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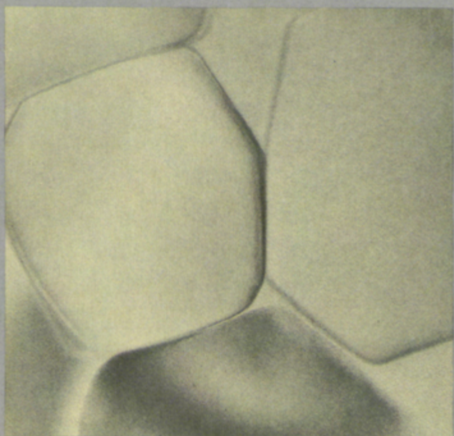

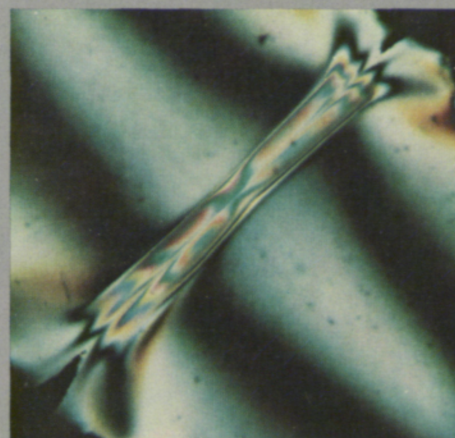

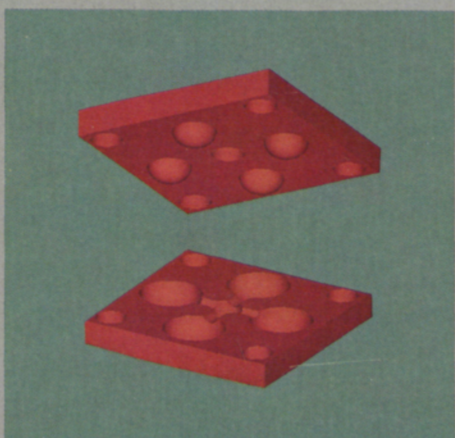

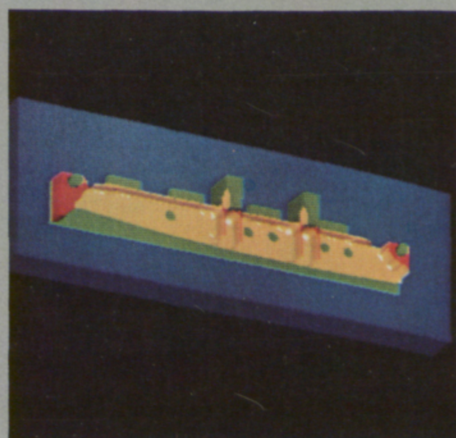

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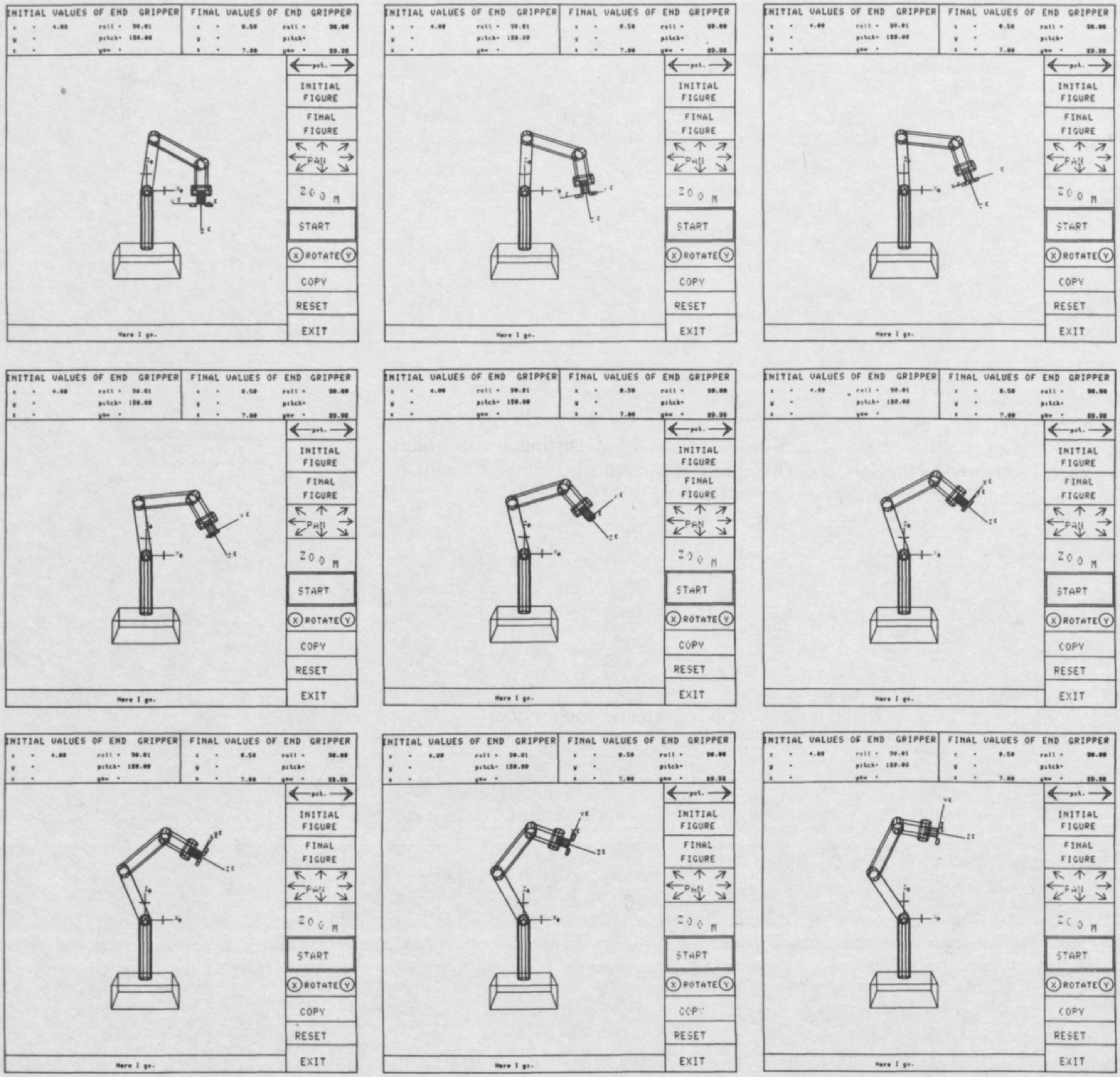
WINTER 1982–83

NEW IDEAS IN MANUFACTURING ENGINEERING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IN THIS ISSUE

CAD/CAM in Mechanical Engineering / 2
Professor K. K. Wang of the Sibley School of Mechanical and Aerospace Engineering introduces the second *Quarterly* issue on subjects relevant to the Cornell Manufacturing Engineering and Productivity Program (COMEPP). Wang is a co-director of COMEPP and heads a research program on injection molding.

Forming and Joining: Basic Processes in Manufacturing / 10
Professor Paul R. Dawson discusses an area of mechanical engineering research that is included in the new COMEPP program.

Materials: Key to Better Products / 16
A survey of research in Cornell's Department of Materials Science and Engineering reveals many projects relevant to manufacturing engineering.

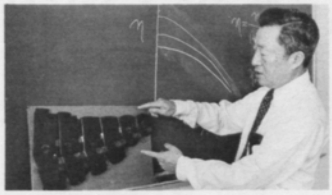
Commentary / 26
A talk by L. Jack Bradt on "The Automated Factory: Myth or Reality?", excerpted here, was presented at Cornell as the third Distinguished Alumni Lecture sponsored by the School of Operations Research and Industrial Engineering. Bradt, a 1953 graduate, is chairman of SI Handling Systems, Inc.

Vantage / 32
The College of Engineering welcomes gifts that are providing new equipment and laboratories for teaching and research.

Register / 35

Faculty Publications / 39

Announcement of an Index/ 44
A cumulative index of Volumes 1 through 16 is available upon request.



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Opposite: "Stills" taken from a dynamic computer-graphics display of the movement of an industrial robot arm (see page 8).

Outside front cover (clockwise from upper left): A transmission electron micrograph of a new glass-ceramic material with a grain size of about one micron; a birefringence pattern obtained in a photoelastic examination of an injection-molded plastic part; photoelastic examination of two plastic parts welded by ultrasonic vibration; a raster display showing a setup for machining the structural frame of an aircraft; a computer-graphics image representing a pair of plates for injection molding.

CAD/CAM IN MECHANICAL ENGINEERING

by K. K. Wang

CAD/CAM has become a buzzword in the manufacturing industry. It stands for Computer-Aided Design and Computer-Aided Manufacturing, and may also include engineering analysis, sometimes called CAE, Computer-Aided Engineering. Computers, from mainframes to micros, have become a key element in industrial enterprise. And they offer one of the greatest potential means of improving manufacturing productivity.

In Cornell's Sibley School of Mechanical and Aerospace Engineering, computers are heavily used in numerous teaching and research activities. Of particular relevance to manufacturing engineering is the innovative Cornell Injection Molding Program (CIMP), which involves a government agency, industrial members, and faculty and students in both mechanical and chemical engineering.

A FUNDAMENTAL APPROACH TO A PRACTICAL PROBLEM

CIMP deals with the practical industrial problem of how to manufacture plastic parts by injection molding, but it takes a systematic approach from a fundamental starting point.

The subject is industrially significant. Plastics are becoming more and more important as engineering materials because of particular properties and because they often show superior performance/cost ratios. New kinds of plastics and composites are continually being developed as attractive replacements for metallic or nonmetallic materials, or as unique materials, suitable for certain applications. And injection molding is an important aspect of plastics manufacture because it provides an efficient way of producing parts of intricate shape to high precision at very low cost.

Unfortunately, as with many other manufacturing processes, there has been very little basic understanding of the physics of injection molding. As a result, the design of molds and the development of manufacturing and process-control systems have been practically an art, heavily based on past experience. The main objectives of CIMP are to establish a scientific basis for the process, and to apply the CAD/CAM system concept in adapting it for industrial implementation.

The program grew out of a research project on computer-aided injection molding systems that has been funded since 1974 by the National Science Foundation. CIMP was established with the formation of an industrial consortium which shares the operating cost and serves to help disseminate the research results. The current CIMP consortium has twelve member companies and contributes about one-third of the annual funds in support of a team of six senior staff members and about seven graduate students.

CAD/CAM APPLIED TO INJECTION MOLDING

The CAD/CAM system concept, as applied to mold design, is diagrammed in Figure 1. A designer seated at a terminal that has interactive graphic capability can simulate and "test" various molds for a particular manufacturing operation. At his or her fingertips is a large number of computer programs, developed at Cornell, that can simulate mold filling and help in the design and

"Computers . . . offer one of the greatest potential means of improving manufacturing productivity."

analysis of mold components and their assemblies.

One of the most important of these computer programs is the one for simulating cavity-filling. An extensive finite-element / finite-difference program describes the filling of thin cavities of arbitrary planar geometry. The use of this program is illustrated in Figure 2, which includes (*a*) a photograph of a superimposed sequence of short shots (injections of material that do not completely fill the cavity) and (*b*) a computer simulation of the filling process for a cavity with variable thickness and a round insert. Comparison of the photographic record and the simulation shows good agreement between the experimental and the pre-

Figure 1

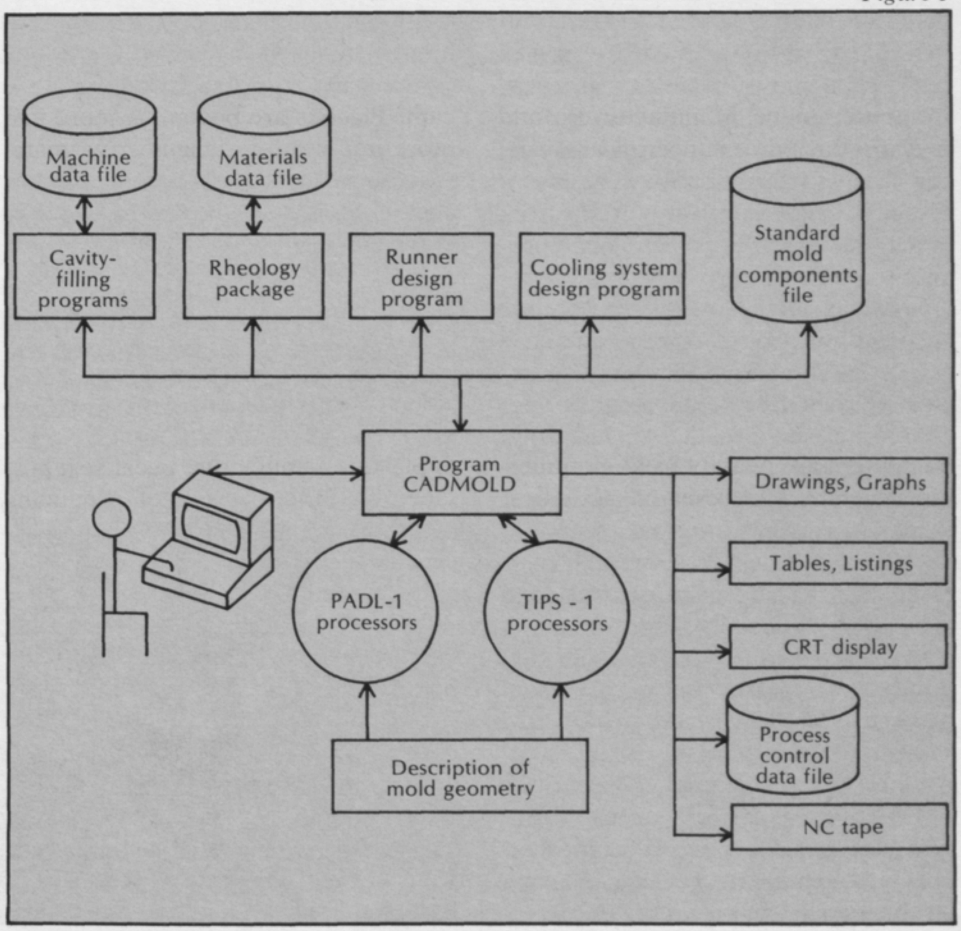


Figure 1. An interactive CAD/CAM system for injection molding, as developed at Cornell. PADL-1 and TIPS-1 are solid geometric modelers (see also Figures 9 and 10). The cathode-ray tube (CRT) display is on the screen of a computer-graphics terminal. The numerical-control (NC) tape is prepared for automatic operation of a machine in a computer-aided manufacturing (CAM) process.

■ The U.S.–Sweden Workshop on CAD/CAM for Tooling and Forging Technology was held at Cornell November 2–4 under National Science Foundation sponsorship. Initiated by a technical agreement between NSF and the Swedish government, the workshop was attended by approximately one hundred invited delegates, including ten from Sweden.

According to K. K. Wang, professor of mechanical and aerospace engineering at Cornell, who organized the workshop, Sweden is particularly known for its high mechanical technology and the United States for computer applications, notably CAD/CAM, and the purpose of the workshop was to bring together experts from both countries. Cornell was chosen as host institution because it is a center of research activity in the area of manufacturing engineering and productivity, Wang said.

Speakers at the workshop sessions included four Cornell faculty and staff members: John F. Abel, professor of civil and environmental engineering, who discussed interactive 3-D solid modeling; Donald P. Greenberg, director of the University's computer graphics programs, who spoke on that subject; Cornelius A. Hieber, senior research associate in mechanical and aerospace engineering, who discussed CAD/CAM in injection molding; and Wang, who moderated a panel on geometric modeling and CAD/CAM systems. Others were involved as coauthors of papers read. Thomas E. Everhart, dean of the College of Engineering, spoke at the concluding banquet on the general topic of manufacturing engineering and productivity.

Above: Researchers from Sweden and the United States attended the CAD/CAM workshop at Cornell.

Right: Chief host K. K. Wang (at right) welcomes Harold Gegel of the U.S. Air Force Materials Laboratory (seated at left) and Gunnar Sohlenius, group leader of the Swedish delegation.

Below: Representing NSF was William M. Spurgeon, program director in productivity research (at center). With him are Al Klosterman of the Structural Dynamics Research Corporation (at left) and John T. Berry, Georgia Institute of Technology.

Figure 2a

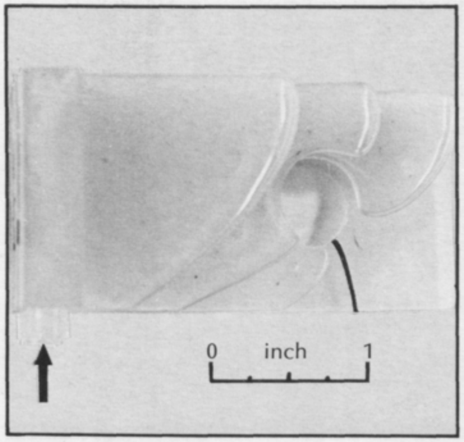
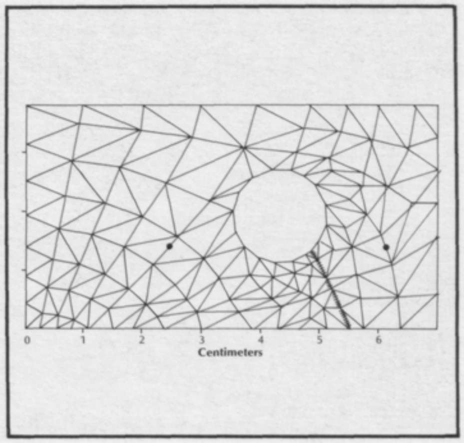


Figure 2b



dicted flow fronts, particularly in regard to the position of the *weldline*, where flowing material that has been separated by an obstacle is reunited.

