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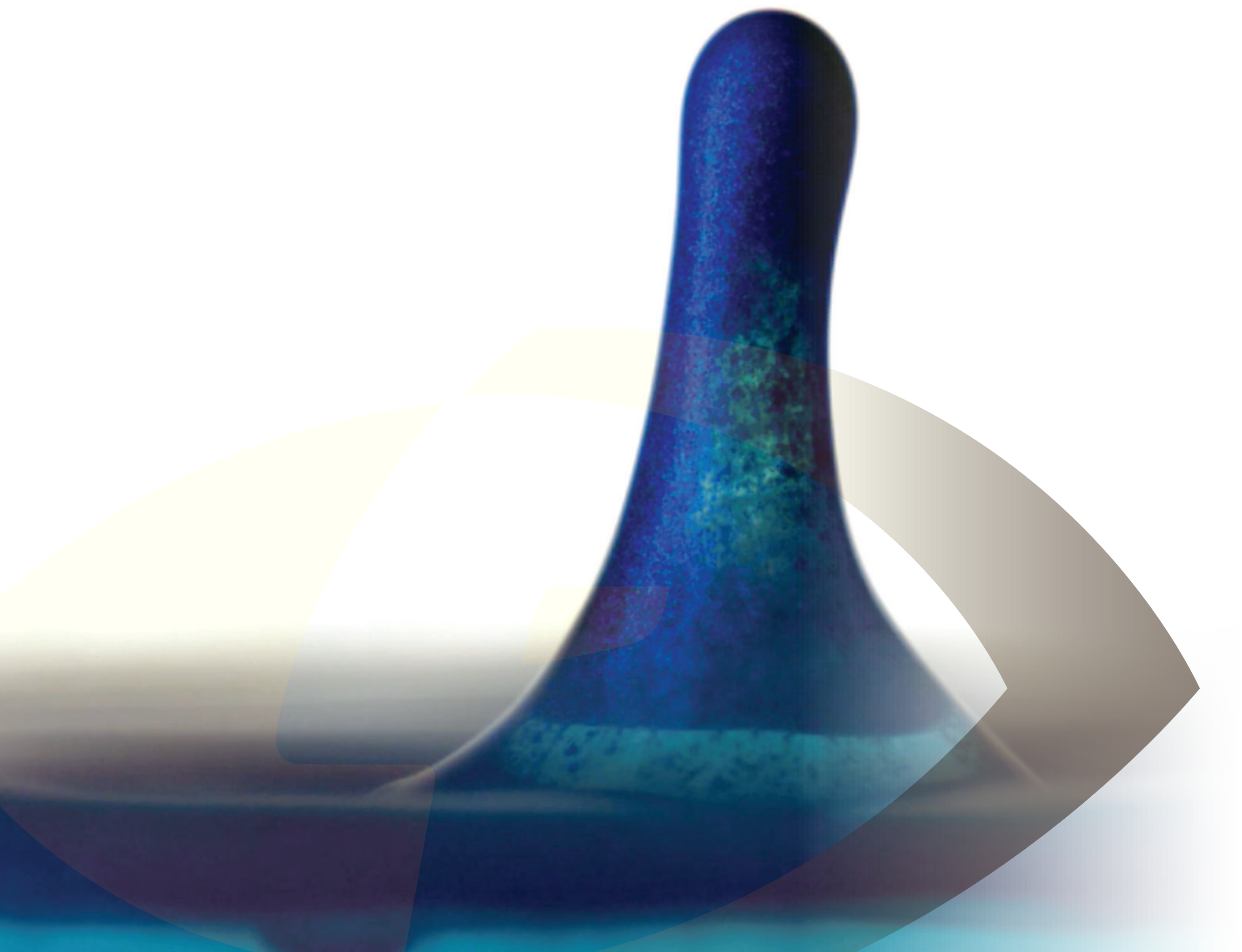

VISION RESEARCH

AMETEK® MATERIALS ANALYSIS DIVISION

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To learn more about Vision Research high-speed imaging equipment,
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CONTENTS

PHANTOM HIGH-SPEED CAMERAS

PHANTOM GOES TO MIT

High-speed photography is alive and well at the Massachusetts Institute of Technology (MIT) Edgerton Center.

Named after Harold "Doc" Edgerton—prominent MIT graduate, professor and pioneer of photography—the Center makes high-speed imaging equipment available to students to help further their education in science and engineering.

"Edgerton did his graduate work on motors—specifically, how motors behave when there's a power spike," explains Dr. Jim Bales, associate director of and instructor at the Edgerton Center. "To understand what was going on, he photographed the motors while tinkering with strobe lights. Then he started looking for other interesting things to take pictures of—like milk splashing or bullets piercing through apples."

Edgerton eventually taught at MIT and remained an integral part of the faculty until 1990. After his death, his lab became the Center that stands today. In addition to offering various imaging courses and programs, the Center continues Edgerton's legacy by providing MIT students with high-speed cameras, strobes and other equipment to assist with their research.

Among these resources is the Vision Research Phantom v2511 high-speed camera, which can record up to 25,000 frames per second (fps) at full resolution—making it a useful tool for MIT students looking to obtain high-resolution images at very high speeds.

THE IMPORTANT ROLE OF HIGH-SPEED CAMERAS

Dr. Bales has been teaching at the Edgerton Center since 1998. Over the years, he has helped hundreds of students understand and implement the fundamentals of high-speed imaging. "There are two ways we use high-speed cameras at the Center," Dr. Bales says. "First, we make them available to students as part of their research. Many of them know they need to perform high-speed imaging, but they don't have much experience with it."

Dr. Bales helps these students step away from the details of their research to talk about what it is they're hoping to learn—and if a high-speed camera is the right tool for the job. "After that, we talk about selecting the right camera, including the lens, and how to properly light the scene."

