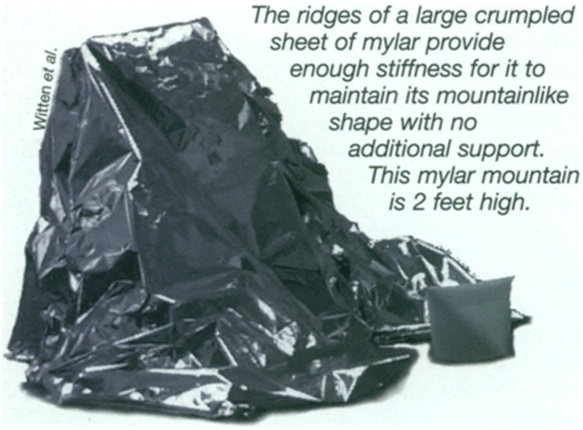
The Sounds of Crumpling

Deciphering the wrinkles of crinkled sheets

By IVARS PETERSON



Witten et al.

The ridges of a large crumpled sheet of mylar provide enough stiffness for it to maintain its mountainlike shape with no additional support. This mylar mountain is 2 feet high.

As a poignant scene unfolds on the giant movie screen, a few sniffles rise above the general hush. Suddenly, the loud, sharp crackle of someone tearing open a cellophane candy wrapper breaks the spell. Additional bursts of sound accompany the crumpling of the discarded wrapper into a ball.

Such sounds are commonplace. Many materials, including paper and plastic sheets, make a distinctive crackling noise when crumpled.

Researchers are now recording and characterizing the sounds of crumpling to obtain insights into how energy is distributed and dissipated in materials under stress. Computer simulations and other laboratory efforts are also contributing to knowledge about crumpled materials.

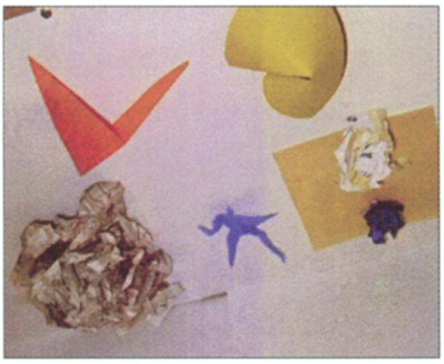
Crumpling is a ubiquitous, though poorly understood, physical phenomenon. It occurs when a fender absorbs the energy of a car crash, when Earth's crust buckles at the interface between colliding tectonic plates to create a mountain range, when a blood cell's membrane folds to allow the cell to pass through a narrow capillary, when a grape shrivels to a raisin as it dries out, and when a storage tank collapses.

New experimental results, combined with computer simulations, are leading to a deeper understanding of the behavior of crumpled materials. These insights may eventually serve to guide the design of improved packing materials, superior energy-absorbing bumpers for cars, and other products subject to buckling.

It takes energy to crumple a sheet—to force it uniformly into a smaller and smaller ball. Where does that energy actually go?

Crumpling a sheet of paper into a tight ball causes some regions to become strongly creased, creating a network of narrow ridges and sharp peaks. The material at these creases bends and stretches in response to the applied force.

To investigate the energy involved in crumpling, physicist Thomas A. Witten and graduate student Alexander E. Lobkovsky of the University of Chicago and their coworkers developed a computer model to determine what happens at a single ridge between two sharp points. They discovered that the energy that goes into bending and stretching the material is concentrated in the narrow ridge rather than being stored in the points or distributed more broadly throughout the sheet.



Houle

Examples of different shapes into which paper sheets can be folded or crumpled.

"Although the force is applied uniformly, the energy gets concentrated in a tiny fraction of the sheet," Witten says.

This finding suggests that crumpled sheets can be described in terms of the patterns of ridges and peaks that cover the surface. By adding together the deformation energies associated with individual ridges, researchers can approximately calculate the total energy stored in a given crumpled sheet.

Because sheets of different materials—whether paper, mylar, or metal—display similar ridges, the basic crumpling process must be similar in these materials. The only condition is that the sheets be large and thin, Witten says.

The researchers also discovered that increasing a sheet's size has an unexpectedly small effect on the total amount of energy required to crumple it. For instance, it takes only twice as much energy to crumple a sheet whose sides are eight times longer, even though the sheet's area is 64 times larger and the ridges are eight times longer.

