon nanotubes are making their way into high-tech vehicles.

By Alan S. Brown, Associate Editor

▲ It looks like conventional epoxy-impregnated carbon fiber cloth, but this prepreg from Nanoledge Inc. contains nanotubes to boost mechanical properties.



An artist's rendering of the Piranha: Its nanotube-enhanced composite hull enabled designers to reduce weight while greatly increasing payload and cruising range.

ZYVEX PERFORMANCE MATERIALS

Workers at Three Point Composites, just south of Seattle, are putting the finishing touches a 54-foot-long boat hull. They are layering tacky sheets of carbon fiber impregnated with epoxy resin, called "prepreg," into the cavity of a large mold.

To finish the hull, the workers will roll the assembly into a 75-foot-long oven and ramp up the temperature. Over the next eight hours, the chemical bonds of the resin will rearrange themselves as the epoxy cures to form a strong, solid composite.

It's the kind of process that manufacturers who use carbon-reinforced composites perform regularly. What makes this boat special is an unusual ingredient in the prepreg: nanotubes. Less than 0.5 percent (by weight) of the prepreg consists of nanotubes. The hull will be one of the largest nanotube-reinforced structures ever built.

The hull will be part of an experimental boat. The Piranha, as the boat is called, is a prototype unmanned surface vehicle, the naval equivalent of the unmanned aerial vehicles flown by the military in Afghanistan and elsewhere.

Nanotube supplier Zyvex Performance Materials of Columbus, Ohio, funded the craft to showcase its nanomaterials.

The Piranha's hull resembles that of other composite craft, though boat designers might pick out small differences. The top of the hull, or sheer line, has a slight arch. The sides of the boat and some stress-bearing sections are thinner than usual. The hull's "V" is narrow enough to fit inside a conventional hull with room to spare.

These subtle clues reflect a far more radical change: The Piranha weighs significantly less than similarly sized craft.

"It's hard to grasp something that big weighs only 4,500 pounds," Zyvex Performance Materials' president, Lance Criscuolo, said about the hull. When fully outfitted with engine, transmission, and deck, the entire craft will weigh just 8,500 pounds. Thanks to its large displacement, it will be able to carry up to 15,000 pounds of fuel, surveillance equipment, and weapons.

NANOLEDGE INC.

Criscuolo compares that with another unmanned surface vessel under development—General Dynamics Robotic Systems' Draco, a 36-foot-long aluminum USV that weighs 17,000 pounds and carries 5,000 pounds of payload. "The Piranha's much longer and weighs half as much," Criscuolo said. "With our greater displacement, we can carry two to three times more payload."

That larger payload can make a real difference. The Piranha can hold more fuel and weapons than its competition and stay out at sea far longer without refueling. Surprisingly, nanotube-enhanced construction is also proving to be economical.

It took nanotubes more than a decade to work their way into exotic baseball bats, hockey sticks, and skis. The Piranha is just one indication that they are poised for bigger things. From boat hulls to sports cars and aircraft wings and fuselages, mechanical engineers are finding new and exciting uses for nanotubes. The result could change how engineers think about nanotubes—and composites—in the future.

IN SPITE OF THEIR WELL-KNOWN STRENGTH AND STIFFNESS, NANOTUBES HAVE PROVED INCREDIBLY DIFFICULT TO HARNESS, ESPECIALLY IN COMPOSITES. Their carbon bonds, which link so tightly with one another, make them highly inert. They do not dissolve in water, oils, solvents, or anything else. As a result, there is no way to disperse raw nanotubes in resins or composites.

Indeed, adding raw nanotubes to a resin can actually degrade properties. Like strands of spaghetti, undispersed nanotubes tangle up and form clumps. In resins, those clumps become places where stresses concentrate and initiate cracks. (This is similar to what happens when a hammer strikes concrete and cracks form around the largest aggregates.)

"When we couldn't disperse the nanotubes properly, the result was worse than the original resin," said Bahram Farahmand, an engineering consultant in Laguna Hills, Calif., who previously headed Boeing Co.'s nanotube research.

Researchers eventually found ways to "compatibilize"

nanotubes by attaching molecules to the nanotube surface. Zyvex, for example, uses molecules that have a strong van der Waals attraction to the nanotubes. Others treat the nanotube surface to break some of the carbon-carbon bonds, then add molecules to the open spaces. In either case, the part of the molecule farthest from the nanotube contains a chemical group that disperses in the resin. As the resin flows, those molecules carry the lassoed nanotubes with them.

This led to another problem. Adding particles to liquids makes them thicker and more resistant to flow, explained Jim Lee, a professor of chemical engineering at Ohio State University. Nanotubes' long, thin shape and high surface area make the problem worse. "When the resin flows, the nanotubes jam up, like all the cars in a parking lot trying to get out at once," Lee said.

It takes little more than a 1 percent nanotube addition to transform an epoxy with the viscosity of light motor oil into peanut butter.

That left researchers with no way to add enough nanotubes to turn a resin into a supercomposite. Yet it turned out that a 1 percent addition was all that was needed to transform the properties of ordinary composites. Composites, after all, are combinations of very strong, stiff fibers and a resin that acts like glue to hold them in place. The resin is the vulnerable component of the composite, the part that is brittle and susceptible to cracking. Strong nanotubes help the resin transfer loads to the reinforcing fibers more efficiently. They also act like tiny dams to keep cracks from spreading.

▲ Aircraft designers have always paid a premium for lightweight composites that improve fuel economy, payload, and cruising range. Nanotubes impart additional strength and durablity to ordinary composites and make them even more appealing. Shown here is a rendering of a nanotube-enhanced amphibious aircraft designed by Harbor Composites.