Another example of mold-filling simulation is shown in Figure 3, which represents the molding of a trim panel for an automobile door. The cavity-filling program predicts the weldline position for given processing conditions, melt properties, and locations of the gates through which the material is fed. Such predictive capability is especially relevant for industrial applications in which structural integrity and appearance (as affected by the presence of a weldline) are major concerns. The computer program enables the mold designer to make rational decisions about the selection of design parameters and the specification of process conditions. Since the flow-simulation program incorporates the rheological properties of the polymeric material, the designer is able to compare the mold-filling behavior of alternative materials.

Other CAD software packages developed by CIMP staff members and students include interactive computer programs for designing runners (passageways for the injection of material), cooling lines, and systems for the automatic selection of standard mold components. Figure 4 shows a computer-graphics display of a mold assembly that was designed with the use of various CIMP programs incorporated into the overall mold-assembly design program, MOLDASM. The technique is to begin with a cavity-filling program (MOLDFIL), which defines the arrangements of cavities

Figure 2. A comparison of actual and computer-simulated filling of a cavity by injection of plastic material.

Figure 2a is a photograph showing a superimposed sequence of short shots made to fill a cavity that has variable thickness (0.32 cm at the upper boundary to 0.079 cm at the lower edge) and a circular insert. The material, which is polypropylene, is fed from a thick reservoir at the left; the arrow indicates the inlet to the reservoir. The flow-front advancement is seen to be nonuniform in plan view. The material flows around the insert and forms a weldline (the dark line) on the other side.

Figure 2b shows the advancing melt front as predicted by a hybrid finite-element/finite-difference scheme. The black lines are the underlying triangular elements, the colored lines represent the melt fronts, and the hatched line shows the position of the weldline. The dots indicate the positions of pressure transducers.

Figure 3

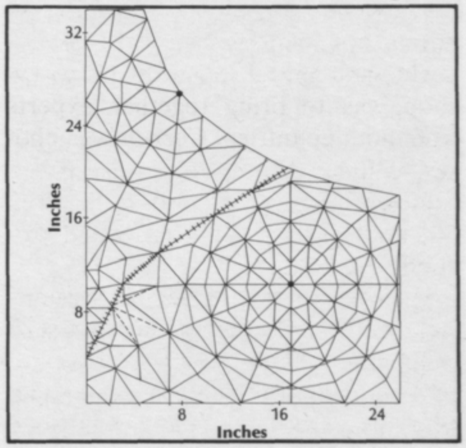


Figure 3. A computer simulation of an injection-molded plastic trim panel for an automobile door. The predicted melt fronts are shown in color and the finite-element grid in black. The material is fed through two gates (the two heavy dots). The weldline where the two flows converge is represented by the hatched line.

Figure 4

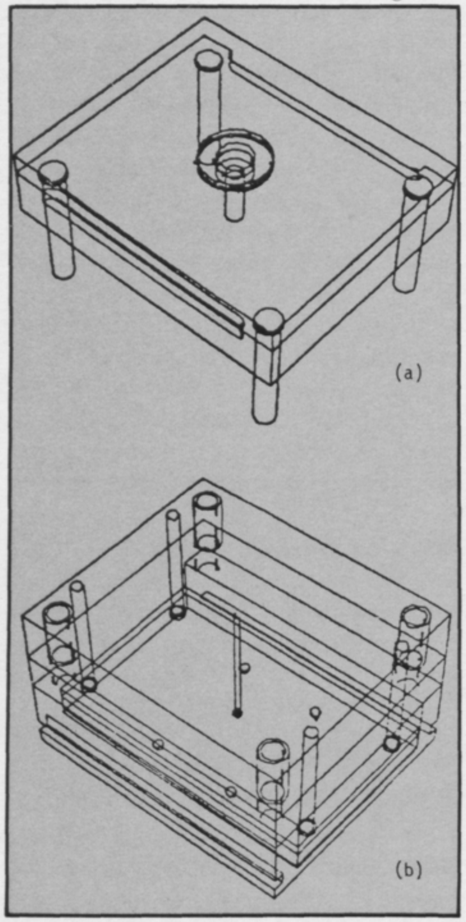


Figure 5

DME PARTS LIST

SN	COMPONENT	QUANTITY	SERIES TYPE	CATALOG NO.	DIMENSION
1	'AX' PLATE	1	X5	1223X- 5 - 37	23.500 X 11.875 X 3.875
2	'BX' PLATE	1	X5	1223X- 5 - 37	23.500 X 11.875 X 1.875
3	TOP CLAMPING PLATE	1			23.500 X 11.875 X 0.875
4	'X' PLATE	1			23.500 X 11.875 X 0.875
5	EJECTOR PLATE	1			23.500 X 8.375 X 1.125
6	EJECTOR RETAINER PLATE	1			23.500 X 8.375 X 0.500
7	EJECTOR HOUSING	1			4.500
8	LOCATING RING	1			
9	SPRUE BUSHING	1			
10	LEADER PIN	4		5207	6.250 - 1.000 DIA
11	SHOULDER BUSHING	4		5732	1.87 - 1.00 ID - 1.38 OD
12	STOP PIN	8			0.625 DIA
13	RETURN PIN	4		7610	4.938 - 0.750 DIA
14	SPRUE PULLER PIN	1		0	0.000 - 0.000 DIA
15	EJECTOR PIN			EX-45	6.000 - 0.875 DIA

PRICE $ 3166.59

Figure 4. A computer-generated graphic display of (a) the upper and (b) the lower assembly of a mold designed with the use of a program, called MOLDASM, for the selection of standard components. The display was generated via PADL-1 (Part and Assembly Description Language), one of the solid geometric modelers used by CIMP.

Figure 5. A "Part List" generated by a software program developed in Cornell research on injection molding.

and runners in the base plate, and to proceed with the cooling-line design program (COOLCH) and the mold-component-selection program (MLDSEL). The MOLDASM program can also generate a "Part List" or a "Bill of Materials" (shown in Figure 5) that includes information on costs. Other output from an integrated CAD/CAM system could include engineering drawings, engineering analysis, numerical control (NC) tapes, and alternative strategies for process control.

OTHER STUDIES RELATED TO MANUFACTURING

The research effort of CIMP is by no means limited to CAD/CAE/CAM aspects of injection molding. Experiments on the properties of polymeric fluids and molded parts are carried out, and considerable attention is paid to such fundamental problems as viscoelastic modeling.

In recent years, for example, CIMP has been conducting an extensive experimental and theoretical study of a problem we have encountered: the viscoelastic behavior of polymers. When molten material of this kind is injected rapidly into a cold-walled mold cavity, it undergoes large elastic deformation under combined shear and normal stresses. This results in "frozen-in" flow and thermal stresses in the molded part, and also introduces orientations of the molecular chains. Any nonequilibrium distribution of such stresses and orientations could cause undesirable shrinkage and warpage of the part. Frozen-in molecular orientation may be detected by photoelastic examination of the molded part (see Figure 6 and also the same image reproduced in color on the outside front cover; this image is a typical example of the isochromatic patterns of birefringence that are obtained). Figure 7 shows quantitatively the distribution of the maximum value of birefringence in terms of location in the molded part, and compares the experimental results with values predicted according to the theory developed as part of the research. Good agreement is evident in the plots.

Computer-graphics techniques are

Figure 6

Figure 6. Photoelastic examination of an injection-molded plastic part, showing "frozen-in" molecular orientation. Birefringence patterns in color are obtained with this technique; the example shown here is reproduced in color on the outside front cover. Different patterns are obtained with measurements at different locations in the molded part. This pattern was obtained near the gate of the mold; in regions farther away, less birefringence is exhibited. See also Figure 7.

Figure 7

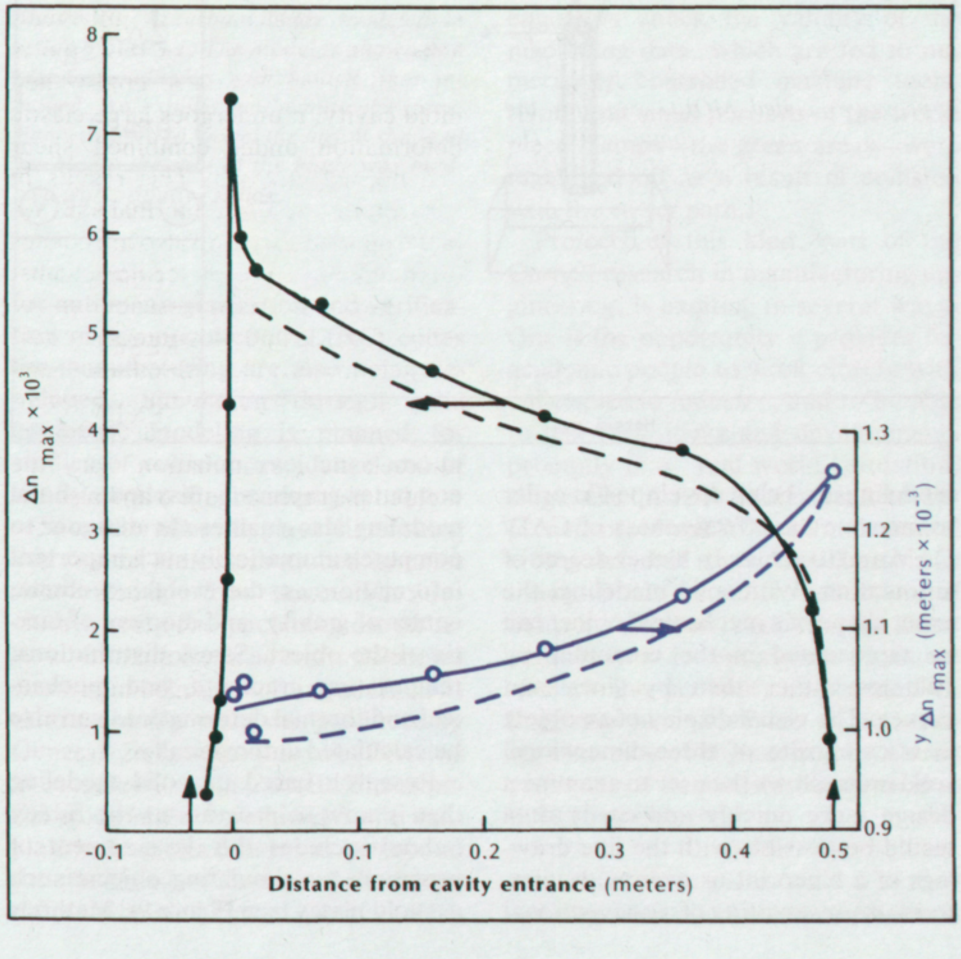


Figure 7. A typical distribution of birefringence in a plastic molded part manufactured by injection molding. Maximum birefringence, Δn_{max}, is plotted as a function of the distance from the opening of the cavity where molten material is entered. Also plotted is the position, $y_{\Delta n,max}$, of the maximum birefringence in the molded strip. The dashed lines show the corresponding theoretical values.

being used to study the dynamics of robotic motion. Figure 8 shows a display resulting from a program developed at Cornell for simulating the movements of an industrial robot arm. The program allows each link of the manipulator to either slide or rotate and the wrist to pitch, yaw, and roll. The program also provides for the computation of velocity, acceleration, force, and torque of any joint along the path of the motion. (See also the inside front cover, which shows a sequence of hard copies from the computer-graphics terminal.)

In other ongoing research in the School, techniques of solid geometric

Figure 8. The simulation of the movement of an industrial robot arm. The Cornell program used to produce this display was developed in graduate research directed by Professor Ming C. Leu. The program simulates the dynamics of the robot up to six degrees of freedom. The entire path of motion and the corresponding manipulator configuration can be displayed at speeds proportional to real time.

Figure 9. A computer-graphics display illustrating the technique of solid geometric modeling. This image, obtained at Cornell, represents a pair of core-and-cavity plates for injection molding. The photograph reproduced here was taken from the screen of a color raster station; the display as it appears in color is shown on the outside front cover.

The plates were modeled using the Technical Information Processing System (TIPS-1) solid modeler, which was originally developed at Hokkaido University in Japan and was enhanced at Cornell. The mold consists of four cavities connected by a rectangular runner system from the sprue. The four holes at the corners are for the leader pins, which provide proper alignment of the plates.

Figure 8

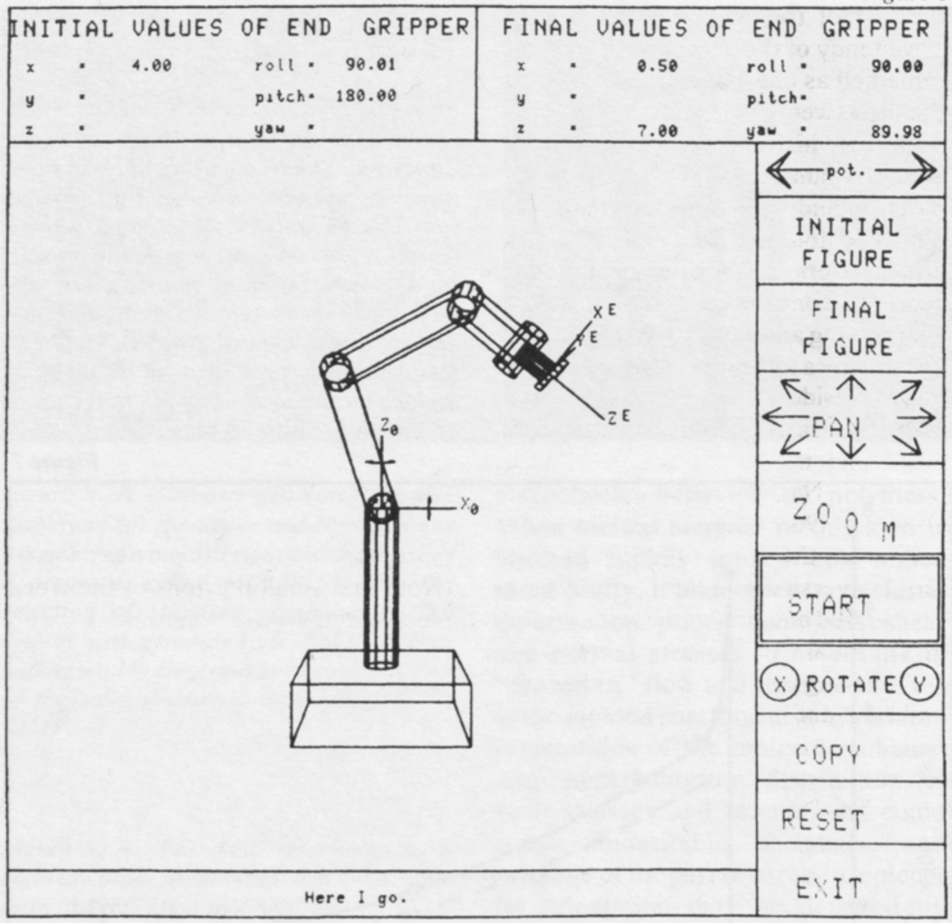
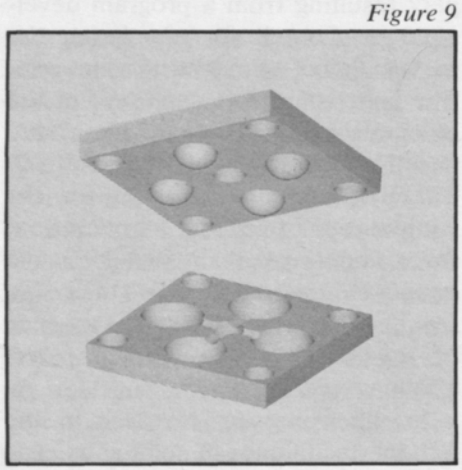


Figure 9



modeling are being developed in order to improve the effectiveness of CAD/CAM and to achieve a higher degree of automation. With solid modeling, the exact shape of a mechanical object can be represented in the computer by volumes rather than by lines and curves. The visual display of an object as a composite of three-dimensional solid units allows the user to examine a design more quickly and easily than would be possible with the line drawings of a blueprint or even with wire-frame representation of a conventional computer-graphics display. Solid modeling also enables the designer to compute automatically such important information as the weight, volume, center of gravity, and moment of inertia of the object. Stress distributions, temperature gradients, and mechanical and thermal deformations can also be calculated automatically.

Research based on solid modeling that is now in progress at the Sibley School includes the development of programs for simulating objects such as mold plates (see Figure 9). Methods

Figure 10

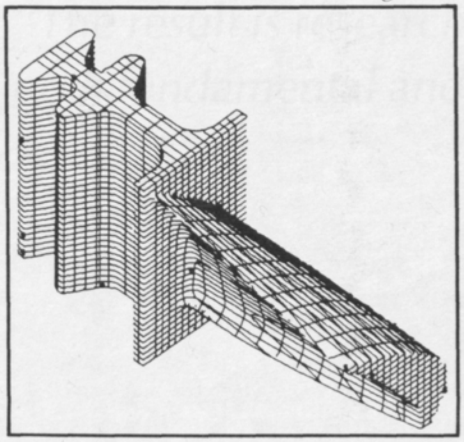
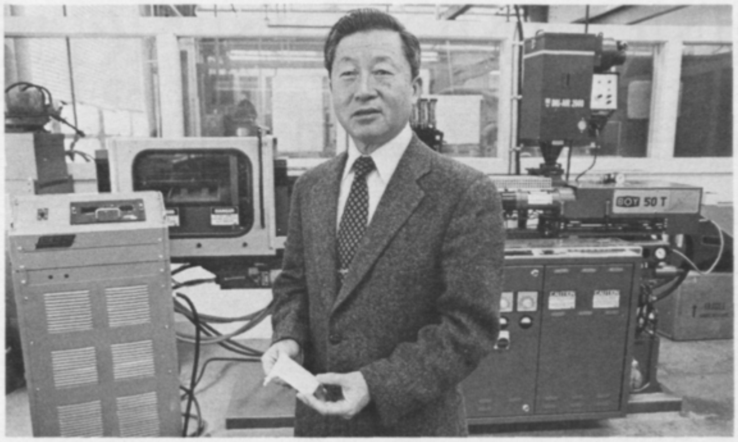


Figure 10. *A turbine blade modeled in solids by TIPS-1. The model is shown in a wire-frame display with hidden lines removed. An explicit mathematical expression was used to model the airfoil shape of the blade; the root of the blade was modeled with primitive solids.*

for automatic generation and verification of numerical-control (NC) codes for manufacturing are also being developed. Simulation through solid geometric modeling is planned for studies of collision avoidance and of the dynamics of robot arms.