A second way the Edgerton Center incorporates high-speed cameras is through teaching. For example, Dr. Bales teaches an introductory class that utilizes an array of strobe lights and high-speed cameras—including the Phantom v2511. "The students learn how to pick the right camera and light a scene," Dr. Bales says. "We also teach them how to get the right information out of the massive pool of data they collect."

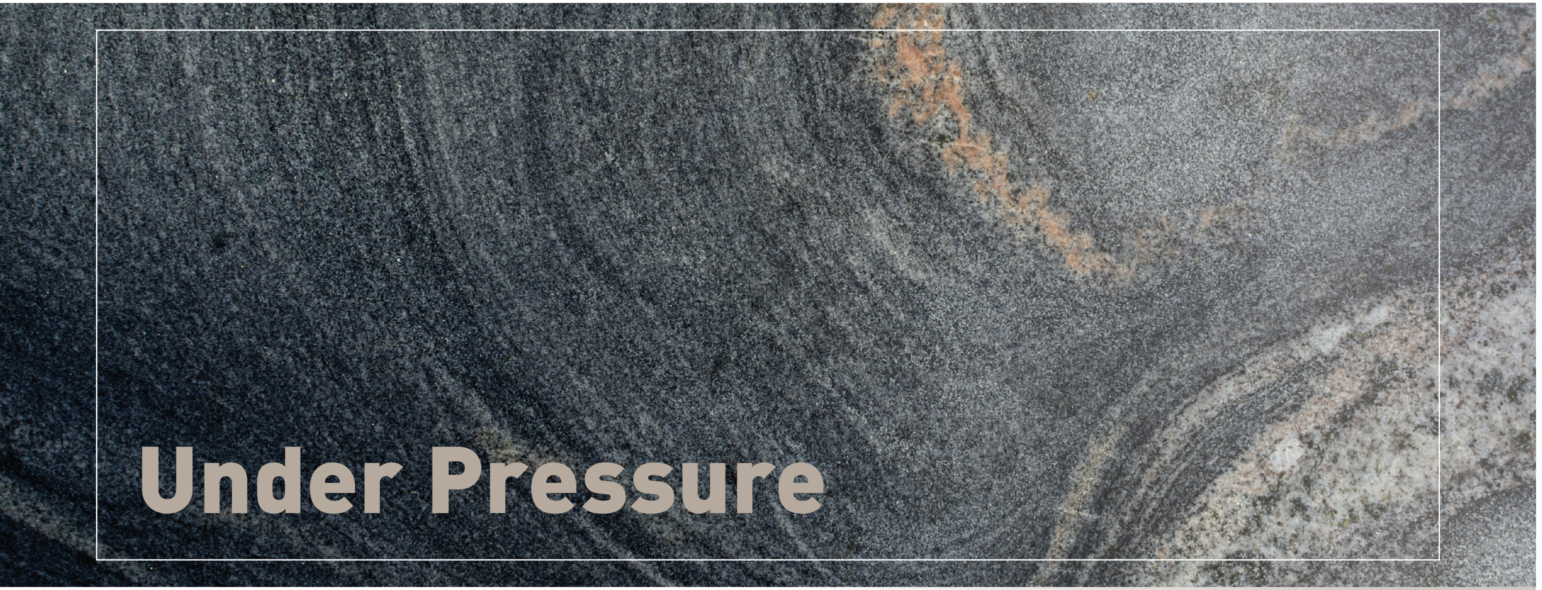
Each year, roughly 50 students enroll in this class. "What makes this interesting is the fact that the class isn't a requirement for anyone," Dr. Bales says. "So students take it simply because it meets some interest of theirs."

An additional 10 to 15 students borrow the Phantom v2511 camera every year as part of their research efforts.

SEEING IS BELIEVING

The ability to use high-speed cameras like the Phantom v2511 allows faculty, staff and students to conduct their scientific research faster and more efficiently. In many cases, the researchers also need a way to test and validate their instruments. Measurements supplied by a sensor that measures bubble size on a micrometer scale, for example, can be cross-checked against measurements taken from high-speed imagery. "This is one of the biggest roles we see for the high-speed cameras," Dr. Bales says. "They allow the researchers to have confidence in their instruments."

Most importantly, high-speed cameras like the Phantom v2511 enable students to test their predictions about how parts of the world behave. "And there are definitely cases where the students wouldn't be able to test their research any other way," Dr. Bales says. "It often comes down to the fact that the only true way to measure something is to observe. Once students have the images, they can extract the information they need."



Under Pressure

To learn more about current fracking practices, MIT researchers are analyzing how high-pressure fluid cracks rock with the help of a Phantom high-speed camera.

Hydraulic fracturing, or "fracking," is a hot-button topic these days. The process involves drilling into the ground and then directing high-pressure water at the rock to release the gas inside. While fracking has had a major impact on the energy industry, many critics have environmental concerns—particularly regarding earth tremors and potential groundwater contamination.

With the help of a Phantom high-speed camera, researchers at the Massachusetts Institute of Technology (MIT) Earth Resources Laboratory (ERL) have been trying to understand the fracking process better. The lab uses the camera to observe how cracks initiate and propagate in various types of rock—including gypsum, marble, granite and shale—under different loading conditions. Since propagation happens very fast, the high-speed cameras are indispensable to the analysis.

Most recently, the team has been studying hydraulic fracturing—relying on fluid pressure to generate the load. "In particular, we're exploring how the hydraulic fracturing process is affected by the shape of the pressurized opening and the penetration of the injected fluid into the matrix of the rock," says Ignacio Martin Arzuaga Garcia, graduate student. "These two factors play an important role in the pressure required to break the rock."