Zyvex said that, by adding carbon nanotubes to the resin in an amount of less than 1 percent by weight, it boosts composite flexural strength and modulus by 30 to 50 percent and tensile properties by 20 to 30 percent.

"Nanotubes improve resistance to impact, fatigue, and microcracking, all properties related to resins. The result is a much stronger and more durable composite," said Patrice Lucas, who heads customer service for Canadian nanotube formulator Nanoledge Inc.

This discovery has led to a race among formulators to find better ways to incorporate small amounts of nanotubes into composites. Some formulators compatibilize nanotubes for infusion processes, which pump resin into reinforcing fiber preforms.

For the most part, though, large parts are made from prepreg, thin layers of woven reinforcing fibers pre-impregnated with nanotube-containing epoxy. Because the layers are so thin, the nanotubes do not have to flow through large volumes of space. The layers are partly cured to solidify the resin. Workers lay tacky layers of prepreg on one another to build up a part, then put it under a vacuum, and heat it to cure the resin and form a solid component.

Unlike most advanced materials, nanotubes provide advanced performance economically. According to Criscuolo of Zyvex, the Piranha hull is made from standard modulus carbon fibers that cost about $10 to $12 per pound. Adding just 1 percent nanotubes to the resin gives it the properties of a boat made from intermediate modulus fibers, which cost about $60 per pound. Criscuolo said his prepreg costs about 10 to 15 percent less than prepreg made from intermediate modulus fibers.

The small nanotube addition improves the craft's ability to meet mission objectives. The Piranha has yet to prove that it can survive military duty on rough seas. Yet the craft has already attracted attention from military contractors, Criscuolo said. The reason is that its greater payload means it can carry more fuel. Zyvex designed the Piranha to cruise more than 2,000 nautical miles at 25 knots per hour and stay at sea for days at a time without refueling.

"That makes us a viable solution for piracy," Criscuolo continued. "Other USVs have to refuel after a few hundred miles. We can carry enough fuel to protect ships against piracy as they travel along the eastern coast of Africa and through other dangerous regions."

NANOTUBES SOON MAY TURN UP ON THE HIGHWAY, AS WELL. Electric hybrid car designer Velozzi is working with Bayer MaterialsScience LLC, a subsidiary of Germany's Bayer AG, to use nanotube-based composites in its high performance electric Supercar and its more affordable plug-in hybrid Solo.

According to company founder Roberto Velozzi, the Supercar's 770 horsepower ac induction motor will take it from zero to 60 miles per hour in only 3 seconds and top out at 200 miles per hour. The Solo will use a multifuel microturbine battery charger to get 100 miles per gallon with a top speed of 130 miles per hour.

"The chassis, the body panels—80 percent of the structure will be carbon composites," Velozzi said about his Supercar. Yes, he plans to use nanotubes because they improve properties and enable him to reduce weight. But nanotubes play another important role in automobiles: They make them safer.

"Composites are very brittle," Velozzi noted. "If you

ZYVEX PERFORMANCE MATERIALS

Velozzi's Supercar (left) will use nanotube-enhanced composites for structural parts, but its less expensive Solo (below) will use them only in high-impact applications.

VELOZZI

crash, they shoot out lots of fragments. Splinters go out everywhere, and the car is beyond repair. Carbon nanotubes let us use 30 percent less carbon fiber. We get the same results as a conventional composite, but the part is lighter and we don't have the brittleness. It's not that the part will never break, but if it does fail, it will fail in a better way, like tempered glass."

Of course, Velozzi can afford aerospace technology. He expects to sell his Supercar for several hundred thousand dollars.

The Velozzi Solo, on the other hand, has a more economical price of $40,000 to $50,000. The Solo will make more strategic use of nano-reinforced composites, starting with energy-absorbing engine mounts and perhaps including front bumpers and some panels.

Another application that can afford aerospace pricing is aerospace itself. Both Boeing and Lockheed Martin are looking at nanotubes to reduce composite weight.

"Lockheed Martin is investigating a whole range of applications for carbon nanotubes in both materials and electronics," said Brad Pietras, who directs the company's nanotechnology research programs. "The early data looks very promising and I expect to see new products in the next year or so."

The company wants to incorporate nanotubes into its established production methods. "Lockheed Martin's approach is to look for ways to improve performance without significant impact on the current manufacturing processes," Pietras said. "For example, in aerospace applications, new materials and processes need to be requalified to ensure that customer requirements are being met; that's just good program management. We consider this every time our company invests in new material development. Any time we can use established manufacturing methods, risk is reduced and the path to insertion is improved."

Like Three Point Composites, Lockheed Martin is working with Zyvex. Drones are a likely aerospace application. "Since lives are not at stake, UAVs don't have the exorbitantly long qualification cycle of man-rated aircraft," said Zyvex's Criscuolo. "It's possible to move much faster on new materials."

One possible application is to add nanotubes to make wings stiffer. "The wings of existing UAVs are strong enough, but they're not stiff enough," Criscuolo noted. "If you load them any more, they start to deflect and they become less efficient. If we can reduce the amount of material in the wing by 30 percent and make them stiffer, we could carry more payload."

MORE PAYLOAD. Lighter components. Stronger parts. Traditional processing. Lower cost. The new mantra for nanotubes sounds very much like the original value proposition of conventional composites and even engineering plastics. Carbon nanotubes can earn their place at the table if they provide highly desired properties without forcing companies to reinvent their production processes.

Of course, issues remain. Today's composites tap just a fraction of nanotubes' potential strength, stiffness, toughness, and low mass. Loadings are likely to remain low for years to come. It may take years before anyone makes large, commercial, nano-enhanced structures by infusion or other processes that rely on resin flow.

Regardless, when the Piranha takes its first cruise later this year, it will certainly help chart the course of future composite-based vehicles. ■