Several raster displays illustrating this research are reproduced in color on the outside front cover. They include a setup for machining the structural frame of an aircraft. Modeled entirely in solids according to TIPS-1, this machining setup was produced by General Dynamics–Convair Division in cooperation with Cornell. The material stock is displayed in red, the base plate in blue, the fixtures in green, and the machined surfaces in yellow; the different colors help the manufacturing engineers check the validity of the machining data, which are fed to numerically controlled machine tools. (Note that small portions of the workpiece clamps—the green areas—were machined off as a result of collision with the cutter path.)

Projects of this kind, part of the Cornell research in manufacturing engineering, is exciting in several ways. One is the opportunity it provides for academic people to work closely with colleagues in industry, and to be able to test their ideas and developments promptly in a "real world" situation. Engineers in universities tend to approach problems from a fundamental viewpoint, but they do like to see things work. Another attraction of industry-oriented research is its direct contribution to enterprises that are vital to the economy of the nation. Programs like CIMP are demonstrating the value of engineering R&D that promotes a continuity between academia and industry.



K. K. Wang, a professor in the Sibley School of Mechanical and Aerospace Engineering at Cornell, is co-director of the new Cornell Manufacturing Engineering and Productivity Program (COMEPP). Since 1974 he has headed the project on computer-aided injection molding of plastics (CIMP) that is discussed in this article.

Wang received his undergraduate education in China and worked for shipbuilding companies in Shanghai and Taiwan before going to the University of Wisconsin for graduate work. He earned the M.S. degree in 1962, worked for four years as a project engineer in process development at the Walker Manufacturing Company in Racine, and completed his Ph.D. in 1968. He joined the Cornell faculty in 1970 after two years of teaching at Wisconsin. In all, Wang has had over seventeen years of broad industrial experience. He has also been a consultant to industrial organizations, including IBM, General Electric, and TRW.

Wang has received the Blackall Machine Tool and Gage Award from the American Society of Mechanical Engineers, and in 1976 he was one of four international recipients of the Adams Memorial Membership Award of the American Welding Society. He was awarded the first TRW Fellowship in manufacturing engineering in 1977.

FORMING AND JOINING
Basic Processes in Manufacturing

by Paul R. Dawson

Central to any strategy for making better products at lower cost are improvements in the actual manufacturing processes. Research on welding, for example, is part of Cornell's new program on manufacturing engineering, which has the overall aim of increasing industrial productivity.

Welding is a simple term covering a range of sophisticated techniques used to join and form materials and parts. Projects we are currently conducting in the Sibley School of Mechanical and Aerospace Engineering, for instance, include studies of ultrasonic joining of plastic parts, solid-state welding of metals, continuous casting of metal alloys, and hot and warm primary metal-forming operations.

Our approach is to develop a better understanding of a wide spectrum of processes by investigating the basic thermal, mechanical, and material response induced by particular operations. Because manufacturing processes usually affect the structure of a material, and therefore its thermal and mechanical behavior, our research begins with an identification of the interrelated physical processes important to a particular operation. Then we construct a mathematical model that is based on principles of mechanics and on observations of the material's behavior. Such a model, used in conjunction with information known about the evolution of the microstructure of materials, allows the outcome of a forming or joining process to be understood in terms of both the outward shape of a body and its inner structure. The equations that describe the system are complex and highly nonlinear, frequently requiring computer-aided solution, and therefore our work also includes the development of solution algorithms. In addition, we perform process-oriented experiments that provide a basis for assessing the adequacy and accuracy of the mathematical models.

The result is research that is both fundamental and practical, a combination that is suggested by the list of sponsors: Alcoa Foundation, Bethlehem Steel Corporation, Eastman Kodak Company, and the National Science Foundation.

FORMULATING AND SOLVING MATHEMATICAL MODELS

The mathematical model consists of a system of equations depicting how a material deforms and heats. The basis is a set of general equations derived from the *conservation principles* of mechanics; and because these are not sufficient to determine the stresses, deformations, and temperatures throughout a body, they are augmented by a set of *constitutive equations* derived from observations of a particular material. The conservation principles embody conservation of mass, of linear and angular momentum, and of energy (the first law of thermodynamics). The constitutive equations might tell how the body deforms under a particular stress, or how it transmits heat when there is a particular temperature gradient. They are the part of the model that distinguishes a material—whether it is steel, aluminum, polystyrene, or mud—from any other material. While these constitutive equations are essentially empirical, their form is often motivated by principles of the microstructural

"The result is research that is both fundamental and practical."

movements of crystalline or noncrystalline materials, and is restricted by the second law of thermodynamics.

A particularly difficult problem in engineering is to arrive at constitutive equations that faithfully express material response over a wide regime of environmental conditions (such as stress, temperature, and motion). Since the purpose of most forming and joining processes is to alter the geometry of a part significantly, the linear constitutive models usually used in the design of a part for its anticipated service are inadequate. Rather, the equations must be valid for large strains over a wide range of temperatures and rates of deformation. While such deformations can all be regarded as including inelastic behavior, the particular form of the equations varies radically because at different levels of stress and temperature, materials deform by different microstructural mechanisms. Thus, a critical aspect of modeling manufacturing processes is the selection of constitutive equations that are appropriate to the forming environment.

HELP FROM COMPUTERS IN SOLVING THE EQUATIONS

The complexity of the mathematical descriptions of manufacturing operations have led engineers to seek approximate solutions using computers. Finite-difference, finite-element, and boundary-integral methods have all been fruitful for analyzing systems described by a set of partial differential equations. The finite-element method, known for its generality and flexibility, is the principal tool in much of the manufacturing research at Cornell.

In the finite-element method, the form of the solution (usually a polynomial) is assumed over a small portion, called an element, of the entire domain. The domain is viewed as a collection of elements, for each of which the form—but not the magnitude—of the solution is known. The conservation equations provide the framework for piecing the elements together; usually, the summed elemental quantities have physical meaning, such as the potential energy or the rate of work. By means of variational calculus, a minimum or stationary value is sought, and this yields the equations required to specify the magnitude of the assumed solutions.

The system of governing equations and the technique for solving them provide the ability to simulate manufacturing operations. They constitute an important tool for studying process variations, and thereby improving operations and products and reducing manufacturing costs.

ULTRASONIC WELDING: AN APPLICATION

One of the specific processes we are studying is the joining of two thermoplastic parts by subjecting the contact area to vibration at ultrasonic frequency (see Figure 1). Since polymers are viscoelastic, they dissipate—usually in the form of heat—the energy associated with the viscous component of the motion, and the heating makes the polymer chains relatively mobile and able to tangle together to form a weld. Joining parts by this method is important commercially—it is used in the manufacture of products such as film cartridges and tool cases.

Figure 1

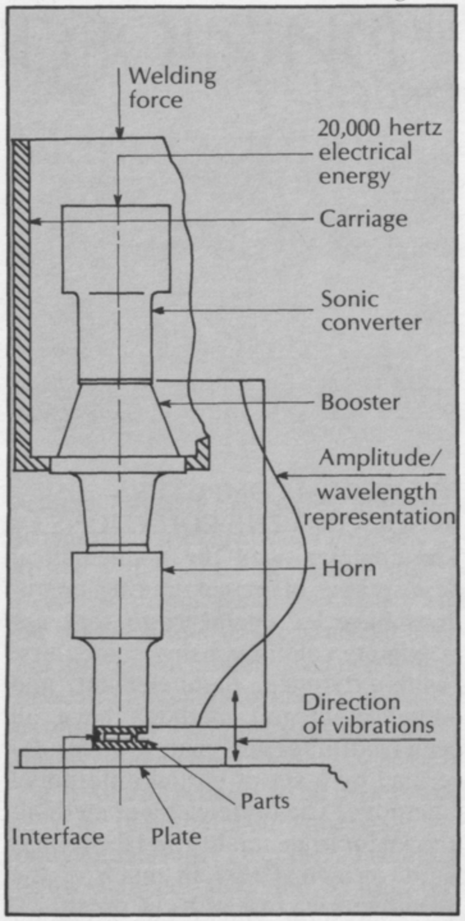


Figure 1. Ultrasonic joining of plastic parts. The thermoplastic polymer parts are subjected to ultrasonic vibration that is produced by conversion of a high-frequency electrical signal to mechanical vibrations and transmitted by the horn. The polymer is viscoelastic and dissipates the energy in the form of heat, which effects the weld.

Figure 2. A history of the heating that occurs in ultrasonic joining of plastic parts.

The temperature rise, caused by strains in the material, is most rapid at the interface (T_{if}), but the process is temperature-limiting at all the depths where measurements were taken ($T_{0.94}$ and $T_{1.91}$ refer to temperatures measured 0.94 and 1.91 millimeters from the interface).

The curve for power represents the wattage needed to drive the converter (see Figure 1). The curve falls off at the end of the test, with cessation of vibration.

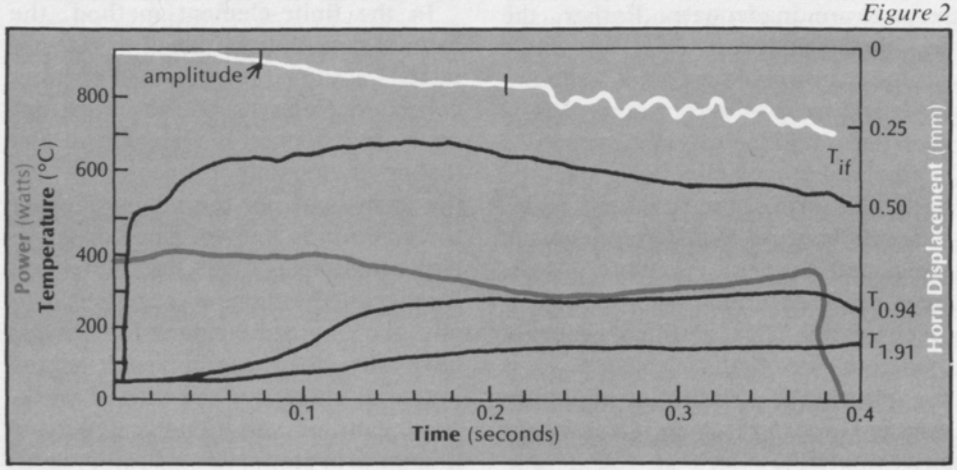
The curve for horn displacement represents the net displacement that results from the squeezing out of material at the interface. (The "wobble" at the end occurs in only a limited number of tests and is not yet explained; it appears to be caused by a coupling between the plastic parts and the machine.)

The parts are vibrated under constant amplitude; the welding force varies. In the particular test represented here, the static load was 15 psi, the duration of oscillation was 0.4 second, and the amplitude of vibration was 0.076 mm.

In our research we have studied the evolution of the heating and correlated it with bond quality. Heating is proportional to the amplitude of strain; the body heats most rapidly in the regions of largest strain. With proper joint design, these regions occur near the bond interface. When the parts are vibrated at ultrasonic frequency, microasperities on the contacting surfaces become very highly strained and cause localized heating at the interface—a desirable effect, since it is the material at the interface that must be heated.

Experiments performed at Cornell show the history of heating quite clearly (see Figure 2). The interface temperature rises rapidly until the material flows, eliminating surface asperities. Farther from the interface, the heating is less rapid. Finite-element computations indicate that in these interior regions, the heat is caused mainly by local strains, and that conduction is not an important mechanism in the early part of the weld sequence. Thus, although energy is dissipated principally near the interface, heating occurs throughout the

Figure 2



body. From the temperature histories, it is also evident that the process is temperature-limiting: the material properties are temperature-sensitive, and as the temperature rises, less heat is generated by strains of constant magnitude.

Photoelastic examination of the interface shows the residual effect of joining two parts. Examples of such images are shown in Figure 3 and—in color—on the outside cover. The colored bands are proportional to the residual stresses; a high density of lines corresponds to a high gradient of stress. The welding process leaves a zone that may be highly stressed or, if the heated material is squeezed from between the parts, may leave the polymer chains aligned rather than tangled.

The experimental and modeling results we have obtained so far have helped us identify how and where heating evolves during the welding process. Indications are that the best bonds result when the polymer is heated sufficiently to give the chains the mobility and time they need to tangle together, but when the softened polymer is not forced out of the weld zone.

Figure 3

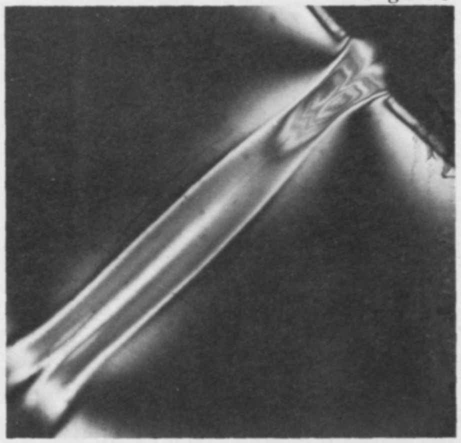


Figure 3. Photoelastic examination of the interface of two plastic parts that were welded by ultrasonic vibration. The actual length of the weld zone is about 0.7 cm.

This photoelastic examination technique is based on changes in optical properties that are exhibited by certain transparent materials when they are subjected to stress. Isochromatic birefringence patterns are obtained. The density of the bands, which appear in various colors, corresponds to the gradient of stress. (For a color reproduction of a similar image, see the illustration on the outside cover.)

UPSET WELDING FOR JOINING METALS

Solid-state welds can be created in metals without the melting that occurs in fusion welding, and with fewer of the detrimental effects caused by microstructural changes that occur during resolidification.

Upset welding is achieved under solid-state conditions of elevated temperature and high stress. A clamping device is applied to the body and an electrical current is passed through the parts (see Figures 4 and 5). The joint design focuses heating at the part interface by causing the highest current densities to occur there. The metal heats rapidly, and under the clamping force, deforms to increase the contact area. A continuous microstructure develops between the previously separate pieces.

Laboratory experiments and numerical modeling of upset are being performed at Cornell. Figure 6 shows a

"Solid-state welds can be created in metals without the melting that occurs in fusion welding . . ."