A COMPLETE PICTURE

For one set of experiments, Garcia tested gypsum—a soft sulfate mineral. He placed a 4 x 2 x 1-foot specimen in a biaxial loading frame under 4.5 megapascals (MPa) axial load and 1 MPa lateral load. Then, he hydraulically pressurized a concentric opening in the rock until it fractured—tracking the internal pressure inside the opening and the volume of the injected fluid using a data acquisition (DAQ) system.

Because the fracturing process is very fast, Garcia recorded the process at 2,000 frames per second (fps) using a Phantom v2511 high-speed camera, which helped him determine the moment of fracture initiation and resulting fracture pattern. The DAQ unit synchronized the high-speed video with pressure-volume curves during the fracturing process.

What makes the ERL team's research particularly interesting is the fact that it generates a complete picture of the fracturing process. Most research groups studying rock mechanics analyze the fracturing process only after it's done. "But lots of cracks open up during the process," explains Omar Al-Dajani, doctoral candidate. "As some open, they end up closing earlier cracks. If you don't see the full process, you'd base your analysis only on the fractures left at the end. For this reason, we're capturing things no one else has seen so far."

SUPERIOR RESOLUTION AND MEMORY

The ERL researchers have been using high-speed cameras in their lab for several years. "They've advanced a lot in that time—especially when it comes to memory and resolution," says Al-Dajani. In the past, he and his colleagues were limited by the small amount of internal camera memory—leading to very short recording windows. Concurrent with this, the sensor resolution of previous high-speed cameras was not high enough to decipher the finer details of the fast fracturing process.

The Phantom v2511 overcomes these issues. It features up to 96 gigabytes of high-speed memory—equating to 33-second recording times at 10,000 fps and 1280 x 800 resolution. Without sacrificing image quality or speed, it achieves 25,000 fps recording speeds at full 1-megapixel resolution and up to one million fps at lower resolutions. Depending on the material under study, various frame rates were utilized including 10,000–15,000 fps for granite and 1,000–3,000 fps for shale. The camera also integrates a custom CMOS sensor with 28-micron pixel sizes for high light sensitivity—overcoming the typical lighting pitfalls associated with high-speed recording.

"The longer recording windows and high-resolution images enable us to capture the cracking process in very high detail," says Al-Dajani. "To my knowledge, we're the only group that runs these hydraulic fracture experiments in a way that creates a full picture of what's happening."

HIGH-SPEED VIDEO AND DATA ACQUISITION

Combining high-speed imaging and data acquisition (DAQ) systems is valuable for any researcher studying fast-moving events. Linking Phantom high-speed cameras with popular off-the-shelf DAQ units lets you easily collect analog data and video data simultaneously. You can then visualize the synchronized video and analog data side by side within the Phantom Camera Control (PCC) software—improving workflow efficiency and leading to new insights about the process at hand.

“The outputs on the back of the Phantom camera let us easily run other acquisition equipment,” says Qiuyi Bing Li, MIT alumnus and PhD. “We wanted to know when in time the video was corresponding to the pressure, load or seismic energy coming out of the rock. This gave us very precise results on what was happening.”

The Phantom v2511 camera.

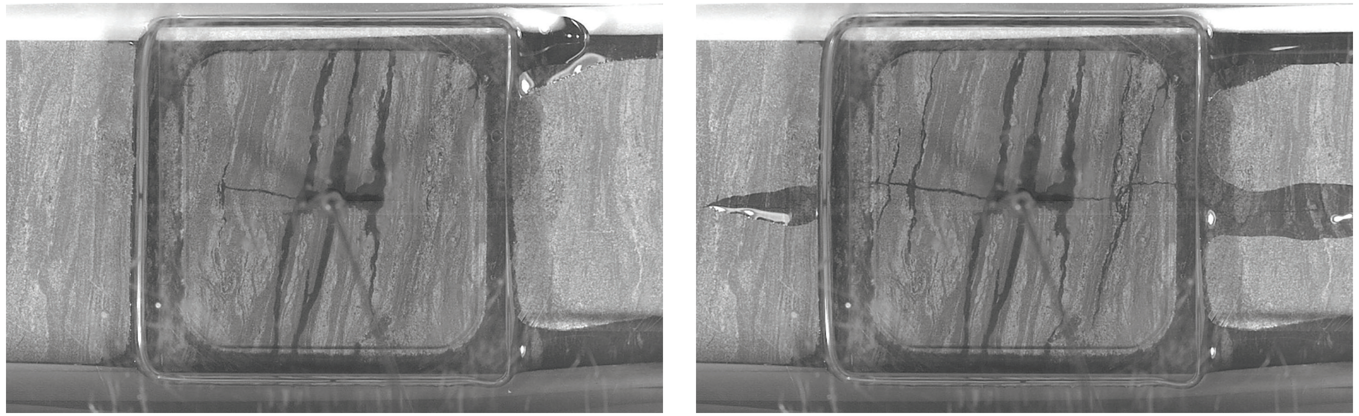
DRAWING CONCLUSIONS

The results of the hydraulic fracturing experiments led Garcia to two conclusions. First, the shape of the pressurized flaw plays a significant role in the pressure required to initiate a fracture—that is, the breakdown pressure. Smoother openings, like circles or ellipses, require higher hydraulic pressure than openings with sharper boundaries, such as a circle with notch. The longer the notch, the lower the breakdown pressure.

Second, the injected fluid to penetrate into the matrix of the rock lowers the breakdown pressure. While these results are not new, the experiments introduce an innovative, high-speed testing procedure that successfully verifies past conclusions.

“Thanks to the Phantom camera, we can determine the exact instant a fracture initiates, including the pressure and location” Garcia says. “Because it can keep up with the fast fracturing process, it also gives us the exact frame where two fractures coalesce—representing a very important piece of the puzzle when describing fracture propagation.”

