FABRIC of STEEL

By Peter Banks

If Superman had been created today rather than in the 1930s, he would probably not be the "Man of Steel", but instead the "Man of Kevlar®". Five times stronger than steel, this super material has some extraordinary powers.

Need to stop a speeding bullet? Kevlar can be woven into bullet-resistant vests and helmets for police and military forces. These Kevlar vests have saved lives from urban streets to the battlefields of Kosovo and Mogadishu.

Want to leap a tall building? Kevlar's combination of being lightweight and strong makes it a natural for the bodies of aircraft and spacecraft. This year, Kevlar served as a component of the pressurized capsule for the Orbiter 3 balloon that circled the globe in March.

And remember those pesky runaway trucks and locomotives Superman was always picking up? Because it withstands high heat and abrasion, Kevlar is widely used in transmissions, cooling systems, and brake linings.

And don't forget the fabric in Superman's cape! Kevlar made the leading edge of fashion this year, when designer Helmut Lang's futuristic spring collection featured Kevlar flight jackets. Call it "geek chic".

Superman may have come from the planet Krypton, but Kevlar's history, equally fascinating, comes from our own world of technology.

Kevlar's composition

Kevlar is a synthetic material known as a polymer. Like a long train of boxcars, a polymer is a chain of similar molecular groups, known as *monomers*. Many important biological molecules, like protein and DNA, are polymers, as are many common household plastics and fibers, among them nylon, Teflon, lycra, and polyester.

For Kevlar, the monomer unit—one "boxcar" of the train—is an aromatic amide, or aramid for short. In this case, aromatic doesn't mean "fragrant". Instead, it means that the molecule contains a group of six carbon atoms attached in a ring called a benzene ring. The amide group is an arrangement of carbon, nitrogen, oxygen, and hydrogen atoms (see Figure 1). This bit of chemical anatomy turns out to be key to understanding Kevlar's strength.

The secret of Kevlar's strength

To gain strength, a polymer chain has to have a certain structure. The chain cannot flop around loosely, like a linked bicycle tire chain. Instead, it should form long, straight chainlike rods. These rods should line up parallel to each other like matches in a box. The polymer gains strength, too, if the chains next to each other stick together in a tight bundle. Making strong polymers is a lot like making strong rope. If you bundle fibers into strands bunched in a regular array, you wind up with a rope tough enough for heavy lifting.

Here's where those aromatic and amide groups work their magic. The bulky aromatic rings stiffen the polymer into long straight rods. The Kevlar chain remains straight because the intrinsically rigid rings keep it from being folded.

The amide group is important for strength, too,

A recent FBI study showed the risk of sustaining a fatal gunshot injury is 14 times greater for officers who do not routinely wear body armor than for those who do. In this test, Kevlar fabric absorbs the impact of a bullet (left photo), leaving a shallow depression in the wall behind it (right photo).

PHOTOS COURTESY OF DUPONT

PHOTO BY MIKE CIESIELSKI

Kevlar flight jackets combine strength and fashion.

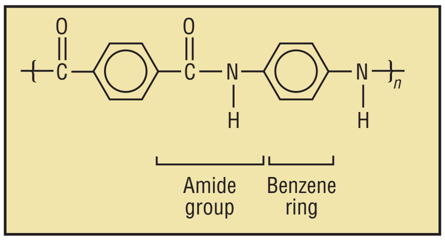

Figure 1. A monomer unit of Kevlar is an aromatic amide, or *aramid*.

but for a different reason. It provides a kind of molecular "glue" to hold adjacent polymer chains together. This glue is actually a type of chemical bond known as a hydrogen bond. Hydrogen bonds form when regions of adjacent molecules with opposite charges attract each other (see Figure 2). In an amide, the oxygen atom attracts some of carbon's electrons to itself, giving it a partial negative charge. By contrast, the hydrogen attached to the nitrogen atoms has a partial positive charge caused by the fact that electrons tend to be drawn toward the nitrogen, partly exposing the positively charged hydrogen nucleus.