Figure 4

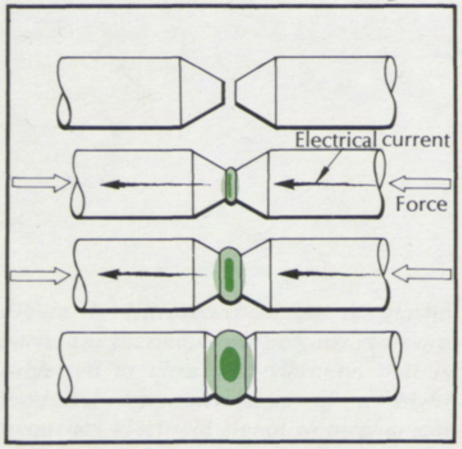


Figure 5

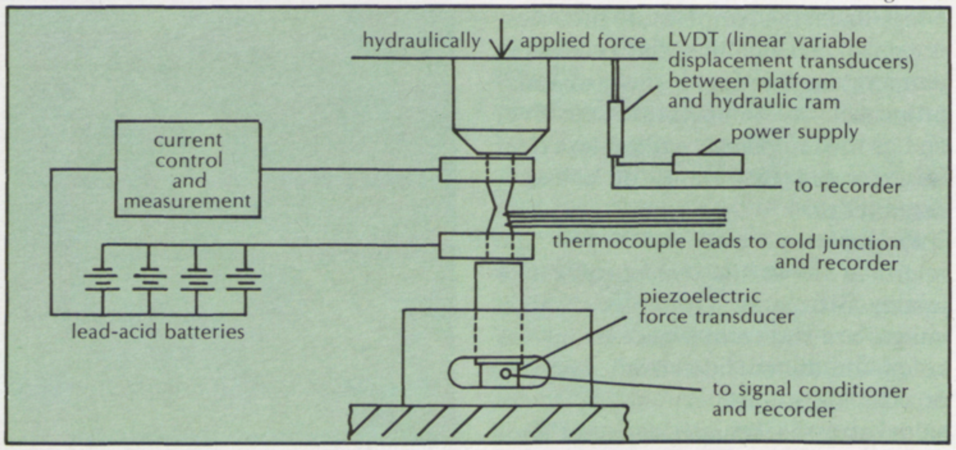


Figure 6

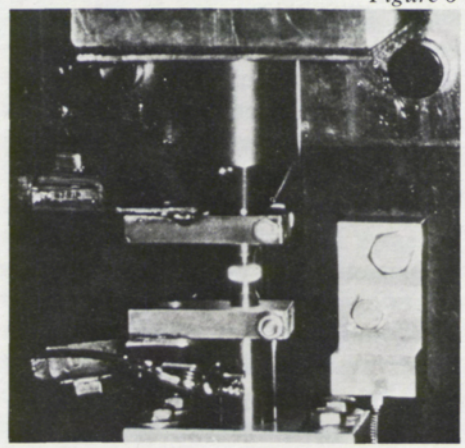


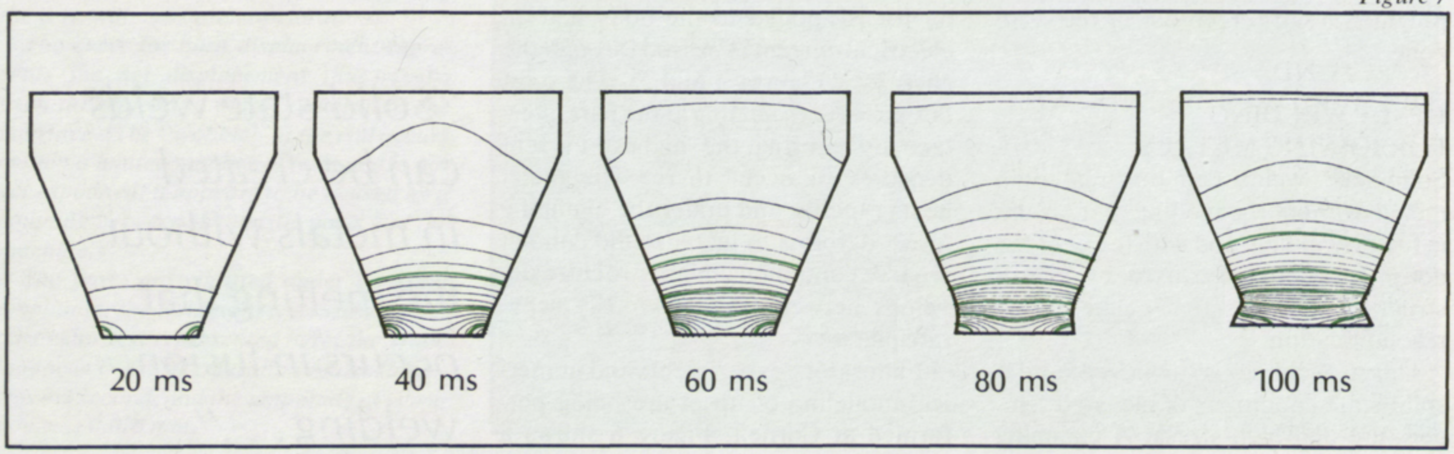
Figure 4. The process of upset welding. The two metal parts to be joined are clamped together and an electric current passed through them. Rapid heating is accompanied by deformation.

Figure 5. A schematic representation of the upset welding apparatus.

Figure 6. An actual photograph of the welding operation. The joined parts are visible as the bright region at center; the bulging is caused by deformation of the material in the contact area. When an elevated temperature has been reached, this material in the bulging zone is yellow.

Figure 7. Temperature distributions predicted by finite-element analysis for sequences in an upset welding process. The drawings correspond to conditions in the metal parts at intervals of 20 milliseconds after initiation of the process. The isotherms are 40°K apart; those shown in color for greater ease of identification are 200°K apart. The upper-surface temperature is 300°K. Note the deformation that occurs as the welding proceeds.

Figure 7

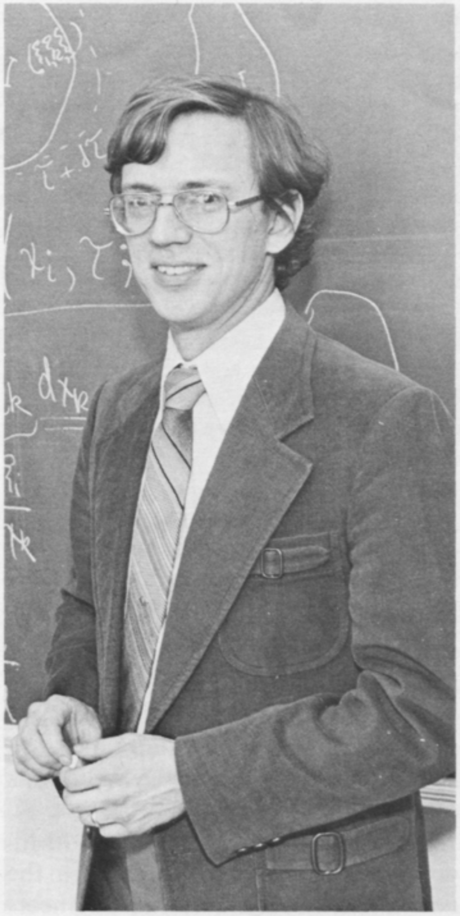


pair of tapereed rods being welded; bulging of the hot rods is evident.

A series of temperature distributions for a similar weld sequence is shown in Figure 7. These distributions, which were predicted by a finite-element solution of a coupled thermoviscoplastic model, show the nonuniform nature of the heating: the highest temperatures occur at the outside radius of the contact zone. Bulging indicated by changes in the outside dimensions is evident here also. Detailed thermomechanical histories will eventually assist in optimizing the weld cycles.

FROM FUNDAMENTALS TO IMPROVED MANUFACTURING

A crucial part of computer-aided manufacturing is the ability to faithfully represent the process behavior with simulation tools. Because manufacturing processes frequently are complex, involving coupled changes in mechanical, thermal, and microstructural states, good simulation depends on a fundamental understanding of all those changes and how they are interrelated.



The research described here is directed at building such a fundamental understanding, and on that basis, developing useful simulation tools. With such tools, engineers can predict the thermal and mechanical response of materials during manufacture in sufficient depth to understand why the product has its derived properties. And with that ability, manufacturers have a rational and effective way of designing better products.

Paul R. Dawson became an assistant professor in the Sibley School of Mechanical and Aerospace Engineering at Cornell in 1979 after three years with the applied mechanics group at Sandia Laboratories in Albuquerque, New Mexico, and a year with the Westinghouse Advanced Reactor Division in Pennsylvania.

He received the B.S. degree in mechanical engineering from Montana State University in 1972 and studied at Colorado State University for the M.S. and Ph.D. degrees in civil engineering, which were granted in 1974 and 1976.

Dawson serves as faculty adviser to several student groups in engineering: the Cornell section of ASME and the local chapter of the honorary society Tau Beta Pi. He is a member of Sigma Xi, Phi Kappa Phi, Tau Beta Pi, and Pi Tau Sigma.

MATERIALS:
KEY TO BETTER PRODUCTS

Without the development of new semiconductor materials and ingenious ways of fabricating them, computers with the capability of today's desk-top models would still be filling large rooms. Without new alloys, ceramics, and plastics, hundreds of industrial and consumer products would not be on the market today.

A look into the future reveals a similar dependence: technologies still in stages of conception or development are contingent on new materials. Large-scale solar energy conversion, for example, will not be commercially feasible until better solar cells, presumably incorporating new and cheaper materials, are developed. Electronic components for the next generation of devices will require new ways of forming and modifying the materials. Correspondingly, new materials will make possible the manufacture of better products. For example, ceramic pistons and ball bearings will enable diesel engines to operate at higher temperatures—thereby increasing fuel efficiency—without the need for water-cooling or lubricating oil; such an engine is now being designed and commercial development is expected by the end of the decade.

The fact is that a basic element of successful industrial manufacturing enterprise, along with innovative design and efficient production, is the material from which products are made. Conversely, the limitations of materials can determine the limitations of products.

The central role of materials in industrial development is reflected in the new Cornell Manufacturing Engineering and Productivity Program. Faculty members who are involved in the program include researchers in the Department of Materials Science and Engineering (MS&E), whose work covers practically the whole range of industrial materials—metals, composites, semiconductors, ceramics, polymers. The substances under study are in forms that vary from thin films less than one micrometer thick to bulk materials, such as steel, for the largest structures. Not only the properties of new materials, but techniques for fab-

TOPICS OF INDUSTRIAL INTEREST

Addressed in Current Research on Materials

- VLSI (very large scale integrated circuits)
- Corrosion-resistant surfaces
- Wear-resistant surfaces
- Catalysts
- Catalytic poisoning
- Hydrogen embrittlement of steel in synthetic-fuel plants
- Radiation damage in nuclear-reactor materials and space vehicles
- Original procedures for computerizing industrial metal-forming processes
- New ways of forming ceramic parts
- New kinds of materials called glassy metals
- New and cheaper materials for solar cells
- Relation between polymer microstructure and toughness
- New ultrastrength polymers

Figure 1

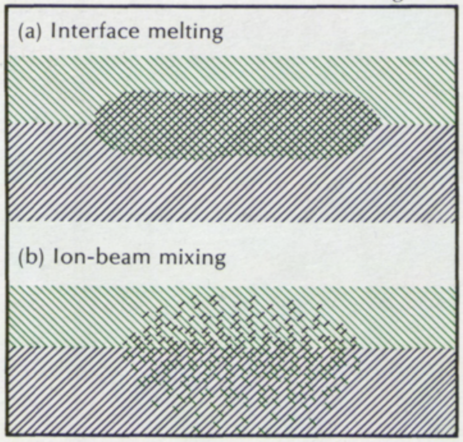


Figure 1. Near-surface modifications that can be made with ion beams according to techniques developed by Professor Mayer and his group.

In the process illustrated in (a), a thin metal film is deposited on a substrate such as silicon or germanium and a high-intensity pulsed ion beam heats the sample, causing melting at the interface. The technique provides a way of creating surface alloys or of forming metal-semiconductor layers such as silicides for use in integrated circuits.

In the process illustrated in (b), ion bombardment causes a mixing of the metal film and the substrate. (See also Figure 2.)

Figure 2

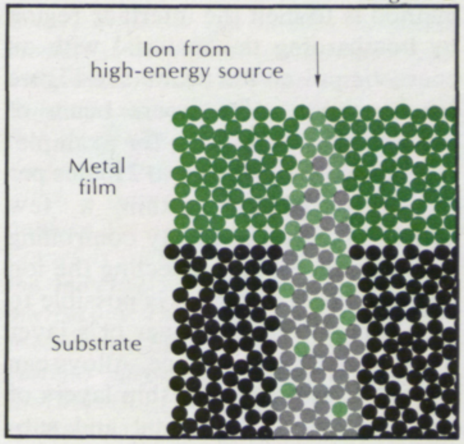


Figure 2. How an energetic ion causes mixing in an interface region between a substrate and a thin metal film deposited on the surface. Sufficient energy is delivered in the collision cascade around the ion track to allow the transport of ion species within the cascade volume (shaded area). Because of the rapid dissipation of heat from the cascade, the process is akin to ultrafast quenching. The effect produced by the action of many ions is the formation of an interface zone across the sample.

ricating them are being investigated. The research may be directed to the solution of a particular industrial problem, or it may be highly theoretical, providing a basis for understanding why and how a material behaves as it does and how it could be altered for better performance.

This diversity is demonstrated in the sampling, given here, of Cornell research in materials with industrial potential. The table summarizes some of the products, processes, and problems to which ongoing Cornell MS&E projects are related.

MACROSCOPIC EFFECTS OF MICROSTRUCTURE

The relation of the properties of materials to their microstructure is an area of MS&E research that is of great technological interest.

Surface characteristics have a special significance, for they determine many of the properties of materials that are important industrially. An outstanding example is the semiconductor electronics industry, which depends on the implantation of energetic ions to control the surface characteristics of silicon semiconductors for integrated-circuit devices. In other technologies, chemical properties such as oxidation and corrosion and mechanical properties such as adhesion and wear are important aspects of product manufacture and these, too, are controlled by surface characteristics.

Mayer

The outermost layers of metals and semiconductors, to depths of a micron or less, are the focus of research headed by James W. Mayer. For example, he is developing ways of modifying the composition and structure of the outer micron and therefore the properties of materials by subjecting them to beams of energetic ions that are controlled so as to act on near-surface regions. Essentially, this research is extending the capabilities of ion-beam techniques used in integrated-circuit technology.

Although related to current ion-beam technology, Mayer's research uses an unconventional approach: a substrate on which one or more thin layers of metal have been deposited is subjected to ion bombardment. One method is to melt the interface region by bombarding the material with an energetic pulsed ion beam (see Figure 1*a*). A pulsed 100-ampere beam of 200-keV hydrogen ions, for example, can deliver energy of up to 2 joules per square centimeter within a few hundred nanoseconds. By controlling the beam power and selecting the ion species appropriately, it is possible to melt just an interface layer or a layer that extends to the surface. Alloys can be formed from several thin layers of deposited metal, or metal and substrate can be melted together to form substances such as silicides, or amorphous layers of silicon or germanium can be melted and recrystallized. Another method is to use a conventional ion-implantation system to intermix the surface metal film and the substrate without melting (see Figures 1*b* and 2). This technique, like the one that causes melting, leads to the formation of interfacial layers and surface alloys.

Surface structure is being studied also by Jack M. Blakely in projects that have relevance to catalytic processes.

Blakely

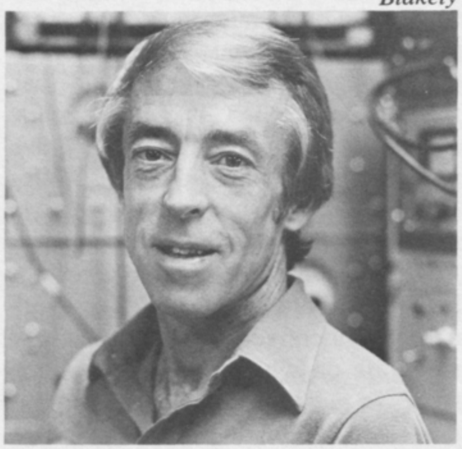


Figure 3

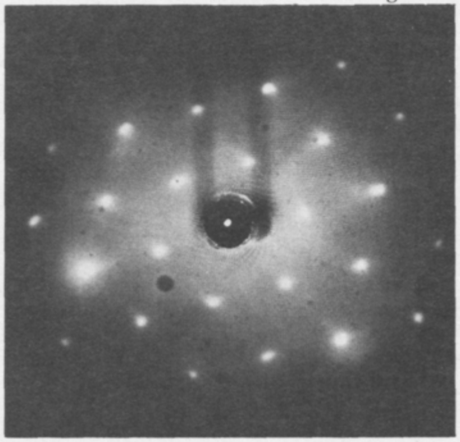


Figure 3. An electron diffraction pattern obtained in Professor Blakely's research on surface structure as related to catalytic processes. The image shows an ordered overlayer of sulfur on a nickel crystal surface. The surface covering is equivalent to one-quarter of an atomic layer of sulfur.

His research group is interested in questions such as why minute amounts of impurities poison transition-metal catalysts, and what reactions occur at the surface of a nickel catalyst when it comes in contact with hydrocarbons (see Figure 3). Although this research is still fundamental in nature, it has potential significance in industrial applications, including automobile manufacture. The work involves sophisticated techniques such as electron diffraction and electron spectroscopy, and many of the experiments are conducted under ultrahigh vacuum and controlled atmospheric conditions.

Research projects directed by Herbert H. Johnson and David N. Seidman are pertinent to the understanding of problems in metals caused by hydrogen attack or irradiation.

Seidman

Johnson is concerned with behavior such as fracture, cracking, and corrosion that is exhibited by steels and other metals, particularly as these phenomena are related to microstructure and as they are affected by processing methods. This research has significance in the design of synthetic fuel plants, for example, or to the development of pipe casings for oil wells from geopressure domes.

Seidman is interested in atomic mechanisms for processes that occur in the solid state on the nanometer to subnanometer scale (see Figures 4 and 5). For example, he and his student, Roman Herschitz, used atom-probe field-ion microscope techniques to study the precipitation of new phases in tungsten (rhenium) alloys as a result of high-temperature neutron irradiation in the Experimental Breeder Reactor II. They were able to distinguish between precipitates that were homogeneously nucleated and those that were heterogeneously nucleated, by determining the chemistry of the precipitates on a scale of less than 10 nanometers. The atom-probe field-ion

Figure 4

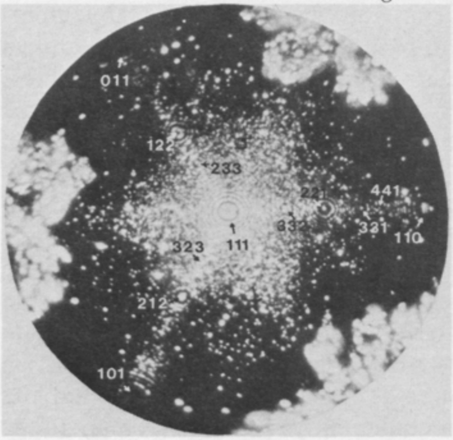
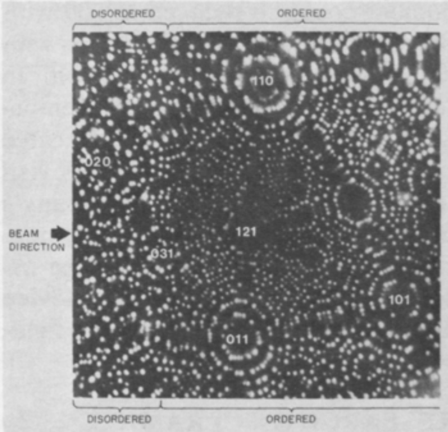


Figure 5



Figures 4 and 5. Micrographs obtained in Professor Seidman's laboratory by the atom-probe field-ion microscope technique. These images represent state-of-the-art microscopy applied to investigations of atomic mechanisms on the nanometer to subnanometer scale.