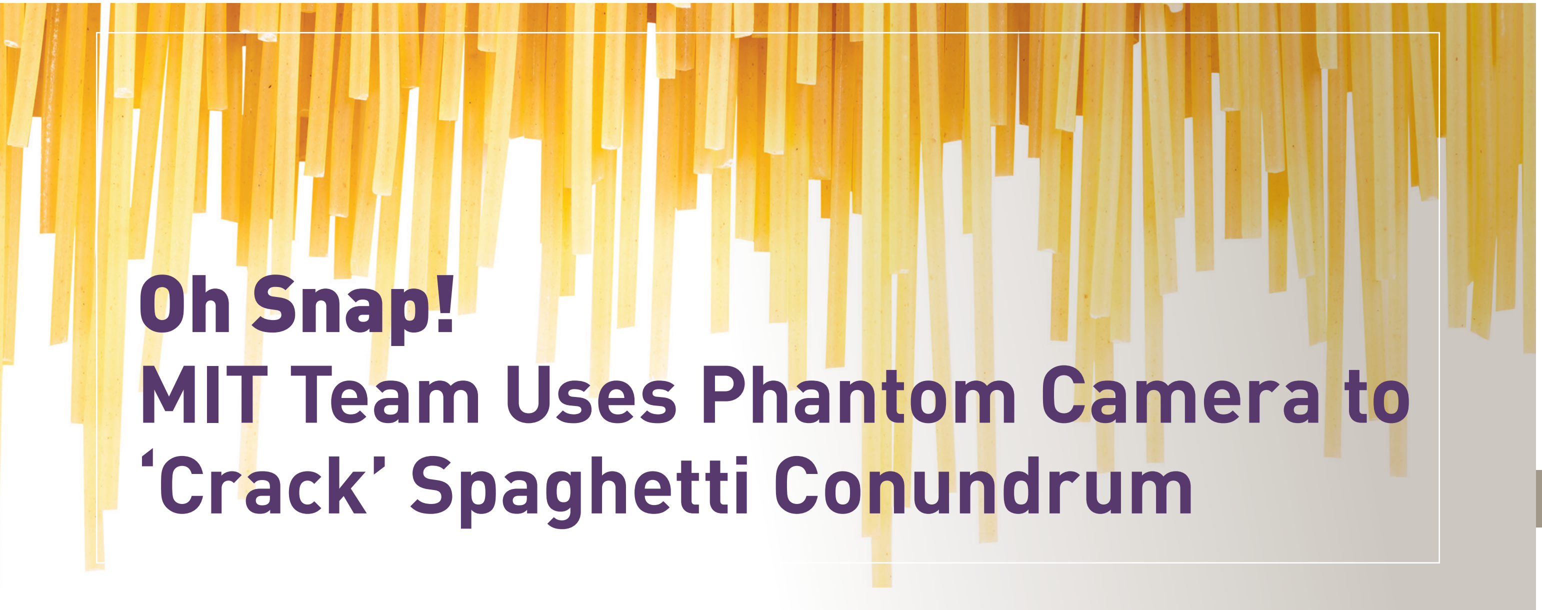
Understanding the exact geometries of produced hydraulic fractures can help inform the design and implementation of fracking practices in the oil and gas industry.



The Phantom v2511 enabled the MIT team to capture the hydraulic fracking process—including when a crack starts and how it spreads. Note the crack’s progression from the first image to the second.

OTHER RESEARCH METHODS

High-speed data acquisition isn’t the only experimental method used by the ERL researchers. MIT alumnus Qiuyi Bing Li, for example, employed digital image correlation (DIC)—a non-contact technique that uses high-speed cameras and special software to optically measure deformation, displacement and strain. Specifically, he analyzed individual pixels of rock from the high-speed recordings in order to quantify their displacement during fracturing. Al-Dajani has also used DIC. “I’m looking into quantifying the damage radius in the fracture process zone—a key question in oil and gas applications,” he says.



Oh Snap!
MIT Team Uses Phantom Camera to 'Crack' Spaghetti Conundrum

High-speed footage reveals how spaghetti can be made to crack into two versus multiple pieces—shedding light on the fracture mechanics of elastic rods.

Have you ever wondered why you can't break a piece of dry spaghetti into two pieces? Richard Feynman wondered the same thing. The physicist and Nobel Prize winner noted that holding a spaghetti stick at both ends and bending it until it breaks always yields at least three pieces. But the reason why eluded him—and dozens of other scientists—for decades.

Turns out this is not some trivial matter, and its implications extend beyond the kitchen. Spaghetti is key to understanding the fracture mechanics of elastic rods (ER), making Feynman's observation an enticing puzzle for a group of researchers at the Massachusetts Institute of Technology (MIT). With the help of a Phantom high-speed camera, the team tested a mathematical model explaining how a piece of spaghetti can be made to break into two pieces—adding a new "twist" to the time-old pasta puzzle.

SPAGHETTI AND ER FRACTURE BEHAVIOR

The fracture behavior of spaghetti sheds light on how ERs, which include building columns, trees, bones and even nanotubes, respond to extreme stresses—making the study of rod fracture and fragmentation critical to a wide range of applications, including the material sciences. "According to the story, Feynman observed that upon bending, spaghetti breaks into at least three pieces," says Vishal Patil, mathematics graduate student. "We became interested in the role of twist—and if twist could be used to break spaghetti into only two pieces."

Patil also wanted to investigate the role of nonadiabatic quenching—a process that, in this case, involved moving the ends of a piece of spaghetti towards each other. He developed a predictive model explaining how controlled twisting and nonadiabatic quenching can cause a rod to break into two pieces versus multiple pieces. According to this model, the unwinding of a twisted spaghetti after it fractures helps dampen the forces that would otherwise cause additional breaks.