"It was a surprise to us to find that even though the elastic energy in a crumpled sheet is concentrated in a small subset of the area, the strains in the sheet are actually small themselves," Lobkovsky says.

The ridge model of crumpling is just one ingredient in the development of an understanding of crumpling phenomena. Nonetheless, "the ridge concept should aid in the design of macroscopic energy-absorbing materials," Witten and his colleagues contend in the Dec. 1, 1995 SCIENCE.

The model suggests, for example, that one could control the placement of ridges by incorporating defects in a material, making certain areas more likely to crumple and other areas less.

To get a somewhat different perspective on crumpling, James P. Sethna, Paul A. Houle, and their collaborators at Cornell University have been busy crumpling sheets of paper into compact balls to elucidate the collective behavior of large numbers of creases.

These studies were originally motivated by the finding that widely varying physical systems emit pulses of energy comparable to the pops and clicks generated by crumpling paper. For example, earthquakes generate irregular trains of seismic shocks, and sudden changes in the magnetic fields trapped in various materials produce bursts of electromagnetic radiation.

Paper crumpling offers a convenient, economical means of studying these effects in the laboratory. By recording and analyzing the sounds generated during crumpling, researchers can estimate the associated energy emissions.

Initially, Houle and his coworkers simply crushed sheets of ordinary paper into small balls by hand. "This had to be performed very slowly, over about 60 seconds, so that the computer could isolate individual pops," Houle says.

To obtain more consistent results, the researchers taped sheets of paper around the ends of pairs of empty cans to make paper cylinders. By twisting the cans while pushing them toward each other, it was possible to wrinkle and crush the intervening sheet in a controlled manner without touching the paper.

The researchers used a computer program to identify individual sound pulses, measuring the energy of each pop and plotting the number of pulses detected at different energies. "Some of the crackles were small, and some of them were large, covering a wide range of energies," Sethna says.

Surprisingly, this distribution of pulse energies stayed roughly the same throughout the crumpling process, even though the sheet started out completely flat and ended up wildly wrinkled.

Moreover, different types of paper and different sheet sizes generated remarkably similar energy distributions. This finding applied equally to freshly crumpled sheets, to previously crumpled sheets that were crumpled again, and to sheets that had been initially folded into a regular, gridlike pattern of creases and smoothed out before crumpling.

Houle described these results at an American Physical Society meeting held last March in St. Louis.

University of Chicago graduate student Eric M. Kramer, working with Witten and Lobkovsky, also studied the crackling sound emitted by crumpled sheets. However, he recorded the noise generated by sheets made of mylar rather than paper.

To get reproducible results, Kramer smoothed out, then recrumpled a mylar sheet as many as 30 times to get a dense network of intersecting ridges. Holding one of these specially prepared sheets by its edges, he would slowly twist and skew it to generate crackling noises.

Like Houle, Kramer detected distinct clicks. These sounds came not from the creation of ridges or peaks but from the sudden shift of a ridge-bounded facet from a slightly concave to a slightly convex profile, or vice versa. These abrupt movements would release energy in the form of heat, vibrations of the material, and clicking sounds. Sheets of paper and aluminum behave similarly.

As Houle also found, neither the material nor its thickness appears to make much difference to the energy distribution of the sounds produced by crumpling. Kramer and Lobkovsky describe these findings in the Feb. 1 Physical Review E.

Kramer has also simulated on a computer the effects of crushing a sheet inside a hard-walled, contracting sphere—an idealized palm of a hand. His model reveals the spontaneous formation of a network of straight ridges where the bending energy is concentrated.