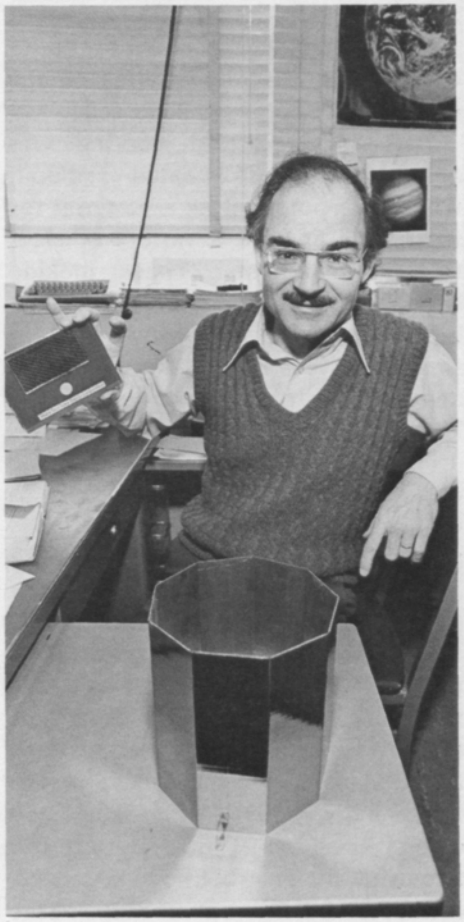
Figure 4 shows an image of silicon surrounded by the remainders of native SiO_2. To get a good specimen, whiskers of silicon were grown by a vapor-liquid-solid (VLS) technique. Ordinarily, native SiO_2 forms relatively quickly over the surface of silicon, forming a protective skin. The numbers superimposed on the micrograph are Miller indices, indicating crystallographic planes. The researchers were J. Charles Barbour and Barbara Moser White.

Figure 5 is a micrograph showing the effect of radiation on the crystalline structure of the intermetallic compound Ni_4Mo. The order-disorder transformation evident in the region on the left was caused by exposure to a 1-keV beam of singly charged neon ions. This image was obtained in doctoral research conducted by Jacob Aidelberg in Seidman's laboratory. The experiment was performed to test theoretical predictions of the damage produced by a single energetic ion.

microscope is being used also to study the chemistry and microstructure of interfacial reactions between metal and silicon that form metal silicides. The silicides are formed by *in situ* thermal treatments or irradiations. The chemical information on a nanometer scale that is obtained is essential for understanding the nature of ohmic contacts and Schottky barriers, and is therefore of interest in integrated-circuit technology.

The interfaces between microstructural elements, such as grain boundaries, are being studied in metals, ceramics, and semiconductors by Dieter Ast, Clive B. Carter, Stephen L. Sass, and David L. Kohlstedt, as part of their overall research programs. Ast's research, for example, includes a large program on grain boundaries in silicon that is supported by the Department of Energy, the Jet Propulsion Laboratory of the California Institute of Technology, and Mobil Solar Energy Laboratories. The work is of technological interest because many of the techniques used to grow inexpensive silicon substrates for solar

Below: Professor Ast exhibits an experimental single-crystal silicon solar cell made by Mobil Solar Energy Laboratories from silicon grown directly in the form of thin sheets. The nine-sided hollow tube in the foreground is a sample of the material, which is cut with lasers and processed to produce the solar cells. Ast's group at Cornell is studying the defect structure of the material with transmission electron microscopy. The defects are characterized in correlated EBIC (electron beam induced current) microscopic studies, conducted with a specially modified scanning electron microscope.



cells generate large-grain material. Ast's group is investigating the influence of the grain boundaries on the electrical properties of solar cells.

Ast's group is also working with amorphous hydrogenated silicon, which has potential as a material for solar cells and for a variety of electronic components. These include large (TV-sized) versions of the liquid-crystal displays now used in smaller devices such as wristwatches, and optical storage disks suitable for laser writing. In Japan, amorphous hydrogenated silicon is already being used commercially; a large factory to produce solar cells of this kind has been built, and another firm markets a xerox-type copier that contains a drum based on the new material.

A difficulty with the use of amorphous hydrogenated silicon for large liquid-crystal displays has been that the size is limited by the necessity to address each element (pixel) in the image individually. For a 350 X 350 display comparable in resolution to a television image, about 120,000 interconnects would be needed. This number could be reduced to 700 with the use of an x-y matrix fabricated with amorphous hydrogenated silicon. In fact, an experimental display demonstrating this possibility was fabricated by Ast during a recent eight-week visit to the Hewlett-Packard Company's Solid State Laboratory. A highly nonlinear element would have to be associated with each pixel; such a device might be a threshold switch or a field-effect transistor.

RESEARCH ON CERAMICS, PLASTICS, AND GLASSES

New uses for structural materials that are strong at both ambient and high temperatures and also resistant to wear and corrosion are causing an increasing interest in ceramics. Silicon nitride, silicon carbide, and materials based on partially stabilized zirconia, for example, are candidate substances for such items as blades for the hot sections of gas-turbine engines, parts for diesel engines, cutting tools, extrusion dies, and ball bearings. Fundamental research of Rishi Raj and his Cornell group is providing insight into new processes for fabricating such ceramic parts. They are studying characteristics such as flow, fracture, and powder compaction under conditions suitable for processing.

One of the techniques they are investigating—a high-temperature, isothermal forging process for shaping parts—is completely new to ceramics manufacturing, although a similar procedure is used in the aerospace industry to form parts from titanium and nickel-based superalloys. Such materials, because of their high intrinsic strength, cannot be forged at room temperature; and even at high temperature they can be worked only within a narrow range of processing variables. Within this narrow range, the materials become *superplastic*—that is, they can be deformed considerably without developing cracks or other flaws. The Cornell researchers are seeking ways of engineering ceramic material on the atomic scale so that it will be amenable to superplastic forming (see Figure 6).

Also conducting research in this area is Dieter Ast, who is studying metallic alloys (such as combinations of iron and boron, palladium and silicon, and copper and zirconium) that form glassy solids when they are cooled rapidly enough from the liquid state. These glasses have attractive technological properties such as high tensile strength, high corrosion resistance, and very soft magnetic behavior. Ast and his research group are investigating methods of influencing the properties of these materials. For example, they have developed novel techniques for adding very small (micron and submicron) crystalline particles to the liquid just before it freezes (see Figure 8); the presence of such particles greatly changes the magnetic properties and improves the mechanical properties of the alloys. A further possibility is the preparation of a ductile superconductor by incorporating a normally brittle superconductor into the alloy as the second phase.

IMPROVING THE PROPERTIES OF PLASTIC MATERIALS

Although polymers have many attractions for the manufacture of parts—generally they are good insulators and show resistance to corrosion, and

Figure 6a

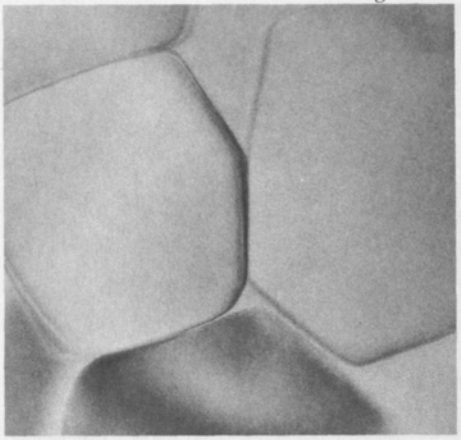


Figure 6. Making ceramic materials superplastic at high temperatures. These illustrations are from research directed by Professor Raj on model glass-ceramic materials that are microstructurally identical to silicon nitride. The new materials are potentially useful for forged machine parts that will be exposed to high temperature. In the forging process, the key to obtaining the desired large deformation without cracking is to maintain an ultrafine grain size (about 1-5 microns) and to accelerate the diffusive transport processes so as to achieve fast strain rates at reasonably low flow stresses. Optimal conditions have been obtained in Raj's laboratory. Figure 6a *is a transmission electron micrograph showing a grain size of about 1 micron.* b *shows a triple grain boundary in higher magnification. The glass phase, which promotes the desired deformation, is the light central zone. The fringed area below is the crystal lattice.* c *shows an undeformed and a deformed specimen.*

Figure 7. Stress-strain curves obtained in the research on ceramics. The material becomes superplastic as the temperature is increased. The strain rate in these experiments was 1.4×10^{-4} per second.

Figure 6b

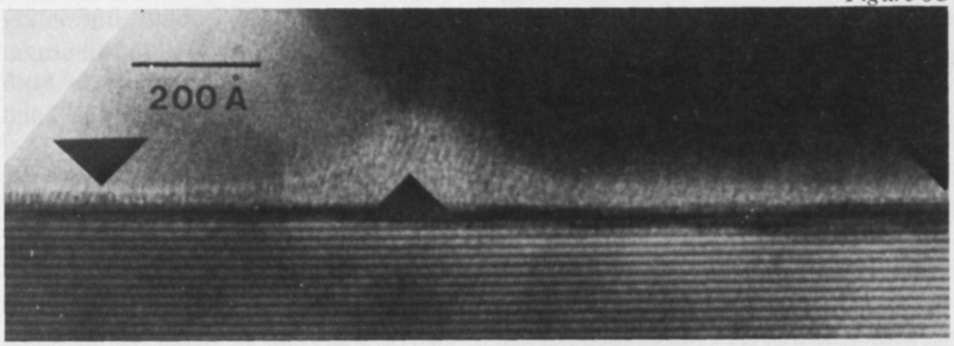


Figure 7

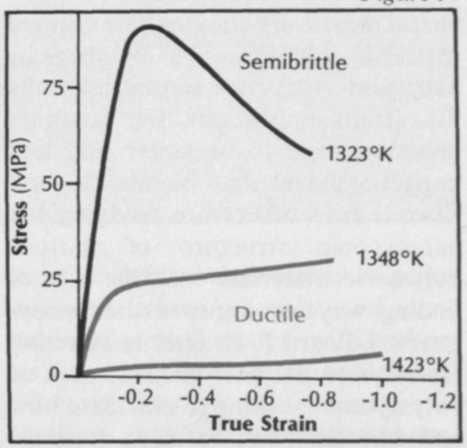
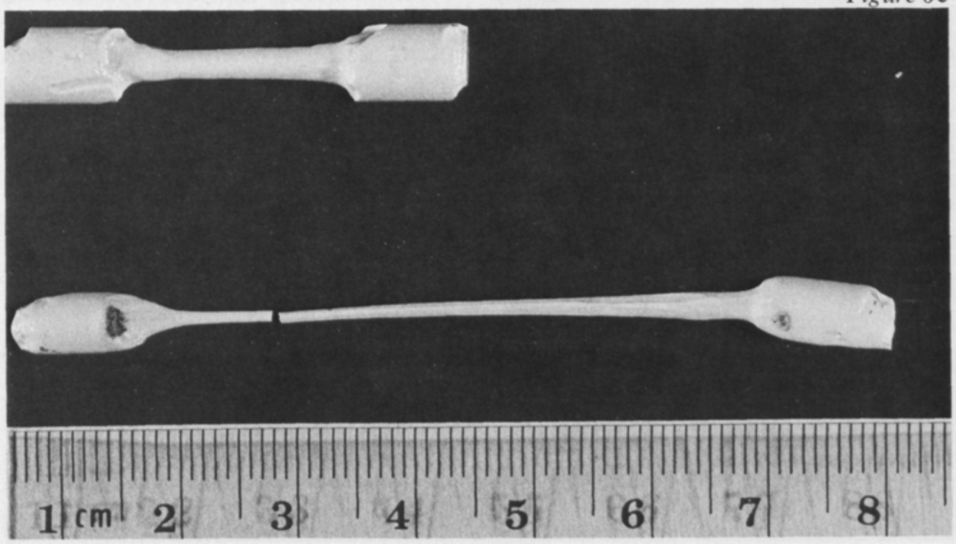


Figure 6c



Raj

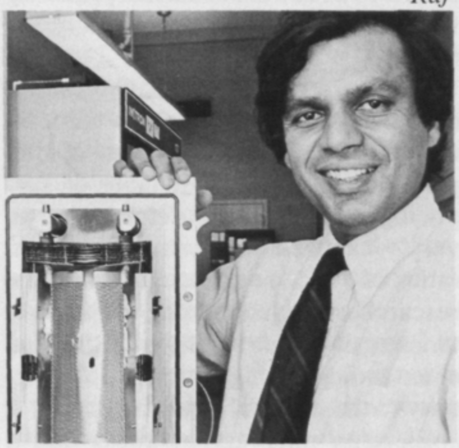


Figure 8

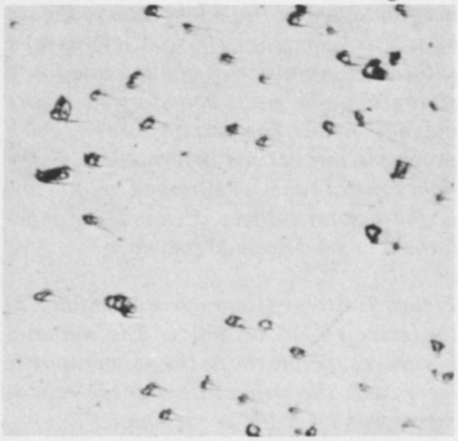


Figure 8. A cross section of a dual-phase glassy metallic alloy, a new composite material developed in Professor Ast's laboratory. Minute crystalline particles improve the mechanical properties of the material.

Figure 9

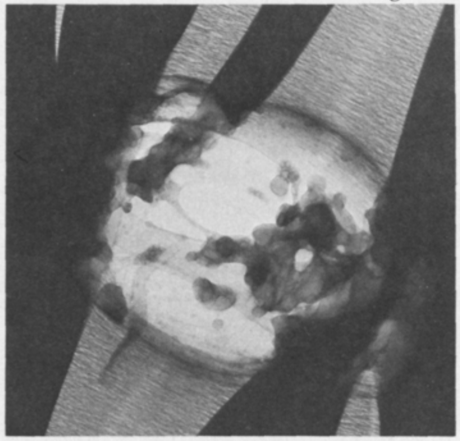


Figure 9. Transmission electron micrograph illustrating research conducted in Professor Kramer's laboratory. The image shows crazes growing from and around a small rubber particle in a thin film of poly (acrylonitrile-butadiene-styrene). The distance across the area shown is about 3.2 microns.

characteristically they can be formed to close tolerances by molding or extrusion—they have some drawbacks for certain applications. For example, polymers tend to be softer and less impact-resistant than metals. Several Cornell researchers are studying the microscopic structure of various polymeric materials with the aim of finding ways to improve their properties. Edward J. Kramer is directing research on polymer glasses, such as polystyrene, seeking to elucidate how and why they can be made tougher. David T. Grubb is concerned primarily with the material properties of polymer fibers.

Kramer's group recently found, using transmission electron microscopy, that polymer glasses of the polystyrene type are capable of surprisingly large plastic deformation in very localized regions. Extension ratios of 4 or 5 are not uncommon. The researchers are examining the characteristics of these regions with the idea of extending the high microscopic ductility to the material as a whole.

Electron micrographs show that a region of high deformation involves the formation of fine fibrils, only 100 angstroms in diameter, between two bulk polymer interfaces, and an associated void structure—a zone of plastic deformation called a *craze*. Although the craze looks like a crack, it does not behave like one, since its fibril structure is strongly load-bearing. This potential source of strength is counteracted, however, by breakages of the polymer chains that occur during the formation of the fibril surfaces; as a result, the fibrils slowly break down to form large voids, which ultimately grow to form cracks within the craze. The craze, then, is a source of both plastic deformation ("toughness") and cracks ("brittleness").