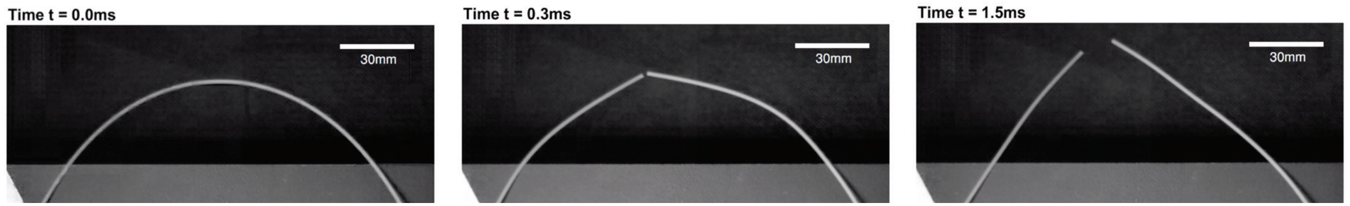
NONADIABATIC QUENCHING

While quenching typically means the rapid cooling of a system, in statistical physics it refers to a change in a control parameter that pushes the system through a phase transition. In this case, the parameter is the speed at which the spaghetti-snapping device moves the ends of the spaghetti sticks together. Nonadiabatic refers to the fact that the quench adds energy to the system.

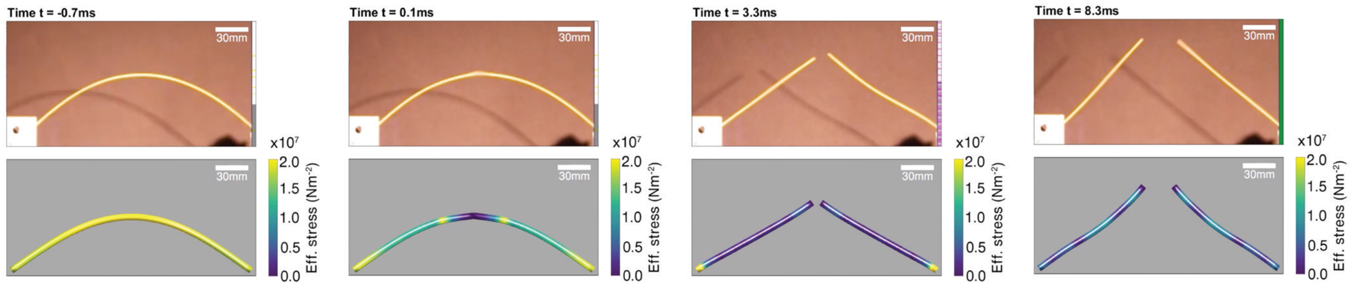
The model itself is based on Kirchhoff's equations, which describe the dynamics of thin rods. Patil and his team employed a discrete differential geometry algorithm to numerically solve the equations—with each rod discretized into 50 elements and with one step of simulation time corresponding to 1 μs of real time.

THE THEORY BEHIND FEYNMAN

In 2005, a group of French physicists finally posited a theory explaining Feynman's observation that dry spaghetti always breaks into three or more pieces. The team discovered that when long, thin rods are bent evenly from both ends, they will break near the center where the rod is most curved. This initial break causes a "snap-back" effect, or bending wave, that further fractures the stick. But despite their Ig Nobel Prize-winning theory, the question remained: could a piece of spaghetti ever be made to break into only two pieces?



Binary fracture of spaghetti may be induced at low quench speeds (2 mm/s). Frame rate = 75,000 fps.



Binary fracture of spaghetti is observed in both trials and simulations at high twist angles (330°). Frame rate = 1,972 fps.

THE SPAGHETTI-SNAPPING SETUP

To test Patil's model of controlled binary fracture, the research team constructed a custom device designed to break hundreds of 24-cm spaghetti sticks with controlled twisting forces and nonadiabatic quenching. The apparatus featured a manual linear stage and two freely pivoting rotary stages on either side. Each rotary stage included aluminum clamps that held the spaghetti samples close to the torsional and bending axes of rotation. For their twist experiments, the team completed 73 trials at various twist angles up to 360 degrees. The kinetic quench experiments consisted of 20 trials, during which the device moved the ends of each spaghetti stick together at various speeds between 0.1 and 50 cm/s. The team found that twisting the spaghetti stick nearly 360 degrees and then slowly bringing the two ends together to bend it caused the stick to break into two pieces.

FRACTURE MECHANICS THROUGH A HIGH-SPEED LENS

In addition to achieving controlled binary fracture, the researchers wanted to capture the fragmentation process to explore why the spaghetti sticks broke into six or more pieces during the higher-speed kinetic quench trials. "There were many questions which we could only definitively resolve by filming the spaghetti at a very high frame rate," Patil says. "When the spaghetti broke into multiple pieces, we wanted to resolve the time between the fractures in the rod."

Because crack propagation occurs on very fast timescales, the team recorded their twisting and quenching trials using a Vision Research Phantom v2511 high-speed camera, which is capable of filming up to 1,000,000 frames per second (fps). To observe the fragmentation process, the team filmed their quench trials at 75,000 fps. By upping the frame rate even further, the camera provided useful insights into spaghetti fracture mechanics at the microsecond scale. "By going to 1,000,000 fps, we saw how a crack propagates through the material and how the beam relaxes immediately post fracture," Patil says.

In many cases, the high-speed footage confirmed Patil's theoretical predictions, which can apply to other rodlike structures—from cellular microtubules, to advanced composite materials. The footage also raised some additional questions. "Using the camera, we observed that crack formation and propagation in spaghetti is itself a multistage process," Patil says. "It appears as if a small pre-crack forms and then persists for a relatively long time before the crack ruptures the spaghetti. This process is quite interesting in its own right and could help us understand some of the randomness inherent in fracture."

