e-lab
Energy Laboratory research and related activities at the Massachusetts Institute of Technology
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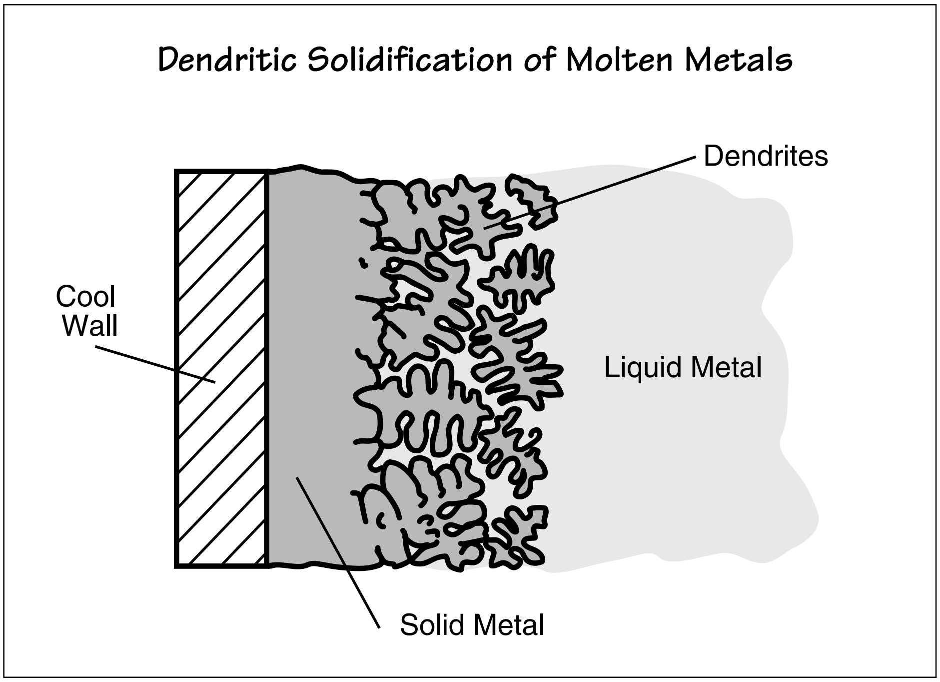
Aluminum Components for Automobiles: Casting Low-Cost, High-Quality Parts

To meet the needs of today's auto industry, manufacturers have begun producing aluminum components by pouring the metal into molds when it is already partially solidified. The lightweight precision parts produced cost less than those made by forging and machining solids and are stronger and more reliable than those made by conventional casting of liquids. "Semisolid processing" became possible 25 years ago, when an MIT graduate student found that stirring molten metal while it solidifies produces a semisolid that can be cast even when it is solid enough to be handled by robotic equipment. Now the MIT researchers are using industrially important aluminum alloys and new experimental techniques to clarify exactly why the process works and how to make it work better. As expected, the more solid the material is, the shorter the distance it flows before stopping—not good behavior for filling a mold. However, partially solidified samples flow farther if they have been formed by cooling the molten metal slowly and stirring it vigorously. Microstructural analysis shows why. Slow cooling and long stirring produce particles that are large and spherical, while fast cooling and short stirring produce small, jagged particles that tend to stick together. As a result, the larger particles slide by each other more easily than the smaller ones do, producing a semisolid with less resistance to flow. High-speed videos show that the semisolid advances smoothly and evenly, producing parts with a consistent microstructure, smooth finish, high reliability, and constant properties.

Traditionally, manufacturers of metal components worked with metals that were fully liquid or fully solid. They forged and machined solid pieces, or they cast liquid metals in molds. Using a material that was partly solid and partly liquid was not an option because such semisolids would not flow well enough to fill the nooks and crannies of typical molds. However, in 1971 an MIT doctoral student made a surprising discovery. In the course of studying how molten metals flow as they solidify, the student,


Dendritic Solidification of Molten Metals

As metals cool, they tend to form tiny pine-tree-shaped particles called dendrites. Because of their jagged branches, the dendrites do not slide easily by one another; so partially cooled metals do not flow well. Stirring molten metal as it cools breaks up the dendrites, knocking off the branches. The result can be a partially solidified metal that flows well enough to fill an industrial mold yet is solid enough to handle without deforming.

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David Spencer, found that if he stirred the liquid all the while it was solidifying, it remained relatively easy to stir, even when much of it had turned solid. He and his thesis supervisor, Professor Merton C. Flemings, recognized that such a “flowable” semisolid material could be the basis of an improved metal-forming process. Aluminum companies could use the stirring procedure to create flowable metals that they could press into molds in semisolid form. They could also use stirring to form special solid ingots that parts manufacturers could buy, remelt, and cast. Parts manufacturers would no longer need to handle fully molten metal.

Despite those and other advantages, semisolid processing did not take off until the mid-1990s, when the automotive industry began calling for parts that were lightweight, low-cost, reliable, and long-lived. Cast or forged components made of iron or steel began being replaced by components of aluminum alloys manufactured by semisolid processing. The advantages of semisolid processing over traditional methods have proved remarkable. Castings of semisolid rather than molten metal form quickly and have lower cooling requirements. Semisolids can be handled by robotic arms and yet still flow well enough to fill intricate molds—in fact, better than molten metals can. Less gas is entrapped, fewer voids form, the surface finish is smoother, and less shrinkage occurs. The parts produced have more consistent and better mechanical properties and closer tolerances; and they need little if any additional shaping after they are formed, saving manufacturing time and expense.