Presumably the material would be tougher if either there were no crazes, or more of them formed under impact loading. In sufficient density, crazes would absorb enough energy to prevent the growth of cracks to a critical size. In some polymer glasses crazing is difficult and deformation tends to occur through shearing rather than

Kramer and Grubb

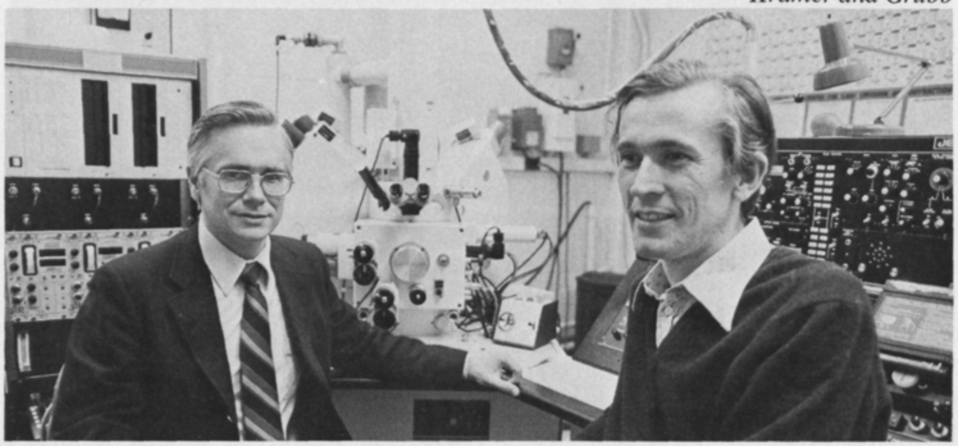


*Figure 10*a

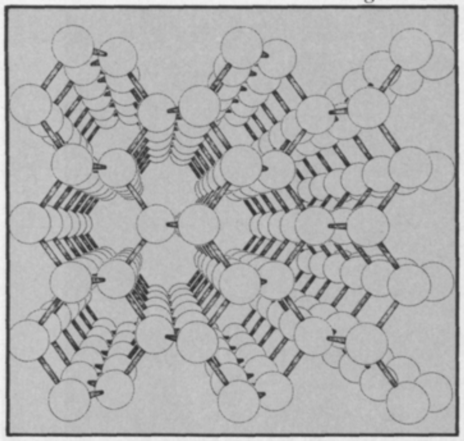


*Figure 10*b

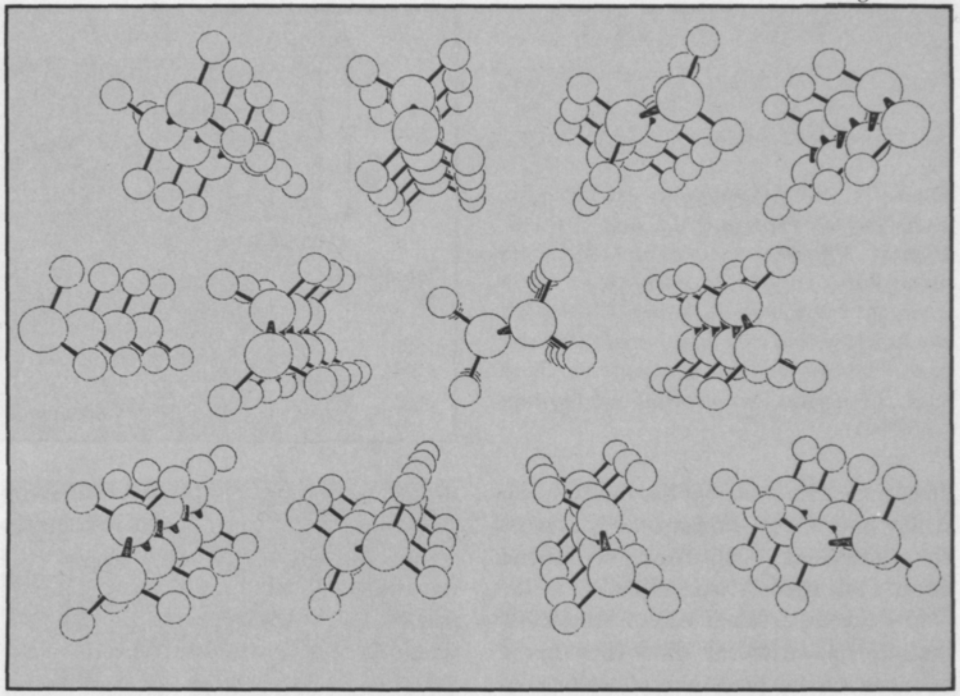


Figure 10. Computer drawings illustrating crystal bonding of concern in Professor Grubb's research. The figures were prepared as a teaching aid.

*The image reproduced in Figure 10*a *shows a diamond crystal with carbon atoms strongly bonded in three directions. The image in Figure 10*b *illustrates fully oriented polyethylene. Although the polyethylene structure has rows of carbon atoms similar to those in diamond, the bonding is strong in only one direction. In the other directions, the carbon atoms are held far apart by hydrogen atoms (represented as the smaller circles).*

through crazing. The Cornell studies show that the major variable influencing the competition between shear deformation and crazing is the entanglement density of the polymer: if it is high, crazes form only with difficulty (many chains must be broken to form fibril surfaces), and if it is low, crazing occurs easily.

Evidence for the influence of crazing on impact toughness of the material is found in electron microscopic studies of polymer that has been modified by embedding small particles of rubber. For some time, it has been known that the addition of rubber particles between 1 and 10 microns in diameter produces a high-impact material. Micrographs reveal that the rubber-modified polymer has a very profuse array of crazes (see Figure 9). Factors such as the size of the rubber particles and the nature of their bonding to the polymer matrix can be studied.

Although polymers can be made tough and impact-resistant by rubber modification, they are still very much softer than metals or covalently bonded materials such as silicon carbide or diamond, and Grubb and his associates are interested in finding out why. One of their principal reasons is to develop ways of making polymer fibers with high strength and elasticity.

Polyethylene, the material used to make such familiar products as gallon milk containers, consists of long chains of methyl groups, with carbon-carbon bonding between the chains. Diamond contains the same type of bonds, at only four times greater concentration; why is it so much harder? The difference (see Figure 10) is that in diamond, lines of strong bonds can be drawn in any direction, while in polyethylene, the strong bonds are only along the chain direction. Between the polymer chains, the bonding is the result of van der Waals or dispersion forces thousands of times weaker, and the stiffness of the material is controlled by these weak bonds.

When polyethylene is deformed in tension, it extends to about five times its original length and the molecular chains become aligned with the draw

Figure 11

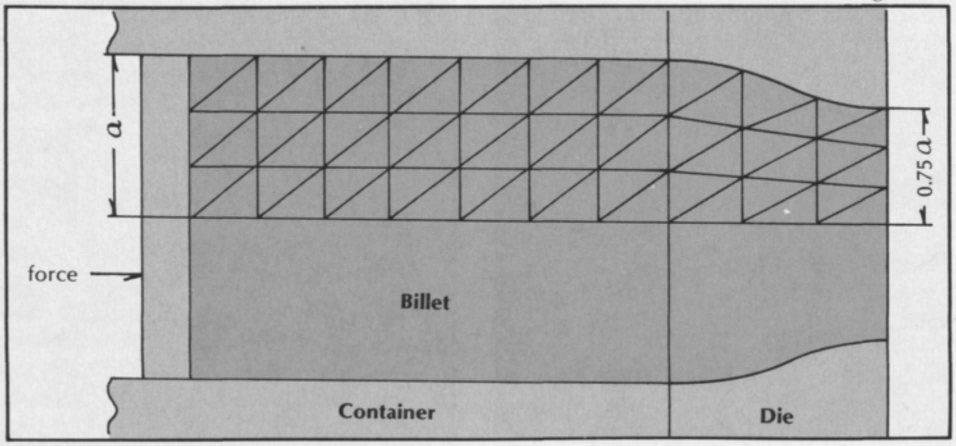


Figure 11. Metal-forming by extrusion, as analyzed by Professor Li and his colleagues. A finite-element model represents the reshaping of a billet to form a part with a smaller cross section. Stress distribution can be expressed as a function of die shape or of other manufacturing variables. Such analyses permit optimization of forming conditions.

direction. The material becomes much stiffer in the draw direction because of the increased proportion of strong bonds, but the stiffness is still very far below the theoretical value. Studies of the internal structure show that this is because of the presence of defect regions surrounding well-organized and oriented crystalline regions. Even though the material in the defect zones constitutes only about a fifth of the total volume, it is so much softer than the crystals (along the molecular chain direction) that the stiffness of the composite is very much reduced.

Grubb's research has shown that higher draw extensions, up to one hundred times the original length of the material, can be obtained by special processing. The polymer is dissolved and reprecipitated to reduce the number of entanglements between chains, and then deformed slowly at high temperature. The researchers have produced fibers with a modulus of elasticity very near the theoretical value, and in some cases the tensile strength has also approximated the theoretical value. Structural studies of the high-modulus material show that the chain orientation is not much different, but the arrangement of defects is. Though disordered material is still present, it is now largely at the sides of long fibrous crystalline regions. The material has become a "self composite" of aligned fibers, with properties that reflect those of the fibers and not of the matrix.

It is unlikely that high-modulus fibers of polyethylene will be of much practical use, since the melting point of the material is low and creep occurs only a little above room temperature. The thrust of current research at Cornell and elsewhere is, therefore, to apply the lessons learned to polymeric materials of higher melting point.

RAISING THE EFFICIENCY OF MANUFACTURING PROCESSES

The research of several department members includes studies that have direct bearing on processes and materials used in manufacturing.

Metal-forming processes such as rolling, extrusion, and forging are being studied by Che-Yu Li in cooperation with Subrata Mukherjee of the Theoretical and Applied Mechanics faculty. The idea is to provide a way of optimizing forming conditions so as to increase productivity rates. Mukherjee's group constructs finite-element computer models on the basis of constitutive equations for mechanical properties of materials that have been developed by Li and his group. These models permit the calculation of stress and strain-rate distributions as functions of various manufacturing variables. For example, stress distribution can be expressed as a function of die shape (see Figure 11) or of the rate of forming (it has not been possible to calculate the latter dependency using more traditional approaches).

The multiaxial behavior of structural materials is being studied by Edward W. Hart. He has developed a theory for the mechanical behavior of metals under complex stress that is based on his very effective theory of creep-plastic behavior. This has important industrial potential because the modeling of mechanical processes and the prediction of service behavior require

"Cornell is particularly well equipped to foster the basic approach to materials development."

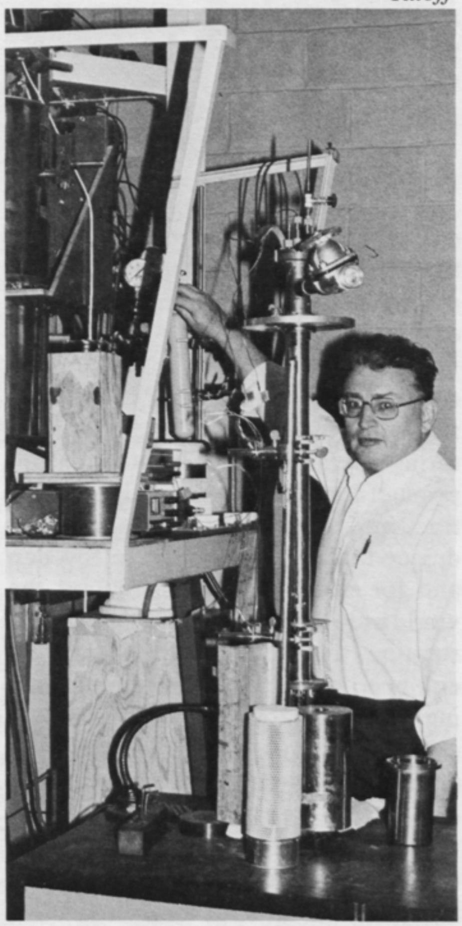
accurate representations of three-dimensional flow relations.

BASIC RESEARCH WITH AN EYE TO APPLICATIONS

Although some of the Cornell research on materials has direct applicability to manufacturing, much of it is fundamental and exploratory in nature, with far-reaching possibilities still only broadly defined.

The research of the MS&E department's chairman, Arthur L. Ruoff, is an example of basic scientific inquiry with important practical implications. Ruoff and his group are investigating what happens when various familiar substances are subjected to pressures in the megabar range—millions of times greater than atmospheric pressure. The inert gas xenon becomes a metal, for example; so does sulfur, which is ordinarily an excellent insulator. Ruoff's measurements are carried out on tiny amounts of material with sophisticated instruments, but some day the knowledge he is acquiring may make possible the production of commercially valuable new materials such as metastable metallic oxygen or carbon. Such materials might have many potential electrical and electronic applications; and a substance such as metallic oxygen would be useful when storage volume is significant, as on a space flight.

Ruoff



Cornell is particularly well equipped to foster the basic approach to materials development. The researchers have access not only to their department's own extensive facilities, but to those of several federally supported centers on campus that provide state-of-the-art equipment and support services. These special laboratories include the University's Materials Science Center and the National Research and Resource Facility for Submicron Structures. Materials research will be an important adjunct of Cornell's new program in manufacturing engineering and productivity.
—G.McC.

COMMENTARY

The Automated Factory: Myth or Reality?

by L. Jack Bradt

This commentary is a synopsis of a talk presented at Cornell on October 22 as the third in a series of Distinguished Alumni Lectures sponsored by the School of Operations Research and Industrial Engineering. Bradt, who is chairman of SI Handling Systems, Inc., of Easton, Pennsylvania, was graduated in 1953 with a degree in mechanical and industrial engineering. Bradt founded SI Handling in 1958 and became its first president. The company sells, manufactures, and installs automated materials-handling systems internationally.

Is a reindustrialization of America really going to happen? Will we, in fact, see the automated factory?

I believe that factory automation is not only feasible, but an absolute necessity if United States manufacturers are going to improve productivity and regain their share of the world market. My contention is that we are at the front end of a virtual revolution—not an evolution, but a revolution—in batch-manufacturing operations, and that an understanding of that revolution is essential for the success and, indeed, the survival of United States manufacturing companies in the not-too-distant future.

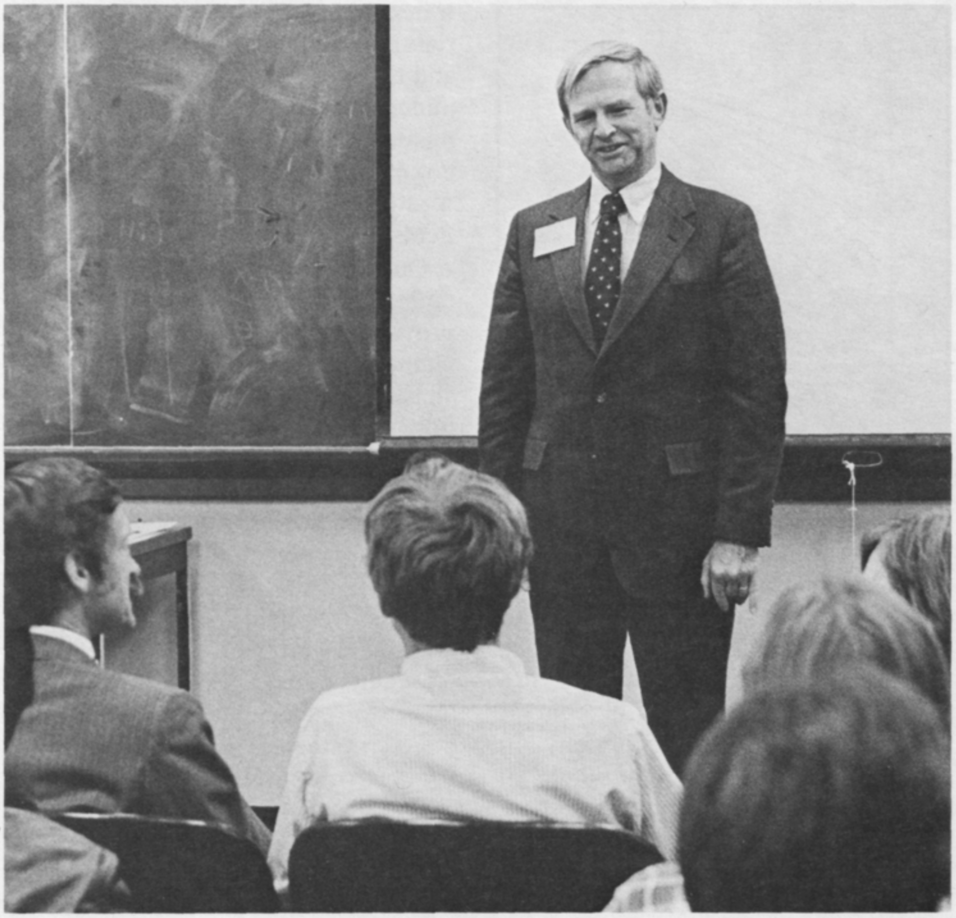
At SI Handling, we are so convinced of the reality of the automated factory that we are making substantial investments in the development and supply of components for it.

We manufacture highly sophisticated computer-controlled systems to automate warehousing and manufacturing operations. Our most important product for factory automation is Cartrac, an ingenious materials-handling device that was developed in Sweden and for which we have acquired the worldwide rights. The basis is a simple rotating tube that conveys carriers equipped with drive wheels; by changing the angle of the tube, one can change the thrust and therefore accelerate or decelerate the carrier. With this system, a carrier can be moved at very high speeds—two to four times the speeds of normal conveyances—and the speed can be adjusted as needed. Cartrac provides what is called nonsynchronous operation, in contrast to a preset assembly-line procedure.

About four or five years ago, companies began using Cartrac to integrate robots into automated manufacturing systems, particularly in the automotive industry. We have a joint venture company in Japan, and there, in particular, a great many Cartrac systems were being sold. It was apparent that something big was going on. We undertook an extensive tour, mostly in Japan, but also in Germany and the United States, to find out what was happening in factory automation, and I would like to present some of the results of that research.

U.S. MANUFACTURING IN THE WORLD MARKET

The situation of American industry is well assessed in a recent article by James Lardner, a vice president of John Deere, which is one of the very few companies that have really moved into the new mode of manufacture. Lardner estimated that equipment and



facilities in United States batch-manufacturing plants are used at an average of only 25 to 35 percent of the time, even at full production, and that material moving through a metalworking plant, for example, spends 80 to 90 percent of the time in storage and less than 5 percent undergoing transformation. His conclusion was that the conventional approach will not begin to solve our problems—a conclusion that he contended is supported by even a cursory examination of Japanese success in steel, consumer electronics, automobiles, and shipbuilding. In almost no case, he said, are elements that are considered by United States manufacturing experts as crucial to improving productivity a major factor in the Japanese approach. Instead, Japanese management has taken a holistic view of manufacturing, and applied logic and common sense to the problem of productivity. Lardner called the "just in time" production system "a triumph of industrial management." With a single central concept, he said, the Japanese have achieved a degree of increased productivity that would be nearly impossible by any other means.

To meet the competition, United States companies must rethink the whole manufacturing process, and universities like Cornell must educate people capable of dealing with the concepts of the automated factory. In short, there must be a major revolution.

FACTORS IN IMPLEMENTING FACTORY AUTOMATION

The issue of factory automation is rooted in competition. It is well known by now that our nation is losing market share—that the Japanese in particular, and Europeans to a large extent, are moving into United States markets. I believe the Japanese now have close to 25 percent of the automobile market within the United States, for example. This situation has created enormous economic problems in this country; people are out of jobs.