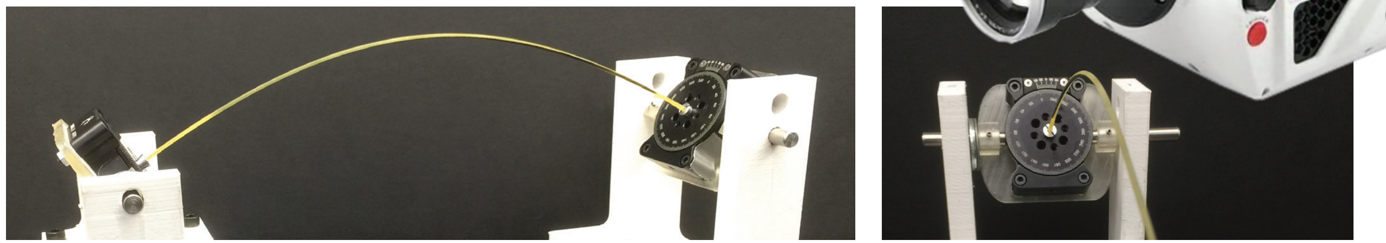
In addition to shedding light on ER fracture mechanics, the high-speed footage opens new doors for further study—particularly in elasticity, where interesting phenomena occur on very short timescales. "I look forward to using the camera again when we find our next question," Patil says. Patil and his fellow mathematicians published their findings in the Proceedings of the National Academy of Sciences.

THE PHANTOM v2511: BALANCING HIGH FRAME RATE & LOW EXPOSURE

At its full 1-megapixel resolution (1,280 x 800), the Vision Research Phantom v2511 high-speed digital camera can record up to 25,000 fps, making it a useful tool for scientists looking to obtain images at full or near-full resolution at very high speeds. At lower resolutions, it can record up to 1,000,000 fps—an exceptionally high frame rate that enabled the MIT mathematicians to take their research a step further by analyzing spaghetti fracture propagation at the microsecond level.

Because the nature of the twist and quench experiments required short exposure times, the research team needed a high-speed camera that could maximize light exposure without sacrificing speed or image quality. This is where the Phantom v2511 shines. The camera utilizes a custom CMOS sensor with 28-micron pixels for high light sensitivity. Each pixel has a bit depth of 12 bits—yielding 4,096 gray levels. Additionally, the camera includes a global electronic shutter capable of exposures as fast as 500 ns. Even at a frame rate of 1 million fps, the exposure time can go down to 265 ns. This capability sufficiently freezes motion while eliminating the motion blur typical of ultra-fast applications.

The Phantom v2511 camera.


For their experiments, the MIT team constructed a custom device to controllably break hundreds of 24-cm spaghetti sticks with controlled twisting forces and nonadiabatic quenching.

New Printing Process Leaves a Mark

Using a Phantom high-speed camera, MIT researchers observed what happens to the ink during a new printing process—opening up new doors for electronics.

How ink behaves when it's stamped onto a surface during flexographic printing might not seem like much of a concern. But as it turns out, understanding ink transfer dynamics is critical to a wide range of applications—particularly, electronics manufacturing.

A group of Massachusetts Institute of Technology (MIT) researchers developed a new printing process that improves on traditional flexography—a technique that applies ultra-thin layers of polymeric and colloidal inks to nonporous substrates. Flexography is important for many industries, including electronics manufacturing, and is often used to print on unconventional surfaces like paper and polymer films. Film transistors, RFID tags and transparent electrodes are just some of the mass-produced devices that benefit from this high-throughput process.

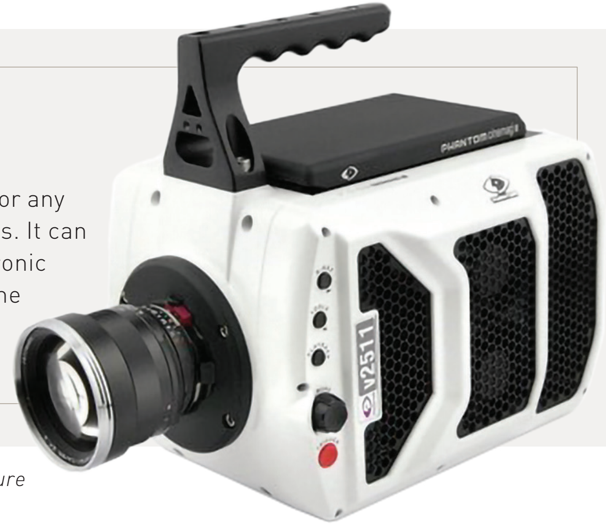
FLEXOGRAPHY AND INK TRANSFER DYNAMICS

During flexographic printing, an elastomer stamp makes contact with the substrate—causing the ink on the stamp's surface to form a liquid bridge between the two surfaces. Separating them ruptures the bridge, transferring tiny amounts of liquid to the substrate under each stamp feature. Despite being a highly scalable and fast process, flexographic printing has its limits. Due to the ink transfer dynamics, this process is limited to resolutions of tens of microns—in turn, limiting the resolution of printed display pixels and the performance of printed devices.

But with the help of a Phantom high-speed camera, the MIT research group has found that nanoporous stamps overcome these challenges, enabling ultra-thin film printing with micron-scale precision. "Specifically, nanoporous stamps don't experience the same squeeze-out and de-wetting instabilities as traditional polymer stamps—achieving significantly finer printed feature dimensions," explains researcher Dhanushkodi Mariappan.

THE PHANTOM v2511 CAMERA

The Vision Research Phantom v2511 high-speed camera is a helpful tool for any researcher looking to capture high-resolution images at ultra-high speeds. It can shoot up to 1,000,000 fps at lower resolutions and includes a global electronic shutter capable of sub 1-µs exposures. Due to these advanced features, the camera successfully freezes fast-moving phenomena while eliminating motion blur.