Each year, companies in the United States, Japan, and Europe now produce or use millions of parts made by semisolid processing, and the number is growing quickly. However, as often happens, the commercial adoption of the new process has far outpaced the development of a detailed understanding of how it works. For example, how do the length of stirring, the rate of cooling, and other processing conditions affect the microstructure of the semisolid material? How does that microstructure affect how the material flows? And how does that flow behavior affect the products formed? An Energy Laboratory team including Professor Flemings, Anacleto de Figueredo, and Yusuf Sumartha has been performing rigorous experiments to answer such questions. While the focus is on expanding fundamental understanding, the results will have practical implications, providing manufacturers better control over the process and the products it yields.

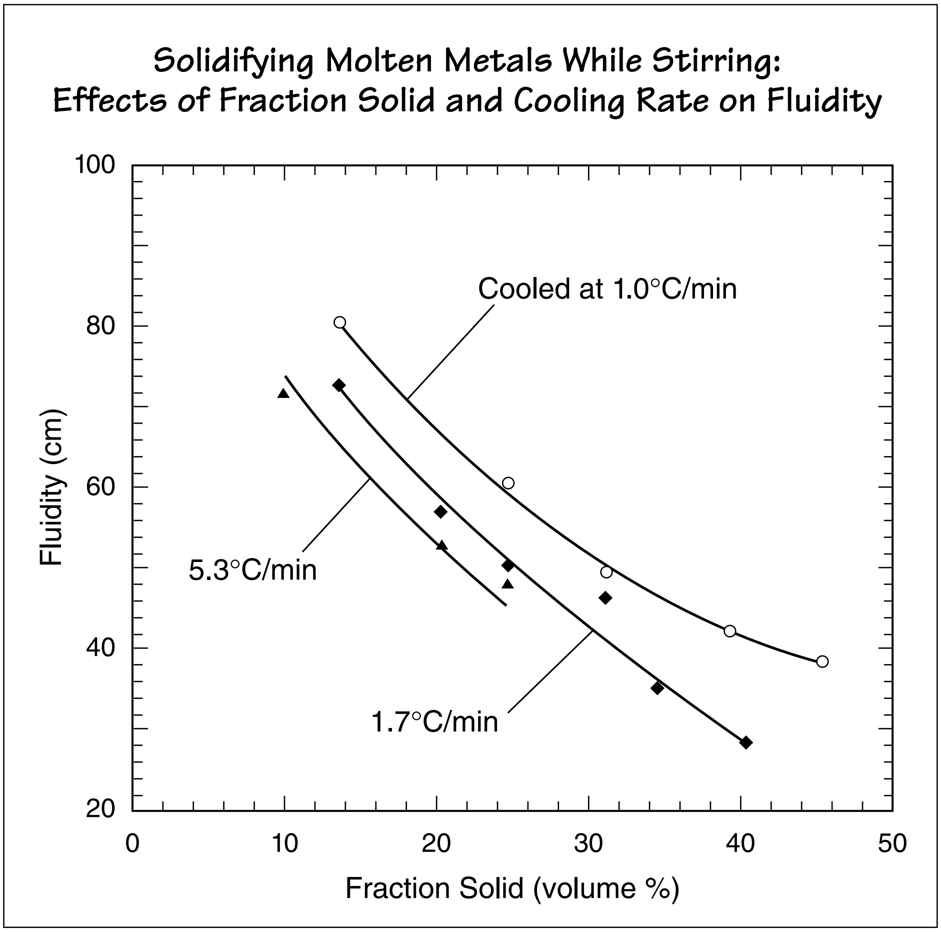
To understand why stirring changes the behavior of semisolids, one must consider the microstructure of solidifying metals. Nearly all metals and alloys of commercial importance solidify “dendritically.” As the liquid begins to solidify, tiny pine-tree-shaped particles called dendrites form (see the figure on page 1). These jagged particles do not slide by one another easily, so the semisolid material does not flow well. Stirring the liquid as it solidifies breaks up the dendrites as they form, tearing their branches off. The particles are smoother and can slide by each other. As a result, the semisolid flows more easily, even when its solid content is relatively high. Professor Flemings likens the process to making ice cream. If you combine all the ingredients for ice cream and place the mixture in a freezer, the material formed will contain big ice crystals—not a very palatable product. But if you stir the mixture while it is freezing, you break up the ice crystals as they form. The ice cream remains smooth and creamy, even when as much as 70% of it is solid.

Previous studies have looked at the flow behavior of semisolids, but their approach typically has not accurately reflected the industrial situation. For example, the studies tended to involve small quantities of semisolid material. The bulk quantities used in a factory might behave quite differently. And they generally involved measuring the viscosity of the semisolids—a property that does not translate directly into how well a semisolid will flow into the little spaces inside an industrial mold.