The most important reason for the loss of market share is the decline in United States productivity as compared to that of foreign competitors. A

Figure 1

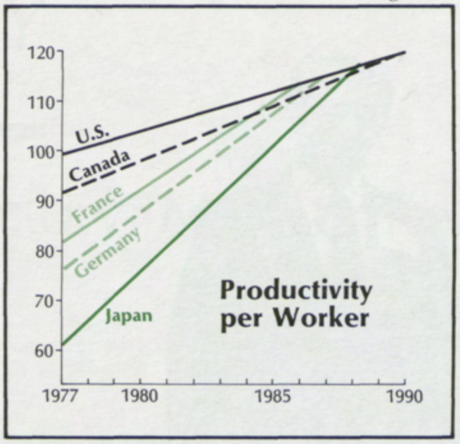


Figure 1. Productivity trends in the United States and other countries. A slower rate of growth in the United States results in a loss of market share.

related factor is product quality; it is becoming increasingly apparent that United States products—consumer goods, particularly—just don't stack up to those of our competitors. Quality depends on both how a product is designed and how it is manufactured. The Japanese have shown that by using robots, precision tooling, and interfacing transportation systems, they are able to produce higher-quality products. With robots, for instance, you get the same quality time after time; you don't get the so-called Monday and Friday cars. If the product is designed well to begin with, you get repeatable top quality.

A major factor in improving productivity is inventory reduction. The Japanese accomplished this with their "just in time" production system, a strategy that is simple conceptually but very difficult to implement. To develop their system, the Japanese used American design and machine concepts, including the use of computers and robots, and applied them in a very ingenious way. Effectively, the idea is to make a batch-manufacturing operation approach a process operation, like that of a chemical plant. The operation is scheduled so that material moves in and through the plant as it is needed; in effect, specific orders rather than stock are manufactured. Batches are smaller, setups and products are changed frequently, and, of course, inventory is reduced substantially. In fact, the inventory reduction that can be realized through the automated factory can to a very large extent pay for the investment.

The "just in time" production system that is central to the Japanese approach to factory automation is central also to what we are now beginning to develop in the United States. Because it requires tremendous flexibility, it leads to the concept of the flexible manufacturing system (FMS), which is at the heart of the automated factory.

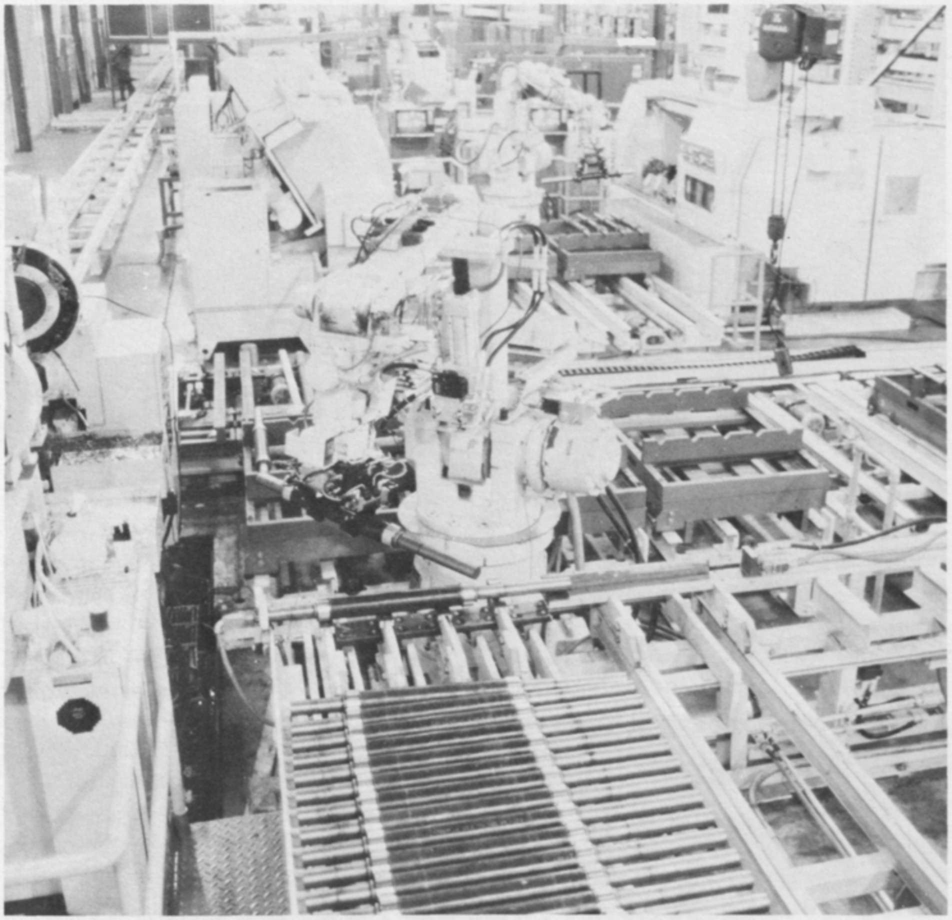
FLEXIBLE MANUFACTURING SYSTEMS: THE CENTRAL IDEA

FMS's are essentially very simple. The components are an in-process storage system and a high-speed, flexible transportation system to move materials and parts among the storage areas and the work stations—all, of course, under computer control. The automated factory will encompass a whole group of FMS's integrated through a master control system. The components are available and proven.

One of the keys is materials requirement planning (MRP), which provides on-line, direct control of the planning and scheduling of the purchasing and the manufacturing operations. Another essential is computer-aided design and computer-aided manufacturing, or CAD/CAM. (Cornell, incidentally, has a great CAD/CAM laboratory.) It is interesting to note that although CAD/CAM is a big business today, only a few years ago it was still just an idea. The business took off when computer manufacturers had the vision to tie components together into a system. The same thing will happen with the automated factory.

The automated factory incorporates a number of additional innovative techniques for improving productivity. One of them, for example, is group technology. The various parts needed for products are classified into families, and similar parts are worked on at flexible machining centers. This has been made possible, of course, by computers. Computerized automatic part inspection is also available: images of a properly made part are put in memory and a camera compares manufactured parts with it. This technology is moving very fast.

Automated assembly by robots is accepted today as integral to the system. Robots are being used extensively in Japanese manufacturing; for



Left: A flexible manufacturing system in the United States uses robots and a Cartrac system to handle parts. This is the Harris Corporation plant in Fort Worth, Texas.

example, in one factory a dozen robots operate in three shifts, with one man on each shift supervising the entire process. In the United States robotics is still very limited, restricted mostly to jobs that must be performed under adverse conditions, but robots are beginning to be used also for boring, repetitive operations, particularly in the automotive industry. Large organizations like General Electric, General Motors, IBM, and Bendix have entered the robot business, along with Unimation, Cincinnati-Milacron, and several small companies. All indications are that the current \$100-million robot-manufacturing business will grow at a rate of 35 to 50 percent a year.

Another feature of the automated factory is numerical control (NC) for automated machining operations. We are already in the second generation of NC tools—the so-called CNC (computerized numerical control) and DNC (direct numerical control) machine tools. A problem is that although these are very efficient pieces of machinery, most of them today are "islands of automation" in the factory. Their utilization time is very low, and therefore the return on investment is low. In order to help increase efficiency and productivity, these tools must be integrated into a system so that they are loaded and unloaded automatically, and are kept in constant use.

An automatic storage and retrieval system (AS/RS) with computer-controlled access is an essential part of the FMS. Robots can be used to remove needed parts from a carousel, for example.

Tying all these components together is a suitable materials-handling system. Getting away from the continually moving assembly line to a so-called nonsychronous system requires drastic changes in the transport of materials, parts, and products. Robots are very effective, provided that the parts they are to manipulate are always brought to an exact location rapidly, and stopped precisely, ensuring high throughput and repeatable quality. New handling systems, such as our company's Cartrac and a variation

Figure 2

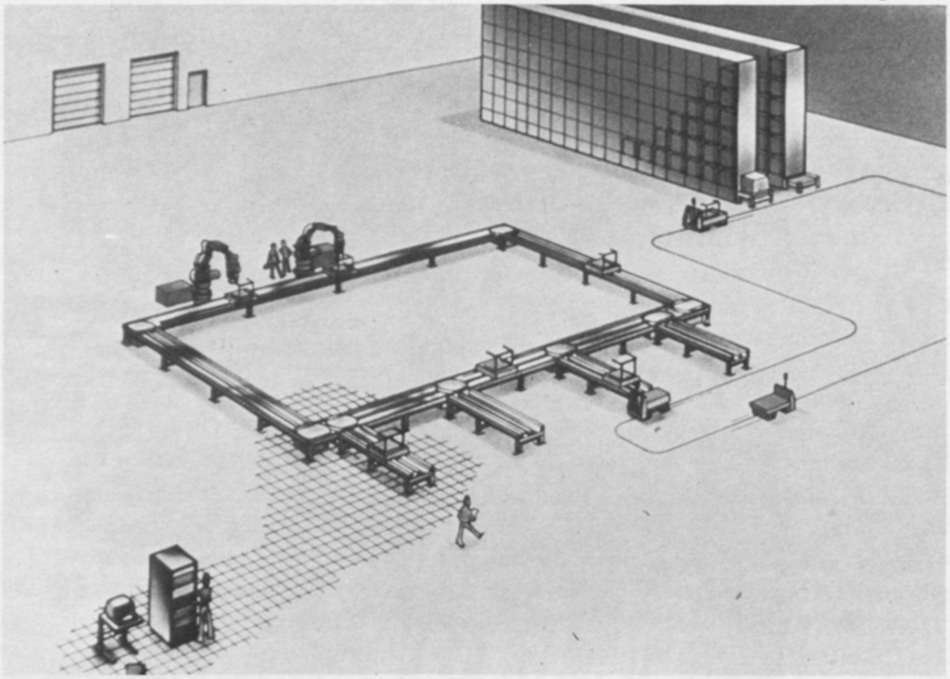
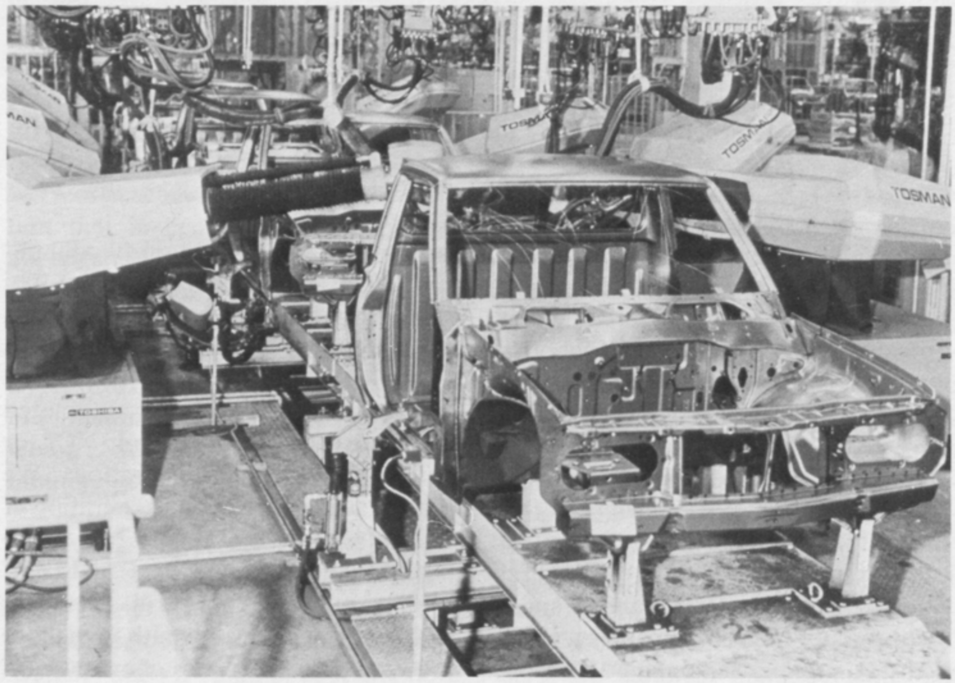


Figure 2. A representation of what a flexible manufacturing system in an automated factory might be like. The basic unit is a "manufacturing cell" such as the one diagrammed here. The central loop represents a Cartrac system which transports the material-in-process from work station to work station. Automatic guided vehicles bring material to and from an automatic storage and retrieval system (at upper right). A process-control computer (lower left) directs the movements and keeps track of inventory.



Right: In a Japanese plant, truck bodies are moved by a Cartrac system to stations where robots perform the assembly operations.

". . . productivity doubles, defects are halved, inventory is reduced by one-half, and space utilization doubles."

called Mini-Cartrac, have been devised to meet the new requirements of nonsynchronous assembly systems. Another example is a computer-controlled Automatic Guided Vehicle System (AGVS), in which the cars follow wires embedded in the floor.

INTEGRATION AS THE KEY TO A WORKING SYSTEM

The key to success in implementing an automated factory is integration of the various components. To develop the necessary systems control, one must use computer simulation, an area in which we see great need and opportunity, and one in which Cornell shines*. At SI Handling we are now developing microprocessor standard controls that will direct the variety of systems for materials-handling, CNC tool input-output, the operation of robots, etc.

With suitable integration methods, an FMS can be adapted to the particular needs of a manufacturing plant. Medium-sized as well as large operations can be successfully handled, and it is quite possible to combine manual, semiautomatic, and fully automatic robot operations. In fact, an increasing number of companies are putting in systems that can be used initially to supply manual assembly work stations, and can be robotized later. In other words, an automated factory can be installed gradually, in a series of low-risk, low-dollar-investment steps.

TODAY'S CAPABILITIES AND THE COMING REVOLUTION

The question confronting manufacturing companies is whether they can justify the investment in an automated factory. The decision requires an understanding of what the system will do and where the economics lie. "Bradt's Rule of Thumb" is that with FMS, productivity doubles, defects are halved, inventory is reduced by one-half, and space utilization doubles. But to achieve such results—which can be demonstrated—the concept must be considered in a large context, no less than a completely new view of manufacturing.

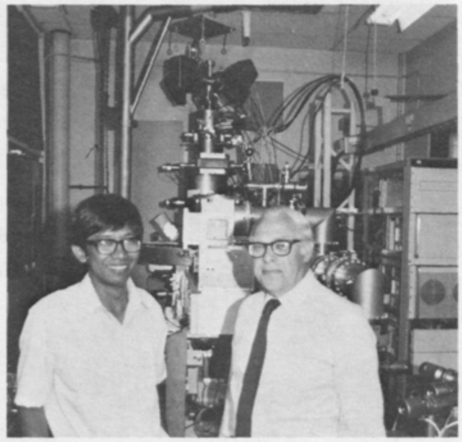
In the United States, however, senior management generally does not yet fully understand the FMS concept and the magnitude of its power. Exceptions are companies like John Deere and Caterpillar that have stepped out and made the investments; they are now far ahead of their competitors.

A further difficulty is a shortage of people who have the knowledge and skills to accomplish the necessary complex integration of components. We need a new group of engineers with experience and background in computers, machinery, processes, and techniques for assembling all these components.

Despite these temporary deficiencies, FMS is here, operational, and proven. It is the heart of the automated factory and without question it will provide the basis for the coming revolution.

**See the articles by Lee Schruben and by William L. Maxwell and John A. Muckstadt in the Autumn 1982 issue of this magazine.*

College Gets New Equipment and Laboratories



Hue-Pei Kuo, "Hermes," and Benjamin M. Siegel pose for a picture in the ion-beam laboratory in Clark Hall. Kuo, an alumnus who is now at Hewlett-Packard, helped arrange the gift of equipment.

■ Faculty initiative has brought several valuable pieces of equipment to College laboratories as gifts from industrial organizations.

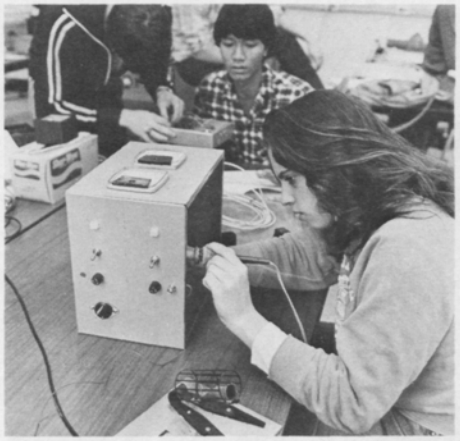
Particularly outstanding is a prototype high-speed, high-resolution electron-beam lithography system nicknamed "Hermes," valued at $750,000, which was donated by the Hewlett-Packard Company. Benjamin M. Siegel of the School of Applied and Engineering Physics faculty first met "Hermes" while visiting his former student, Huei-Pei Kuo, at the Hewlett-Packard Laboratories in Palo Alto, California. Later, when Siegel learned that the machine was no longer being used, he asked Kuo if the company would consider sending it to Cornell, where it could be modified for research in ion-beam lithography. The donation was made through Donald Hammond, director of the Physical Research Center at Hewlett-Packard Laboratories, who also serves on the Policy Board of the National Research and Resource Facility for Submicron Structures, located at Cornell. "Hermes" was shipped to Ithaca in July, and is now in Clark Hall undergoing conversion for ion-beam research.

The Department of Computer Science also received equipment from Hewlett-Packard, in the form of four powerful H-P9836 desk-top personal computers valued at more than $35,000 each. The award was made in response to a proposal drawn up by department members Richard W. Conway and Dale Skeen; Cornell was one of twelve institutions selected as recipients. The computers, which were received in October, are now installed on the fourth floor of Upson Hall, where they will be used as work stations for programmers involved in developing software tools.

IBM recently gave a Balzers ultrahigh vacuum system valued at $400,000 to the Department of Materials Science and Engineering. This gift was arranged through Jerome Cuomo, senior scientist at IBM's T. J. Watson Research Laboratory, who is a courtesy professor at Cornell. The turbomolecular-pumped system is equipped with an automatic gas-handling apparatus and a mass spectrometer for *in situ* gas analysis. It will be used by Professor Arthur Ruoff's research group in a study of the mechanisms of reactive-ion-beam etching.