Thanks to its high light sensitivity, the Phantom v2511 enabled MIT researchers to capture the ink transfer dynamics during nanoporous stamp flexography.

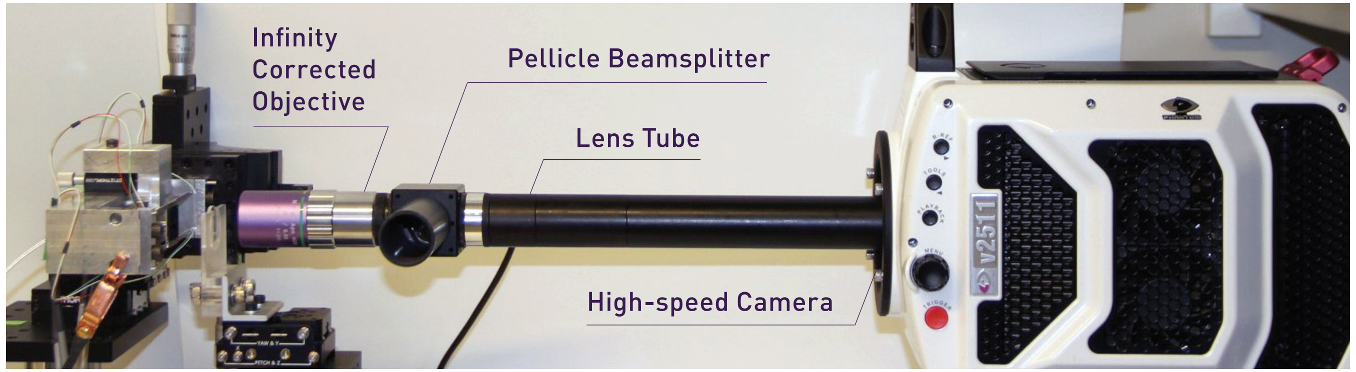
SOME HIGH-SPEED HELP

To help them better understand how nanoporous stamps transfer ink, the researchers needed a way to capture the micron-scale stamp features during the fast flexographic printing process. "The high-speed camera was critical in this process," says Mariappan.

Using a Vision Research Phantom v2511 camera, Mariappan and his team investigated the liquid transfer dynamics between the substrate—in this case, a transparent, spherical lens—and a nanoporous stamp made of polymer-coated carbon nanotubes (CNT). Their experimental setup included a CNT stamp, which they affixed to a flexure stage, as well as a capacitance probe that measured the contact force between the stamp and substrate.

The stamp pattern included an array of 100-μm circles with 30-μm spacing. The apparatus also incorporated a single-axis motion stage to align the two surfaces, as well as a custom microscope and Phantom v2511 camera positioned behind the transparent substrate.

After inking, the team placed the wet stamp on the flexure and brought it into contact with the lens. The Phantom v2511 recorded this critical step—including the stamp's approach and retraction at different speeds—at 25,000 frames per second (fps). "Essentially, we wanted to capture what's happening at the interface between the two surfaces," Mariappan explains. "To our knowledge, this kind of experiment has never been done before."



The apparatus that captured the contact between the CNT stamp and spherical lens. Images were taken through the back side of the lens using a Phantom v2511 camera.

SHEDDING LIGHT ON A HIGH-SPEED PROCESS

In general, lighting can be a challenge during high-speed photography. Due to the nature of the stamping experiments, having enough lighting became more important than ever. "Essentially, we're pressing two surfaces against each other," Mariappan explains. "Closing the gap restricts the light."

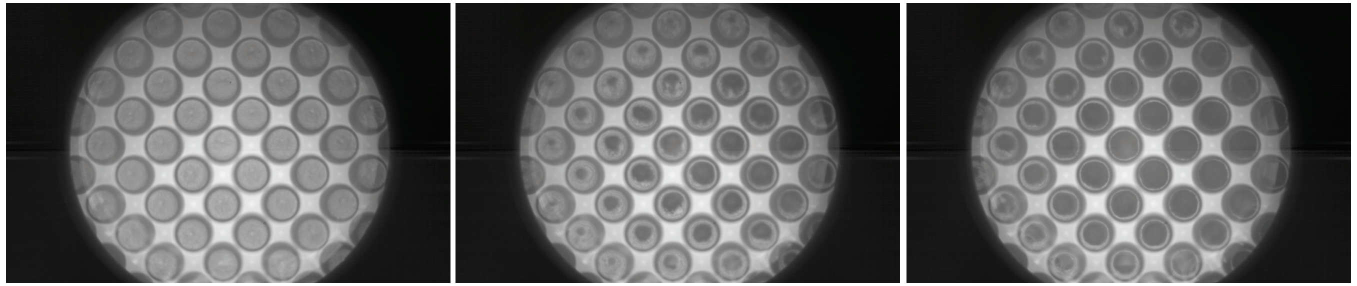
The highly sensitive Phantom v2511, as well as its successor, the Phantom 2512, are designed to maximize light response without sacrificing image quality or speed. The v2511 hits 25,000 fps at full 1-megapixel resolution and integrates a custom CMOS sensor with 28-micron pixel sizes for high light sensitivity. Each pixel has a depth of 12 bits, yielding 4,096 gray levels, for high-quality, detailed images. Together these features achieve a very high native ISO of 32000D mono and 6400D color—successfully overcoming typical high-speed lighting challenges.