Professor Flemings and his colleagues therefore use a different approach—one that involves both a larger amount of metal and a different method of quantifying flow behavior. They melt an ingot of an aluminum alloy in a crucible. They then cool the molten metal while stirring it at a controlled speed between 0 and 1000 rpm. When the metal is partially solidified, they use a partial vacuum to suck some of it up a silica tube and then measure how far it travels before it solidifies. That technique, specially adapted for use with semisolid materials, is a simple but effective means of establishing “fluidity,” a foundry concept that describes the ability of a metal to flow before being stopped by solidification.

In the experiments, thermocouples placed in the metal directly measure its temperature. Videos taken at 40,000 frames per second track how fast the semisolid moves up the tube, and quantitative metallographic analysis shows the microstructure of the specimens collected in the tube. (Although the specimens are solid, their microstructure is similar to the material in semisolid state: solidification occurs so quickly in the tube that the microstructure has no time to change.) Based on all the experimental evidence, the researchers relate fluidity to the microstructure of the semisolid, and the microstructure to processing conditions such as cooling rate, cooling time, and “fraction solid” (the fraction of the semisolid that is in solid rather than liquid form).

With so many interacting factors involved, identifying conditions that increase the fluidity of the semisolid is not straightforward. The figure on page 3 summarizes some of the experimental results. The curves show how fluidity changes as the fraction solid changes, with each curve representing a different cooling rate. Not surprisingly, as the semisolid becomes more and more solid, its fluidity decreases, regardless of the cooling rate. For a given fraction solid, a slower cooling rate produces higher fluidity. Thus, if the material is about 14%


Solidifying Molten Metals While Stirring: Effects of Fraction Solid and Cooling Rate on Fluidity

Results from MIT experiments show that as a molten aluminum alloy becomes more solid, its ability to flow ("fluidity") goes down, even if it is stirred continuously. But as these three curves show, the more slowly the alloy is cooled to reach a given fraction solid—and therefore the longer it is stirred—the more fluid it ends up.

solid (by volume), cooling it at 1.7°C per minute produces a semisolid that travels about 73 cm up the tube, while cooling it at 1.0°C produces a semisolid that travels about 80 cm. The explanation for that trend is clear. If the molten metal is cooled more slowly, it will take longer for it to reach a given fraction solid. Assuming that stirring is continuous, the longer processing time translates into a longer stirring time, thus fewer dendrites and higher fluidity. (Stirring the solidifying ice cream longer makes it more creamy.) Videos taken with the high-speed camera show that even at a high fraction solid, the well-stirred semisolid material moves up the experimental tube smoothly and consistently.

Almost more interesting are the microstructures that occur under the different processing conditions. For example, the figure on page 4 shows the microstructures of two specimens collected at the same fraction solid. The bottom one was cooled more slowly, thus stirred longer, than the top one. The lower cooling rate and longer stirring time produce larger particles. Yet the fluidity tests show that longer stirring increases fluidity. Several factors explain that seeming contradiction. For one thing, the larger particles are spherical, while the smaller ones are irregular in shape, thus less able to slide by one another. In addition, the smaller particles have a higher surface area and are more likely to interact and stick together than the larger particles are. The result is irregular agglomerates that move less easily than the large spherical particles do.

In those experiments, the researchers completely melted the aluminum alloy and then worked with the semisolid as it formed during cooling. But that approach replicates only one procedure used by industry. Parts manufacturers may heat solid ingots made from stirred liquids to produce semisolid materials to cast. To explore that situation, the researchers performed experiments following the same procedure. They heated solid ingots specially prepared by the Alumax Company until they were partly solid and partly liquid. They then stirred the mixture for variable periods of time before sucking samples up into the experimental tube.

The results are quite different from those of the tests starting with molten metals. The researchers were able to make a semisolid shape that was solid enough to be handled without deforming but soft enough to form in a mold. However, for a given fraction solid, the specimens collected in the experimental tube have substantially lower fluidity than do those produced directly from liquids. Stirring the reheated semisolids makes them flow more freely, but even after a full hour of stirring they are not as fluid as the materials produced by stirring molten metal continuously as it cools.