One more factor adds to Kevlar's strength. The benzene rings can stack on top of one another, like pancakes on a plate. This stacking, combined with their straight conformation and the hydrogen bonding that cements them together, makes Kevlar polymer chains line up in a perfect array. In fact, although Kevlar is woven into fibers, it's much less like thread than it is like steel or ice—a hard crystal in which the molecules interlock in a neat, flawless package.

There's only one problem with something so tough—making it in the first place. Because Kevlar chains line up so precisely and cling together so tenaciously, almost no solvent will dissolve them. Heat doesn't work either, because Kevlar remains stable at high temperatures. In fact, its molecules disintegrate before they ever reach their melting point. It is a huge challenge, then, to process amide polymers into long Kevlar fibers for vests and other products. Imagine using a spinning wheel to make thread out of a chunk of steel, and you get the picture.

From crystals to fibers

Fortunately, an enterprising chemist at chemical manufacturer DuPont in Delaware found the chemical concoction needed to prepare Kevlar. Polymer chemist Stephanie Kwolek and her colleagues were looking for a material that could be used to replace steel in radial tires.

Kwolek's innovation was to make workable solutions of Kevlar in an unusual form—the liquid crystal. Widely used in digital watch and calculator displays, liquid crystals represent a strange state of matter halfway between a true liquid like water and a true solid like ice. (See "Smart Windows", opposite page.)

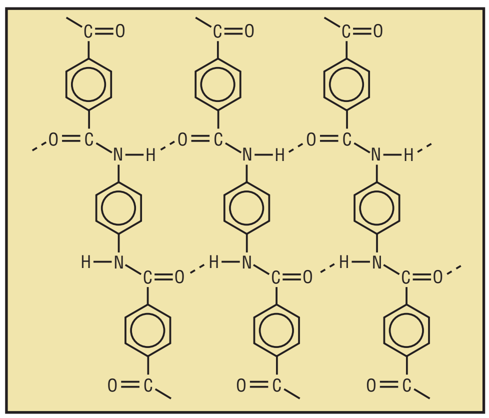

Figure 2. The attraction between hydrogen and oxygen on adjoining polymer chains binds the chains solidly together.

Kwolek began working on a new way to dissolve Kevlar. She picked organic solvents and then added calcium, which prevents the amide group from forming hydrogen bonds. The positively charged calcium ions surround the negatively charged oxygen atoms and prevent them from grabbing on to hydrogen. What Kwolek made was in fact a liquid-crystal solution. In such a solution, polymer chains can still swim about somewhat, but they interact with one another to form organized clumps, like logs lashed together for a raft.

Stephanie Kwolek

To make fibers from Kevlar, the chemists further dissolved the clumps in strong sulfuric acid (H_2SO_4) and then forced the solution through a fine pore filter, which serves as a molecular spinning wheel. As the solution flowed through the tiny holes in the filter, the liquid crystals were forced into parallel alignment with one another and long fibers were "spun".

At first, the technician running the spinning equipment at DuPont was reluctant to process Kwolek's solution. It was cloudy-looking, and he worried it would clog the fine pores. When he relented, however, the results were amazing—fibers with a strength never seen before! Kwolek hesitated to report her results for fear mistakes could have been made. But there was no mistake. It took a few years to perfect the manufacturing process, but when it was brought out in 1971, Kevlar quickly found hundreds of uses—vests, aircraft, sports equipment, protective gloves, fiber-optic cables, boats, and many other products.

Among Kwolek's many awards she receives, her most satisfying is to be recognized at meetings of the Kevlar Survivors Club. With a membership topping 2,300, the members are police officers whose lives were saved because they wore Kevlar armored vests.

We don't need to look to Krypton for the source of this super polymer. The making of Kevlar, a feat worthy of Superman himself, is a product of down-to-earth chemistry by chemical problem solver Stephanie Kwolek and her research team.

Peter Banks is a freelance writer living in Fairfax, VA. His most recent *ChemMatters* article was "Weighting in the Wings", which appeared in the December 1997 issue.

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