In response to a proposal submitted by the School of Electrical Engineering, Data General Corporation has given the School an MV/8000 computer valued at $275,000, including software. Preparation of the proposal was coordinated by Professor Hwa C. Torng, and alumnus John Barlow of Data General arranged the transfer. Considered the best of the "big minimachines," the MV/8000 has a 32-bit word length and is capable of supporting 128 interactive terminals. Its development was featured in the Pulitzer-Prize-winning book, *The Soul of a New Machine*, by Tracy Kidder. It was installed in November in Phillips Hall, where it will be used in both undergraduate teaching and research.

Mechanics students use a new testing machine in the recently renovated statics laboratory.



Undergraduates build lasers in a new teaching laboratory of the School of Applied and Engineering Physics.

The new Terak microcomputer facility is available to students for computer programming and word processing.

■ A few mechanical testing machines dating back to the nineteenth century were still in use in the statics laboratory in Thurston Hall when the Department of Theoretical and Applied Mechanics began a recent effort to update its teaching laboratories. Although this is an extreme case, departments and schools throughout the College recognize the accelerating need to upgrade laboratory teaching facilities, and are accomplishing this with substantial help from industry.

The statics laboratory is now equipped with four new universal testing machines, purchased in part with funds from the Garrett Corporation and the ARCO Foundation. The laboratory has also added computerized data-acquisition equipment given by the United Calibration Corporation. Other testing and analytical equipment is on order. A similar development of the department's dynamics laboratory is now in progress; here the main addition has been minicomputers, some of which were donated by the Hewlett-Packard Foundation. In all, about $150,000 worth of equipment in the two laboratories is being made available to the more than one thousand undergraduates taking courses in solid mechanics, dynamics, and engineering mathematics. The nearly completed dynamics laboratory is used also by graduate and faculty researchers; according to technical services supervisor Peter Brown, it is busy practically twenty-four hours a day.

The School of Applied and Engineering Physics has established a new undergraduate teaching laboratory, funded by a $75,000 grant from the United States Steel Foundation, that has enabled Professors Terrill A. Cool and Aaron Lewis to introduce a freshman course emphasizing laser physics and its applications. The students actually build lasers. A special feature of the course is a series of talks by scientists from industrial research laboratories on aspects of laser technology such as isotope separation, diagnostics in combustion, the use of lasers in ophthalmology, and solid-state optical communications. The laser laboratory is located in Rockefeller Hall, which is itself undergoing a major renovation.

Another laboratory that has made a large impact on undergraduate education is a Terak microcomputer facility recently installed in Carpenter Hall. Established chiefly as a teaching facility for the introductory course in computer science, it is also open to other Cornell students who wish to run computer programs or use word-processing equipment. Some thirty terminals are available. Other computer centers for student use have been set up at various locations on campus, and eventually they will be linked in a coordinated system. ARCO Foundation funds supported this.

■ The Eugene W. Kettering Energy Systems Laboratory, which will provide the most complete real-time model of a bulk power system ever constructed, was dedicated on October 30 in Phillips Hall. A $250,000 grant from the Kettering Fund financed the laboratory, which is being used for both teaching and research.

The late Eugene W. Kettering was a Cornell engineering student in the class of 1930 who became director of research and then research assistant to the general manager of the General Motors Corporation's Electromotive Division. He was the son of Charles F. Kettering, president of the General Motors Research Corporation and cofounder of the Sloan-Kettering Institute for Cancer Research. For ten years prior to his death in 1969, Eugene W. Kettering concentrated his attention on the family's philanthropies and interests in cancer research and photosynthesis; he succeeded his father as chairman of the board of the Charles F. Kettering Foundation. Among the honors he received were the Elmer A. Sperry Award, given in 1957 for development of the diesel-electric locomotive, and a number of honorary doctoral degrees.

Participants in the dedication program included Thomas E. Everhart, dean of the College of Engineering; Joseph M. Ballantyne, director of the School of Electrical Engineering; James S. Thorp, one of the electrical engineering faculty members who makes intensive use of the new facility; and Virginia Kettering, widow of Eugene W. Kettering.

Thorp emphasized the importance of a sophisticated model system for

Left: Virginia Kettering appears with Dean Everhart at the entrance to the Eugene W. Kettering Energy Systems Laboratory in Phillips Hall. The occasion was the laboratory dedication in late October. Mrs. Kettering is the widow of the automotive engineering leader and philanthropist in whose honor the laboratory is named.

During the dedication ceremony, Everhart presented Mrs. Kettering with a plaque that included a piece of the original cable used in the nation's first outdoor electrical lighting system, which was installed on the Cornell campus in 1877 under the supervision of Professor William A. Anthony.

Left below: Professor Thorp works with students in the new laboratory. A full-time technical manager is also present to aid students and researchers. The power-system model has a central computer system, as well as microprocessors for monitoring and control.

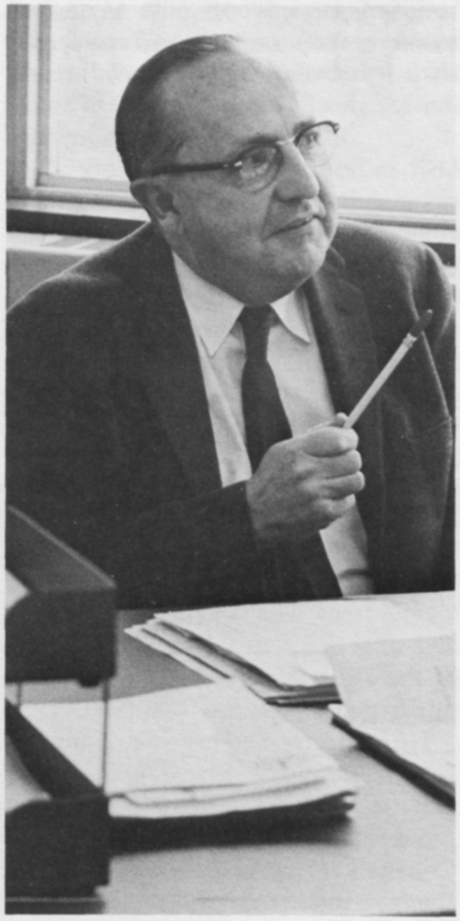
studying the actual massive and complex electrical power systems. The new laboratory has small-scale physical models of transmission lines, transformers, and buses, and a central computer system and microprocessors for monitoring and control. The system will operate on the model just as computers do in large-scale power systems. One of the unique aspects of the laboratory system, Thorp indicated, is the ability of researchers to model protective equipment and study its impact on the dynamic behavior of a real system. It has been argued, he said, that protective equipment has played a part in all the major blackouts of the past twenty years. Cornell researchers have been involved in developing some of the new digital relays recently introduced for protective schemes.

REGISTER

Four men who made important contributions to the development of Cornell University and its College of Engineering died in recent months. Two of them, *Howard G. Smith* and *George Winter,* were professors, emeritus. The others, *Leroy R. Grumman* and *John M. Olin,* were alumni prominent in University affairs.

■ *Howard G. Smith,* who died on October 28 at the age of seventy-two, was associated with Cornell for fifty-six years as a student, professor of electrical engineering, and administrator. At the College of Engineering he is recognized especially as the founding director of the Division of Basic Studies, a position he held for ten years prior to his retirement in 1974. The division, an innovative feature in engineering education, supervised the first two years of undergraduate work, before students selected their upperclass majors.

Smith received three degrees in electrical engineering from Cornell—the baccalaureate in 1930, a master's degree in 1931, and a doctorate in 1937. He joined the staff in 1931 as a teaching assistant in physics, and became an electrical engineering faculty member three years later. He taught in his specialty fields of communications engineering and electrical circuit theory, and for many years he served on the policy committees of the School of Electrical Engineering and the College of Engineering.



During World War II, Smith was in administrative charge of a Pre-Radar School operated at Cornell for the U.S. Signal Corps. Later he administered a school operated on campus for engineering employees of the New York Telephone Company, and was instrumental in establishing the University-affiliated General Electric Advanced Electronic Center in Ithaca. He was active as an industrial consultant and spent sabbatic leaves consulting with administrators in engineering schools in the United States, Europe, and the Far East.

He is survived by his wife, Jane, a daughter, two sons, and two grand-

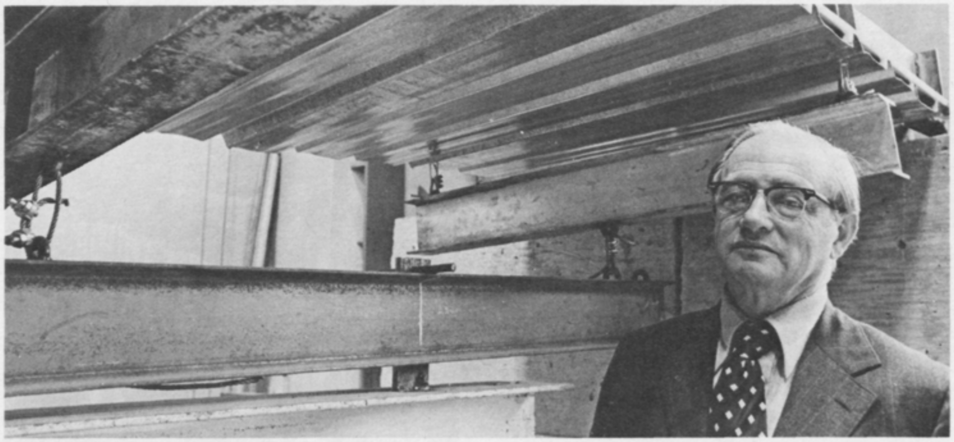
Left: Howard G. Smith was a Cornell student, professor, and administrator.

sons. The Howard Godwin Smith Memorial Fund, which will be used to provide reading material for the student lounge in Phillips Hall, is being administered by the School of Electrical Engineering.

■ *George Winter,* an internationally known expert in structural engineering, died November 3 at the age of seventy-five. He retired in 1975 as The Class of 1912 Professor of Engineering, emeritus, and was honored at that time with the naming of the structural test bay in Thurston Hall as the George Winter Laboratory.

Born in Vienna, he received his first engineering degree, the Dipl. Ing., in 1930 from Technical University in Munich (which awarded him an honorary doctoral degree in 1969). After eight years of practice in Europe, he came to Cornell as a graduate student, received the Ph.D. degree in 1940, and joined the faculty. For twenty-two of his thirty-five years on the faculty, he served as chairman of the Department of Structural Engineering.

Winter was a leader in research and building-code development in the three major contemporary building materials—concrete, structural steel, and cold-formed light-gauge steel. He directed the research for a number of editions of *Design for Cold-Formed Steel Structural Members,* and he was a co-author of several editions of the textbook *Design of Concrete Structures*, which has been widely used around the world. He was active as a consultant and as a member of professional organizations, and he received many honors for his professional and educational contributions. These honors include medals from the American Concrete Institute, the American Society of Civil Engineers, and the American Iron and Steel Institute, and election to the National Academy of Engineering. This fall he was awarded the International Award of Merit from the International Association for Bridge and Structural Engineering.



Above: George Winter built an international reputation in structural engineering during his long career at Cornell.

At Cornell Winter served on the Faculty Committee on Music, which he chaired, the Friends of Music at Cornell, and the University Lecture Committee. His interests extended also to archeology—he was a member of the American Archeological Institute expedition to Egypt in 1966.

He is survived by his wife, Anne, his son, Peter, and two grandchildren. The George Winter Graduate Fellowship Fund has been established by the College's Department of Structural Engineering.

■ *Leroy R. Grumman,* a leader in the aeronautics industry, is commemorated at the College of Engineering by Grumman Hall, which was built in 1959 to house the aerospace engineering school, and by a long record of service to the College and the University. He died October 11 near his home in Plandome Manor, Long Island, at the age of eighty-seven.

Grumman was graduated from Cornell in 1916 as a mechanical engineer, attended graduate school at the Massachusetts Institute of Technology, and began his career in aeronautics in 1920 as a test pilot, engineer, and later general manager for the Loening Aeronautical Engineeering Corporation. In 1929 he founded an airplane repair shop that developed into the Grumman Aircraft Engineering Corporation, now the Grumman Aerospace Corporation, with headquarters on Long Island. The company was a principal builder of military planes during World War II, moved into jet aircraft manufacture after the war, and built the lunar excursion module. Grumman, who lost his sight toward the end of the war, relinquished the presidency of the company in 1946 but remained as chairman of the board for the next twenty years.

During his career, Grumman invented a number of important aircraft parts, including a wing-retraction system that doubled the capacity of aircraft carriers, and a retractable landing gear. His contributions to aeronautical engineering and the industry were recognized by a number of honors, including a Presidential Medal for Merit in 1948, the Hawkes Memorial Award in 1958, and the first Hunsaker Medal from the National Academy of Sciences in 1968. At Cornell Grumman served on the Board of Trustees and the University Council, and in 1961 was named one of the University's first Presidential Councillors.

Surviving are his wife, Rose, four children, and twelve grandchildren.

Below: A portrait of Leroy R. Grumman '16 in Phillips Hall was presented in 1975 by his granddaughter, Kathryn Noel Phillips; his daughter, Mrs. Ellis L. Phillips, Jr.; and his wife.

Left: This picture of John M. Olin was taken in 1960 at the cornerstone laying of Olin Library, the University's research library named in his honor.

■ *John M. Olin,* honorary chairman of the Olin Corporation and a noted philanthropist, died September 8 at his home in East Hampton, Long Island. He was eighty-nine years old.

He graduated from Cornell in 1913 as a Bachelor of Chemistry, began his career as a chemical engineer for the family firm, and became president of Olin Industries when it was formed in 1944. In 1954 he was elected chairman of the combined Olin Mathieson Chemical Corporation. He served on the Cornell Board of Trustees and was a major benefactor of the University.

The Olin family, beginning with John's father, Franklin W. Olin, has had many Cornell ties. Franklin was graduated from the University as a civil engineer in 1886, and all three of his sons were Cornell alumni. Olin Hall of Chemical Engineering was a gift of Franklin in honor of Franklin, Jr., a mechanical engineering graduate of 1912. Hollister Hall, home of the School of Civil and Environmental Engineering, was a gift of Spencer T. Olin, a mechanical engineering graduate of 1921, in honor of his father.

John M. Olin's business interests extended to the manufacture of arms and ammunition, and he held twenty-four U.S. patents in that field. He was also an ardent sportsman and conservationist. In 1953 he established the John M. Olin Foundation to support the principles of free enterprise and capitalism.

His honors included the Charles F. Kettering award, given by Washington University, the Chevalier de la Légion d'Honneur from France, and the Grand Ufficiale-Ordine al Merito from Italy. He was a trustee of the Johns Hopkins University, as well as of Cornell, and an honorary director of the American Museum of Natural History in New York.

He is survived by his wife, Evelyn, his brother Spencer, a daughter, eight grandchildren, and four great-grandchildren.

Right: Dudley N. Schoales was presented the Engineering Award by Thomas E. Everhart, dean of the College. Schoales' wife, Tauni deLesseps, is at left.

■ A silver medal emblematic of Cornell's Engineering Award was presented to *Dudley N. Schoales,* a 1929 mechanical engineering alumnus whose career has been in investment banking with specialization in offshore oil and gas exploration. The medal, inscribed "in recognition of his support in the development of the College," was presented at the fall dinner meeting of the Engineering College Council held on campus October 30.

In addition to his membership since 1965 on the Engineering College Council, Schoales has served on the University's Board of Trustees and the Cornell University Council, and in 1981 he was named a Presidential Councillor. The program included remarks by Cornell President Frank H. T. Rhodes. Presentation of the medal was made by Thomas E. Everhart, dean of the College of Engineering.

Schoales is a former managing partner and current advisory director of the investment firm of Morgan Stanley and Company. He has twice been decorated by Queen Elizabeth for his service to Australian business.

■ A 1981 Cornell civil engineer who died in an accident while serving in the Peace Corps in Nepal has been commemorated with the dedication of a structure built by his fellow students. *Marshal Case Haggard* was honored at a ceremony this fall at the site of the new YMCA pavilion in Treman State Park near the University campus.

Haggard was president of the Cornell student chapter of the American Society of Civil Engineers (ASCE) in 1980–81 and, according to Richard N. White, director of the School of Civil and Environmental Engineering, was the driving force behind the design and construction of the pavilion.

Participating in the dedication ceremony were Haggard's parents, Dick and Connie (A.B. '58) Haggard of Ft. Washington, Pennsylvania; Bryan Clark, this year's president of the student ASCE chapter; Thomas D. O'Rourke, 1980–81 faculty adviser to the student group; and Paul Grennell, executive director of the YMCA.

The pavilion, which will be used for a summer day camp, is a 2,100-square-foot L-shaped timber structure with a concrete base and a peaked, shingled roof. Materials were purchased by the YMCA. A community-service project of this kind is carried out by the ASCE members each year.

Below: Attending the dedication of the YMCA pavilion in memory of Marshal Case Haggard '81 were, left to right: Elmer Blomgren, former YMCA director, who supervised the establishment of the summer camp the pavilion will serve; Marshal's parents, Connie and Dick Haggard; and Paul Grennell, executive director of the YMCA.

FACULTY PUBLICATIONS

Current research activities at the Cornell University College of Engineering are represented by the following publications and conference papers that appeared or were presented during the three-month period June through August, 1982. (Earlier entries omitted from previous Quarterly *listings are included here with the year of publication in parentheses.) The names of Cornell personnel are in italics.*

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