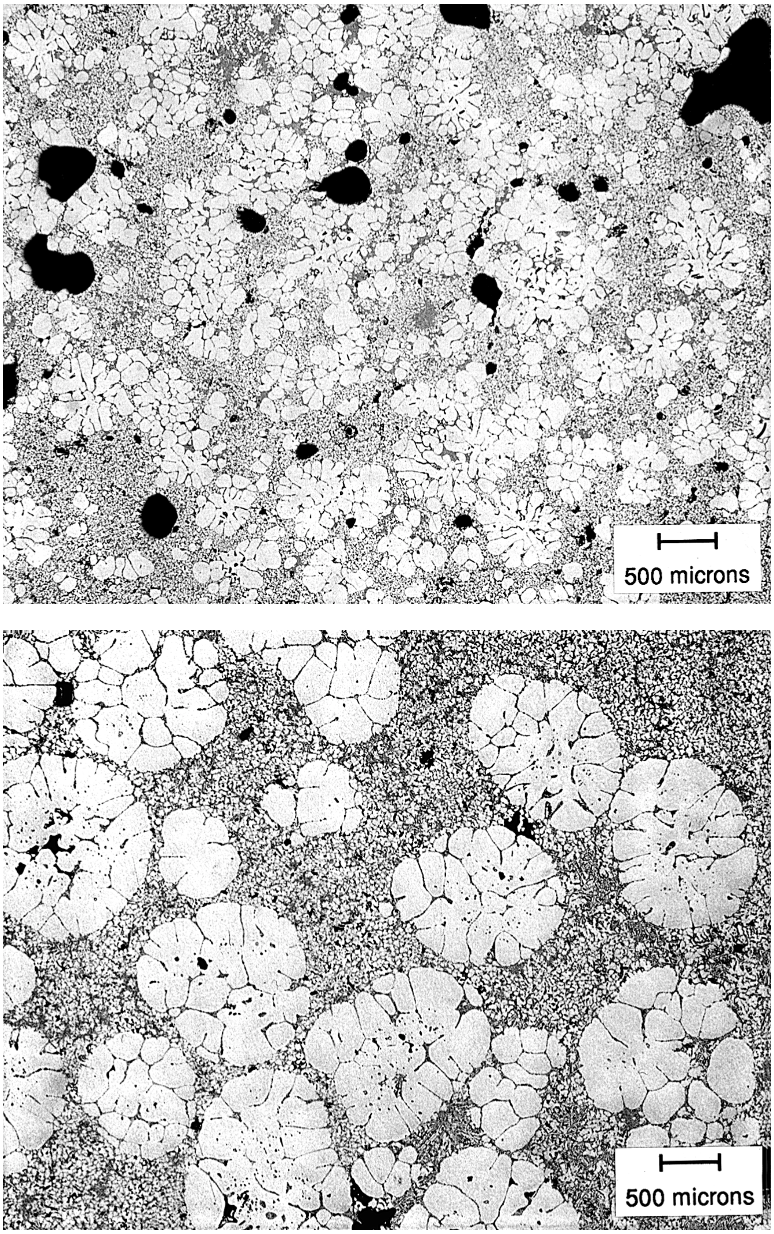
Micrographs show that the original ingots contain relatively fine, rounded particles. On remelting, those particles tend to form three-dimensional, entangled strings. The strings are still present after an hour's stirring, and some of them are as long as the experimental tube is wide.

Thus, starting with remelted solid ingots is not as good as starting with fully molten metal. However, the drawbacks of using remelted solids are easily offset by the convenience and cost savings of not having to deal with large quantities of molten metal. While homemade ice cream may have a nicer taste and consistency than store-bought, most people choose to buy their ice cream in the store and let it melt a bit so it becomes smooth and creamy.

Experimental equipment now being designed and built by James Yurko will provide the research team with an even closer look at how semisolids flow. Instead of sucking the stirred semisolid up a tube, the new experimental apparatus will push it through a small hole, much like pushing toothpaste out of a tube. As a result, the semisolid will move about ten times faster than in the previous experiments, achieving velocities close to those that prevail in important industrial processes such as die casting. In addition, the new equipment will be highly instrumented. The direct measurements of velocity, pressure, and other important characteristics will provide the researchers with a much improved fundamental understanding of how semisolids flow during industrial processing.

Merton C. Flemings is Toyota Professor of Materials Processing. Anacleto de Figueredo is a research staff member and James Yurko is a PhD candidate in the Department of Materials Science and Engineering. Yusuf Sumartha received his SM from the same department in fall of 1997. This research was supported by the University Research Consortium of the Idaho National Engineering and Environmental Laboratory and by the Alumax Corporation. Further information can be found in references 1–7.

Microstructures of Partially Solidified Aluminum Alloys



Micrographs of an aluminum alloy that has been stirred continuously as it cooled. Both samples were 28% solid (by volume) when they were solidified suddenly, capturing the microstructure of the semisolid. The top sample was cooled at 5.3°C per minute, the bottom at 0.6°C per minute. The bottom sample therefore took longer to reach the desired fraction solid and as a result was stirred longer. The result is larger particles that are less jagged, more spherical, and less apt to stick together—thus, a semisolid that flows more easily.

Monitoring the Solidification of Metal Castings

If manufacturers of metals could see exactly how their molten metals solidify, they could control their operations to make their products faster and better. Energy Laboratory researchers have invented a novel way to monitor the solidification process directly without affecting the metal object being formed. They use computed tomography, or CT, the technique used in taking brain scans. A small linear accelerator fires high-energy X-rays along many pathways through a solidifying metal object. How much of the X-ray beam makes it through the object depends on the density it encounters. The solid and liquid forms of a metal differ substantially in density, so a CT image of the object based on the density data shows which areas are solid and which are liquid. This method has yielded minute-to-minute images of an aluminum sample as it solidifies during an hour. The results are consistent with temperature measurements taken within the solidifying sample. The researchers are now developing a new analytical technique that should reduce the scanning time to 1-3 seconds—fast enough for real-time process control in industry. The MIT team is starting to work with important industrial alloys of aluminum and is getting ready for field tests in a commercial casting plant.

A critical part of today's manufacture of aluminum, steel, and other metals is "continuous casting." Molten metal pours out of a large container through a rectangular mold where it is cooled and shaped and begins to solidify. The resulting elongated shape, the "strand" of metal, is pulled out of the mold and cooled until it is completely solid and can be cut.