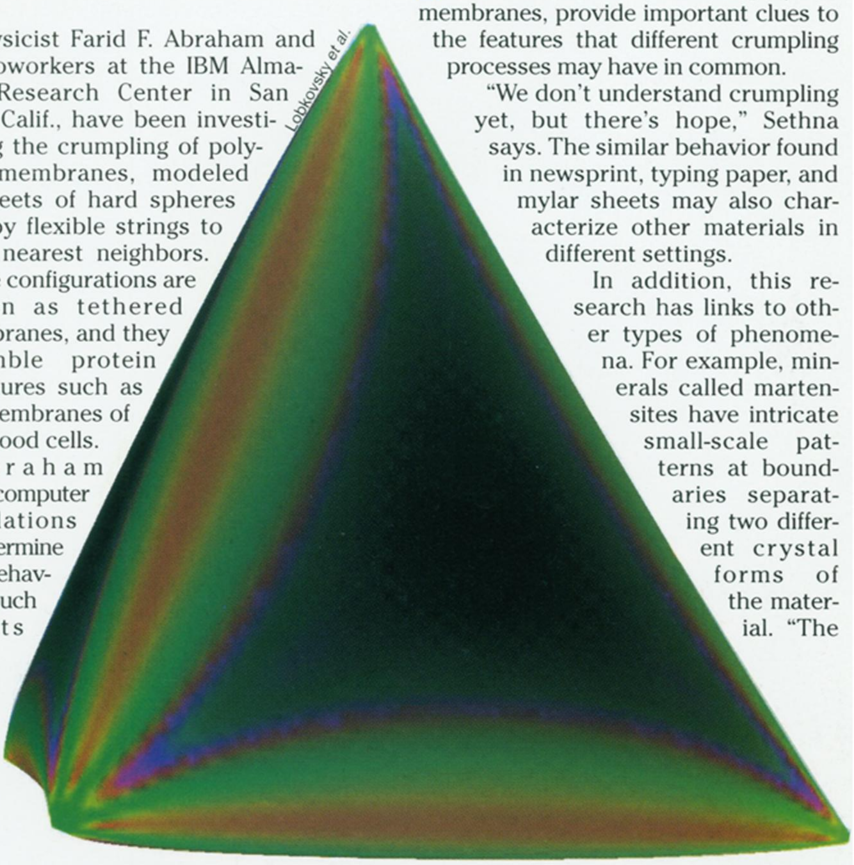
"In real materials, these ridges [represent] strains in the sheet whose effects are responsible for the rough texture of a crumpled piece of paper," Kramer notes.

Crumpling can occur not only on the scale of a paper or plastic sheet but also at a molecular level.

Physicist Farid F. Abraham and his coworkers at the IBM Almaden Research Center in San Jose, Calif., have been investigating the crumpling of polymer membranes, modeled as sheets of hard spheres tied by flexible strings to their nearest neighbors. These configurations are known as tethered membranes, and they resemble protein structures such as the membranes of red blood cells.

Abraham used computer simulations to determine the behavior of such sheets immersed in a solvent, looking particularly at the conditions that produce a flat, loosely crumpled, folded, or fully collapsed membrane. He found that if the balls in his model didn't attract each other, the sheet would tend to roll up or wrinkle into a corrugated pattern rather than collapse into a crumpled ball. With an attractive interaction between the balls, however, the membrane would immediately collapse into a remarkably tight clump with very few voids.

Abraham also discovered that changing the temperature of the solvent in his simulation has a surprising effect on a membrane with attractive interactions between particles. At high temperatures—meaning that the atoms of the simulated solvent vibrate vigorously—the membrane tends to maintain its flat shape. In contrast, lowering the temperature of the solvent below a certain threshold causes the membrane to fold in half, lowering the temperature further produces a second folding, and so on.



Lobkovsky et al.

Computer simulations reveal the distribution of bending and stretching energy in a thin, flat sheet cut and joined to form a tetrahedron. The tetrahedron's edges correspond to the ridges of a crumpled sheet. The colors indicate variations in the ratio of stretching to bending energy. Near the points, the bending energy is more than 10 times the stretching energy. In the middle of the ridges, the bending energy is only about three times the stretching energy. The brightness of the colors indicates the total energy involved, showing that most of this energy is concentrated in the ridges.

The results of both experiments and computer simulations, whether they involve paper sheets or polymer membranes, provide important clues to the features that different crumpling processes may have in common.

"We don't understand crumpling yet, but there's hope," Sethna says. The similar behavior found in newsprint, typing paper, and mylar sheets may also characterize other materials in different settings.

In addition, this research has links to other types of phenomena. For example, minerals called martensites have intricate small-scale patterns at boundaries separating two different crystal forms of the material. "The boundary structures inside the martensite look very much like the scrunched edges of a folded paper structure," Sethna says. Interestingly, martensites can also generate a crackling noise when deformed.

The force required to fold and crumple paper typically gets focused into the creases that form within the material. The same kind of thing can happen when magnetic fields penetrate superconductors or defects appear in crystals.

"It's not that we think there are going to be important applications of paper crumpling itself," Sethna says. But the physical principles involved in paper crumpling could very well apply in situations beyond origami and spitballs. □