STAMPING OUT THE RESULTS

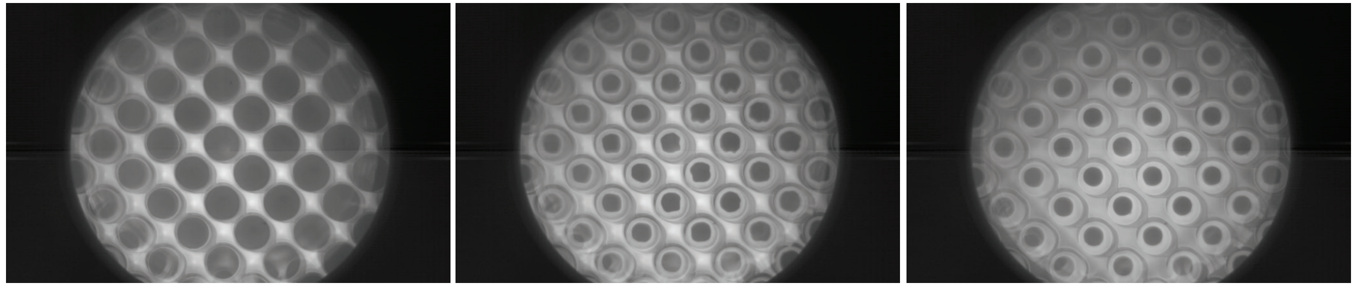
Using high-speed imaging and analytical modeling, the team successfully observed how the ink spread during stamping—shedding light on the transfer dynamics of nanoporous stamps at high and low approach speeds. Specifically, they demonstrate that the volume of printed ink and resulting thickness are both independent of contact pressure. They also show that thickness decreases with retraction speed.

"Nanoporous stamp flexography successfully prints nanoparticle films with thicknesses less than 100 nm at speeds commensurate with industrial equipment," Mariappan concludes. "Thanks to the camera, we've been able to show the potential of nanoporous stamps in industrial-scale electronics printing."

Mariappan and his colleagues published their findings in Langmuir in April, 2019.



The Phantom v2511 captures how the ink spreads when the stamp approaches the substrate at 10 mm/s.



The Phantom v2511 captures the evolution of the liquid bridge when the stamp retracts from the substrate at 10 mm/s.

SPAGHETTI
case study video

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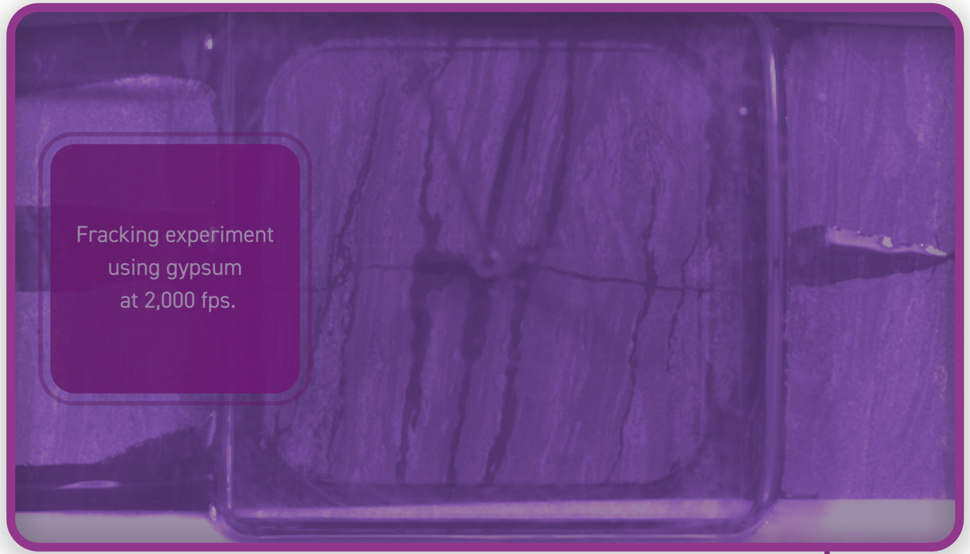

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FRACKING
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NANOPOROUS STAMPS
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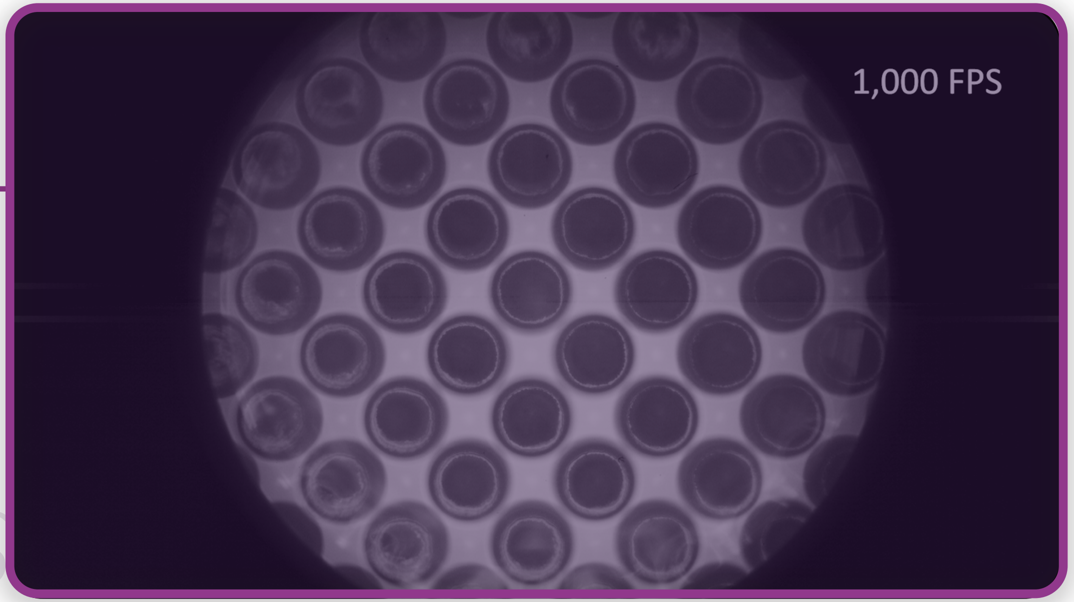

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