How the strand solidifies affects both the rate of production and the quality of the product. The strand solidifies from the outside in and exits the caster with a solidified shell around the outside of a still-molten core. How quickly that solidified shell thickens determines how quickly the strand can be extracted from the caster without breaking. How quickly the entire molten core becomes solid determines how soon the strand can be cut without leaking molten metal. And the location, shape, and movement of the "solidification front"—the point at which the liquid metal becomes solid—directly influence the formation of flaws such as voids, surface defects, and cracks. A monitor that could track the behavior of the solidification front in real time would enable manufacturers to control cooling rates and other operating conditions so as to run the continuous caster as quickly as possible while avoiding accidents and reducing defects in the products.

Developing a monitor that can be used on a moving, solidifying continuous casting in industry is a major challenge. During the past three years, Professor Jung-Hoon Chun and his Energy Laboratory coworkers have made significant progress toward that goal by working with metals solidifying in stationary molds—an approach known as "discrete casting" used by manufacturers to make final parts such as engine blocks. The interdisciplinary research project, dubbed "CastScan," involves Professor Chun, Dr. Nannaji Saka, Dr. Richard C. Lanza, Mark M. Hytros, and Imad M. Jureidini. The project also involves a consortium of interested industrial collaborators and sponsors.

Techniques for monitoring solidification in the industrial setting—whether for continuous or discrete casting—have their limitations. Various experimental techniques yield valuable information about the solidification process, but none is suitable for use in industry. Thermocouples inserted into the metal casting can directly measure temperature and thereby track the moving solidification front. But the presence of the thermocouples damages the part produced. Nondestructive methods involving sonic, infrared, and conventional X-ray imaging cannot handle the thick cross section of the typical manufactured strand and the high temperatures of the metals being cast. Computer models that simulate the solidification process produce useful information, but better experimental data are needed to refine and validate them.

Professor Chun and his colleagues have therefore been pursuing a new approach—one that combines high-energy radiation with computed tomography (CT), the technique used in taking medical images. Key to their approach is the behavior of high-energy electromagnetic radiation as it passes through metal. When a beam of high-energy X-rays or gamma rays encounters a metal object, photons in the beam penetrate the object; but not all make it through. Some are absorbed or scattered. How much reduction, or "attenuation," of the beam occurs depends on the density of the metal object. The density of a solid metal can be 4% to 12% higher than the density of the same metal in liquid form. As a result, the attenuation of a radiation beam differs depending on whether it has passed through the liquid or solid part of a solidifying metal. Taking attenuation measurements at many angles through a solidifying metal object—the scanning technique used in the medical procedure—yields data that can form a CT image distinguishing solid from liquid.

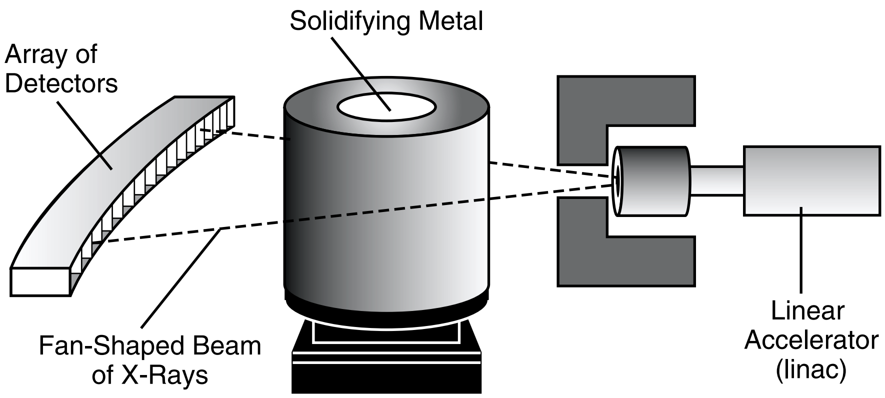
In early experiments, the MIT researchers used their approach to locate the solidification front in a crucible of tin. Part of the tin was heated and part cooled to produce both liquid and solid regions and a stationary solidification front. They aimed a narrow beam of gamma rays from a radioisotope (cobalt-60) through the crucible of tin and onto a detector. The detector measured the incident photons over a certain time period and determined the amount of attenuation that occurred. The researchers then moved the crucible slightly so the beam entered it at an adjacent position. After taking measurements through many positions on that face of the crucible, they rotated the crucible slightly and repeated the scanning procedure. CT analysis of the entire set of attenuation measurements yielded an image that shows where the interfaces between the solid and liquid regions occur.

The experimental results confirmed the feasibility of the approach. However, collecting the data took fully 14 days! Moreover, the image produced was imprecise because temperatures inevitably fluctuate and the solidification front moves during such a long time period.

To solve those problems, the researchers turned to a different radiation source: a 6-MeV X-ray linear accelerator (linac). During a single second, the linac fires about 4 trillion photons through a square centimeter located a meter away—about a million times more than generated by the cobalt-60. The photons also have higher energy levels and can penetrate pieces of metal as much as 60 cm in thickness. The linac does not generate a continuous beam but instead emits 200 pulses of radiation per second. That pulsed operating mode allows the linac to be small in size but required the MIT team to specially adapt the data acquisition system for measuring the X-ray attenuation.

To further decrease the data acquisition time, the researchers use the linac not with a single detector but with an array of 128 detectors. The figure on this page shows the experimental setup. The high-energy X-rays exit the linac in a fan-shaped beam. The photons pass along different pathways through the metal object to different detectors, all at the same time. The object still must be rotated within the beam, but moving it from one place to another is unnecessary unless its dimensions exceed the width of the fan beam. (The beam can also be focused into a "pencil" configuration.)

Monitor for Imaging the Solidification Process During Metal Casting



In this experimental setup, Energy Laboratory researchers demonstrate a novel technique for producing computed tomographic (CT) images of molten metal as it solidifies—information that could help manufacturers increase productivity and decrease flaws in their products. A small linear accelerator sends a fan-shaped beam of high-energy X-rays through solidifying aluminum to an array of detectors. How much the beam is reduced along different pathways through the aluminum depends on the densities it encounters. CT analysis of density measurements from all angles produces an image that shows the position of the "solidification front," the interface between the liquid and solid metal.

The researchers perform their experiments in the "CastScan Laboratory," which is located on the grounds of the Bates Linear Accelerator Center in Middleton, Massachusetts. They use a small, portable linac provided by the Idaho National Engineering and Environmental Laboratory. The team specially built the remainder of the setup, including a shielded room with 75-cm-thick concrete walls that houses the equipment. Unlike the cobalt-60, the linac does not emit harmful radiation when not in use; but shielding is still necessary to protect operators from radiation hazards.

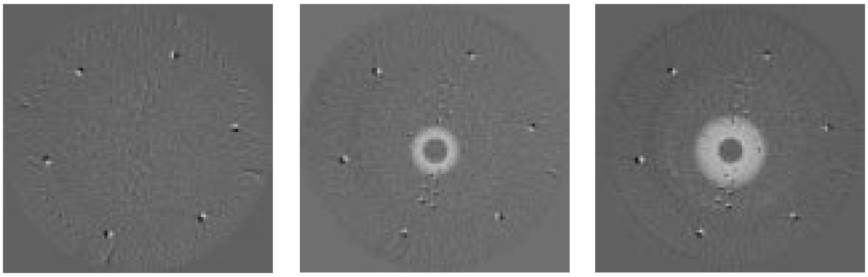
The researchers have now demonstrated their new technique using aluminum, an important industrial metal with a melting point of 660˚C as opposed to the 232˚C of the pure tin used in the early studies. Page 7 shows sample results. In this experiment, a pure aluminum casting almost 15 cm in diameter was melted in a cylindrical crucible placed inside a cylindrical furnace.

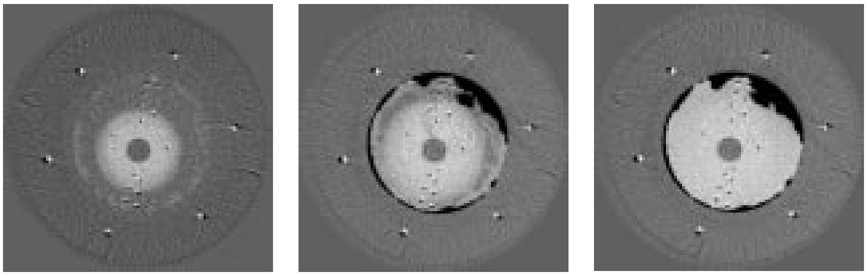
Cool air was then passed down a tube immersed in the middle of the liquid aluminum, causing the aluminum to solidify. The furnace was completely rotated once per minute, during which time each detector took 2700 measurements. After every complete rotation the furnace was shifted to a new position and rotated again. This procedure yielded an image for every minute, each one based on density data averaged over two minutes. Thermocouples placed in the liquid independently measured temperature.

Using the images, the researchers have produced a movie that shows the aluminum as it gradually solidifies over the course of an hour. The complete movie is available on the World Wide Web at <http://castscan.mit.edu:80/castscan/solidifi.htm>. Selected images are shown here. The dark circle in the center is the tube of cool air. The light areas indicate high density, the solidified regions. (Differences in density have been amplified by image enhancement techniques.) The six bright spots are steel support rods. At 24 minutes, the aluminum is still completely liquid. At 31 minutes, the metal begins to solidify around the cooling tube, appearing as a bright ring at the center of the image. The thermocouples now show up as small bright spots in the still-liquid aluminum. The bright area at the center continues to expand as solidification progresses outward. At 52 minutes, dark areas show the formation of an air gap between the aluminum and the wall of the crucible—the result of the metal's shrinking as it solidifies. The last figure shows the aluminum in a completely solidified state.

The CT images unmistakably show the evolution of the solidification front. The position of the front matches the thermocouple measurements within 2 mm. The maximum and minimum intensities of the pixels in the images differ by 7%, as do the densities of solid and liquid aluminum. The locations and sizes of cavities created during solidification are clearly evident—information critical to improving the quality of cast parts.

CT Images of Solidifying Aluminum


24 minutes 31 minutes 40 minutes


44 minutes 52 minutes 60 minutes

These CT images show a melted aluminum sample as it solidifies. Bright areas represent high density, thus solid material. (Bright spots in the images were created by the experimental apparatus.) In the first image the aluminum is liquid. At 31 minutes, the molten metal begins to solidify around a tube at the center that carries cooling air. The next few images show solidification progressing outward until the whole sample is solid at 60 minutes. The final solid is not perfectly round because the metal shrank as it solidified, leaving an air gap between the aluminum and the wall of its container.

While the data-acquisition time is dramatically shorter than in the cobalt-60 experiments, it is still too long for real-time industrial use. In addition, the technique cannot be used on continuous castings because of their size and geometry. To solve those problems, the researchers are developing a new method of analyzing the data. The method, called "partial view tomographic imaging," involves constructing a three-dimensional image based on scans from only one direction, so the casting need not be rotated. Based on known facts about the geometry, density, and other properties of the metal casting, a computer model calculates the location and shape of the solidification front after one second and compares its answer to measured data. If the outcomes do not match, the computer model alters its assumptions slightly and performs its calculation again. When the calculated and measured results match, the model moves to the next second and performs the iterative process again. Successful implementation of this approach should reduce the data acquisition time to as little as 1-3 seconds—well within the range needed for industrial use—while making the monitor suited for use on continuous as well as discrete castings.

Another prerequisite to the monitor's commercial usefulness is its ability to deal with alloys—combinations of pure metals and other elements that yield high strength or other desirable properties. Alloys pose a particular challenge because the different elements generally have different solidification points. The solidification "front" therefore typically occurs within a partially solidified area known as the "mushy zone." The researchers believe that the linac-based system will prove sufficiently sensitive to detect the gradual variations in density that occur within the mushy zone. Experiments with aluminum alloys are now under way. The researchers are also making plans to test their linac-based monitor on a continuous caster in a manufacturing plant. Those field tests will show both the technical and economic viability of using the monitor in the commercial industrial environment.

Jung-Hoon Chun is an associate professor of mechanical engineering. Nannaji Saka is a principal research scientist and Mark Hytros is a PhD candidate in the Department of Mechanical Engineering. Richard C. Lanza is a senior research scientist and Imad M. Jureidini is a PhD candidate in the Department of Nuclear Engineering. This research was supported by Aluminum Company of America; Analogic Corporation; Inland Steel Industries, Inc.; the National Science Foundation; Reynolds Metal Company; and the University Research Consortium of the Idaho National Engineering and Environmental Laboratory. Further information can be found in references 8–15. Most are available through the CastScan site on the World Wide Web. Go to <castscan.mit.edu/castscan/publicat.htm>.

News Items

Almost 70 people from industry, government, and academia attended the **spring workshop** of the **Center for Energy and Environmental Policy Research**, which was held on April 30 and May 1. Topics on the first day included electric utility restructuring in Europe and Japan, electricity markets in the western United States, the future of nitrogen oxides emissions trading, and international gas pipelines. The lunchtime speaker was Thomas W. Malone, Patrick J. McGovern Professor of Information Systems, who spoke about the effects of changes in information technology. At dinner Mr. John Mitchell of the Royal Institute of International Affairs discussed the changing geopolitics of energy. Presentations on the second day focused on oil production in the North Sea and post-cold-war perspectives on Asian energy.

The **Joint Program on the Science and Policy of Global Change**, in association with the **Royal Institute of International Affairs**, held the **Thirteenth Global Change Forum** in London on June 14–16. The title of the forum was "**Climate Assessment and Policy Development After Kyoto**." The meeting opened with a keynote address delivered by Mr. Tom Spencer, member of the European Parliament. Subsequent sessions focused on the following topics: detection and attribution of climate change; new developments in the science of climate change; new dimensions in the IPCC assessment process; implementation of Annex I flexibility (bubbles, trading, and joint implementation); implementation and extension of provisions involving non-Annex I parties; and prospects for ratification and implementation of the Kyoto Protocol. Meeting participants included about 80 representatives from industry, government, and academia, worldwide.

On June 22–23, the Energy Laboratory hosted a "**Stakeholders' Workshop on Carbon Sequestration**." The event is part of a broader effort by the Federal Energy Technology Center to foster communication and collaboration among researchers, industry, government, and various other stakeholders who are interested in the sequestration of carbon as a response to climate change concerns. About 120 people attended. Plenary sessions included a series of talks focusing on sequestration technologies, terrestrial sequestration, and the international outlook. The workshop then divided into breakout sessions by industry groups to solicit stakeholder feedback and to explore possible partnerships between industry, government, and universities. The workshop concluded with reports from the breakout sessions and a general discussion. Special presentations included a keynote address by Rita Bajura, director of the Federal Energy Technology Center; "Technology's Role in Carbon Management," by Henry D. Jacoby, William F. Pounds Professor of Management at MIT; and "The Future of Fossil Energy," by Morris A. Adelman, MIT professor of economics, emeritus. The workshop was organized by Howard J. Herzog, principal research engineer in the Energy Laboratory, who has led a series of MIT research projects on various aspects of carbon dioxide mitigation (see *e-lab*, April–September 1989, October–December 1992, and January–March 1996).

Anne M. Mayes, Class of 1948 Associate Professor of Polymer Physics, has received the **1998 Outstanding Young Investigator Award** from the **Materials Research Society**. The award was established "to recognize outstanding interdisciplinary materials research by a young scientist or engineer." Professor Mayes was cited for "incisive theoretical and experimental investigations of macromolecules at and near surfaces and interfaces leading to tailorable surface properties, especially novel biocompatible substrates." Professor Mayes leads a team of Energy Laboratory researchers who are developing self-organizing polymer electrolytes and other novel materials for a new lithium solid polymer battery (see *e-lab*, July–December 1996). The high-performance battery promises to be thin, flexible, long-lasting, and cheap and easy to fabricate. Funding for the research comes from the University Research Consortium of the Idaho National Engineering and Environmental Laboratory and from the Furukawa Electric Company.

Marija Ilić, senior research scientist in the Department of Electrical Engineering and Computer Science, has co-authored a new book entitled ***Power Systems Restructuring: Engineering and Economics***. Dr. Ilić's co-authors are Francisco Galiana of McGill University and Lester Fink of KEMA-ECC, Inc. (Charlottesville, Virginia). The book addresses problems inherent in restructuring the electric power industry. Topics include currently evolving market structures, mechanisms for implementing market requests, price incentives and transaction adjustments, and secure and optimal operation of the system under open access. The book addresses technical, economic, and regulatory questions related to making services market-based and analyzes market power problems related to transmission provision. The 576-page book is part of the Power Electronics and Power Systems Series of Kluwer Academic Publishers, Boston. The price is $145. For ordering information, call (781) 871-6600 or send e-mail to agreene@wkap.com. Related Energy Laboratory research performed by the authors is described in *e-lab*, January–March 1998.

PUBLICATIONS AND REFERENCES

The following publications of Energy Laboratory and related research were released during the past period or are cited as references in this issue. An order form for the **MIT Joint Program on the Science and Policy of Global Change** is available by request to the MIT Joint Program on the Science and Policy of Global Change, Publications, Room E40-271, Cambridge, MA 02139-4307, tel.: (617) 253-7492; fax: (617) 253-9845; e-mail: tzh@mit.edu. **MIT theses** may be ordered from the Library Document Services, MIT, Room 14-0551, Cambridge, MA 02139-4307. Other publications may be ordered from Energy Laboratory Publications, MIT, Room E40-473, Cambridge, MA 02139-4307, *only* if a price is assigned and *only* if prepaid by check payable to "MIT Energy Laboratory." Prices are postpaid surface mail. For air delivery, add 15% to US, Canada, and Mexico, and 30% elsewhere. A list of publications is available on request.

Reports and Working Papers

Bailey, E. *Allowance Trading Activity and State Regulatory Rulings: Evidence from the US Acid Rain Program.* March 1998. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 98-005. 38 pages. $10.00

Bailey, E. *Intertemporal Pricing of Sulfur Dioxide Allowances.* March 1998. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 98-006. 17 pages. $10.00

Ellerman, A., T. Stoker, and E. Berndt. *Sources of Productivity Growth in the American Coal Industry.* March 1998. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 98-004. 64 pages. $12.00

Schennach, S. *The Economics of Pollution Permit Banking in the Context of Title IV of the 1990 Clean Air Act Amendments.* May 1998. Center for Energy and Environmental Policy Research Working Paper No. MIT-CEEPR 98-007. 49 pages. $10.00

Other Publications

Adams, E., J. Caulfield, H. Herzog, and D. Auerbach. "Impacts of reduced pH from ocean CO_2 disposal: sensitivity of zooplankton mortality to model parameters." *Waste Management,* v. 17, no. 5/6, pp. 375–380, 1997.

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NEW AND RENEWED PROJECTS, APRIL–JUNE 1998

Topic	**Donor or Sponsor**	**Investigators *(Department)***
GIFTS AND CONTRIBUTIONS		
CEEPR membership	Cyprus Amax Coal Co.; Exxon Education Foundation; Mobil Corp.; Shell	
Gifts	Anne H. Foster Trust; Daimler-Benz AG	
NEW PROJECTS		
Transportation and Storage Markets for Natural Gas	CEEPR	A. Ellerman *(Sloan School of Management)*
The Idaho National Engineering and Environmental Laboratory (INEEL) University Research Consortium (see *e-lab*, July–September 1995)	INEEL	J. Tester *(Energy Laboratory and Chemical Engineering)* M. Kazimi *(Nuclear Engineering)* E. Drake M. Weiss *(Energy Laboratory)*
Nuclear Development Program	above	M. Kazimi *(Nuclear Engineering)*
Methane Hydrates Program	above	J. Tester *(Energy Laboratory and Chemical Engineering)*
Advanced Materials Program	above	M. Flemings *(Materials Science and Engineering)*
CO_2-Sequestration Program	above	H. Herzog *(Energy Laboratory)*

NEW AND RENEWED PROJECTS, CONTINUED

Topic	**Donor or Sponsor**	**Investigators *(Department)***
CONTINUING PROJECTS		
Research Study in Ocean Disposal of CO_2	US Department of Energy	H. Herzog *(Energy Laboratory)* E. Adams *(Civil and Environmental Engineering)*
Experimental Investigation of the Fuel Distribution in Gasoline Direct Ignition Engines	Sandia National Laboratories	S. Hochgreb *(Chemical Engineering)* John Heywood Wai Cheng *(Mechanical Engineering)*

Note: CEEPR = Center for Energy and Environmental Policy Research

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