National Research Council
Manufacturing Studies Board

CONFERENCE ON TECHNOLOGY TRANSFER: REDISCOVERING AMERICA'S COMPETITIVE EDGE IN TECHNOLOGICAL INNOVATION

Aspen Institute for Humanistic Studies
Aspen, Colorado

June 28 to July 1, 1987

PROGRAM

Chairman:
Dan Dimancescu
Partner, Technology & Strategy Group

Purpose of Conference

Approximately 30 participants representing researchers and managers from government, universities, and private industry with experience in past and current technology transfer efforts, understanding of technology needs, business strategies, and corporate culture, and knowledge of technology developments will focus on defining problems in technology transfer and devising pragmatic solutions to those problems. Included will be such issues as evaluation criteria for technology transfer mechanisms, cultural barriers to effective technology transfer, improving the demand function, and mechanisms for improving data availability and communication about technology developments. The steering group will prepare a report that will incorporate the opinions of participants. The report is expected to propose initiatives and strategies to improve the process of technology transfer in the United States, including initiatives that NASA and the Jet Propulsion Laboratory can use to improve the effectiveness of their technology transfer programs.

PROGRAM

Sunday June 28	**Event**	**Speaker**	**Location**
6:15 p.m.	*Reception*		Terrace (Aspen Meadows)
7:00 p.m.	*Dinner*		Ortega Room (Aspen Meadows)
	Purpose of the Conference	**Dan Dimancescu**	
	NASA's Technology Utilization Program	**Henry Clarks**	
Monday June 29			
7:00 a.m.	*Breakfast*		Dining Room (Aspen Meadows)
8:00 a.m.	**Managing the Flow of Technology: Do We Perceive A Problem? Why?**	**Dan Dimancescu**	Laughlin Commons (Seminar Building)
8:30 a.m.	**Effectiveness of Technology Transfer and Management in the United States:** *Discussion groups (academe, industry, government)*		Laughlin Commons Board Room* President's Office*
10:45 a.m.	*Coffee Break*		Laughlin Commons Terrace
11:00 a.m.	**Group Reports**		Laughlin Commons
12:30 p.m.	*Lunch* **Technology Transfer Abroad**	**Thomas Eagar** *Japan* **Graham Vickery** *Europe*	Ortega Room (Aspen Meadows)
2:00 p.m.	**A Discussion to Build Consensus:** **1. Common definitions/terminology** **2. New approaches/concepts**	**Debra Rogers**	Laughlin Commons
3:30 p.m.	*Coffee Break*		Laughlin Commons Terrace
5:30 p.m.	**Conclusion of Discussion to Build Consensus**		
6:00 p.m.	*Dinner*		Ortega Room (Aspen Meadows)
	The Public Policy Framework for Technology Transfer: How is the Federal Government Structured to Help?	**Lee Rivers**	

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* located in Paepcke Building

Tuesday June 30	**Event**	**Speaker**	**Location**
7:00 a.m.	*Breakfast*		Dining Room (Aspen Meadows)
8:00 a.m.	**The Public Policy Framework for Technology Transfer: State Government Initiatives**	**Walter Plosila**	Laughlin Commons (Seminar Building)
8:30 a.m.	**Improving the Innovation-to-Commercialization Cycle:** *Discussion groups (Structures, Resources, and Methods/Tools)*		Laughlin Commons Board Room* President's Office*
10:45 a.m.	*Coffee Break*		Laughlin Commons Terrace
11:00 a.m.	**Group Reports**		Laughlin Commons
12:00 noon	*Lunch* **Manufacturing for the Future**	**Keith Gardiner**	Ortega Room (Aspen Meadows)
1:00 p.m.	*Recess (Optional raft trip on the Roaring Fork River)*		
5:30 p.m.	*Departure for dinner at Ashcroft Ghost Town*		Toklat

Wednesday July 1			
7:00 a.m.	*Breakfast*		Dining Room (Aspen Meadows)
8:30 a.m.	**Discussion: Synthesis and Critique**	**Richard Smith**	Laughlin Commons
10:30 a.m.	*Coffee Break*		Laughlin Commons Terrace
11:00 a.m.	**Conclusions: Setting the National Agenda**	**Dan Dimancescu**	Laughlin Commons
12:00 noon	*Lunch*		Dining Room (Aspen Meadows)
1:00 p.m.	*Adjournment*		

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* located in Paepcke Building

STEERING GROUP

Wednesday, July 1		
Afternoon	**Steering Group Discussions**	Laughlin Commons Board Room
Thursday, July 2		
Morning	**Steering Group Discussions**	Laughlin Commons Board Room
Afternoon		
Friday, July 3		
Morning	**Steering Group Discussions**	Laughlin Commons Board Room

Coffee breaks will be taken at 10:00 a.m. and 3:30 p.m. each day.

STATE TECHNOLOGY DEVELOPMENT PROGRAMS

1. STATE TECHNOLOGY OFFICES (30) -- independent public agency, private non-profit, advisor to governor, state agency

2. TECHNOLOGY/RESEARCH CENTERS -- university-based centers with field of concentration

3. RESEARCH GRANTS -- joint or university; match

4. RESEARCH PARKS -- may include incubator and center of excellence

5. INCUBATORS

6. TECHNOLOGY TRANSFER -- information exchanges, outreach

7. TECHNICAL/MANAGERIAL ASSISTANCE (25) --

8. SEED/VENTURE CAPITAL --

9. TECHNOLOGY TRAINING

STATE TECHNOLOGY SPENDING LEVELS FY 86

DOLLARS SPENT	NO. of STATES
$0	7
$0.1 to $1m	8
$1m to $10m	15
$10m to $20m	10
$20m to $30m	4
$30m + over	6

EXPENDITURES FOR TECHNOLOGY PROGRAMS

PER CAPITA	NO. of STATES
$0	7
$0.01-$1.99	23
$2.00-$3.99	8
$4.00-$5.99	5
$6.00 + over	7

SHARE OF $700 MILLION STATE TECHNOLOGY FUNDING IN THE UNITED STATES BY TYPE OF PROGRAM, FY86

ACTIVITIES	PERCENT OF DOLLARS
Technology/Research Centers	40.8%
Venture Capital	21.2%
Research Grants	18.1%
Research Parks	5.6%
Incubators	5.2%
Equity/Royalty Programs	2.0%
Seed Capital	1.6%
Technical/Managerial Assistance	1.5%
Technology Transfer	1.2%
Technology Office	1.2%
Technology Training	1.1%

MODELS FOR UNIVERSTIY/BUSINESS COLLABORATIVE R&D

- TRADE/INDUSTRY ASSOCIATION (e.g., MCC)
- UNIVERSITY-BASED CONSORTIA

  (e.g., NSF's university-industry coop centers and ERC's)
- FULL-SERVICE R&D PERFORMERS

  (e.g., Pennsylvania's Ben Franklin Partnership and Ohio's Thomas Edison Partnership Advanced Technology Centers)
- FEDERAL FACILITIES/LABORATORIES

  (e.g., NBS)

Source: Draft Study Prepared for OTA by Industrial Technology Institute, Ann Arbor

TRADE/INDUSTRY ASSOCIATIONS: Dating back to the early part of the 20th century, a series of trade and industry associations have operated as "pools" of research funds, combining part of their research resources to pursue an agenda of common interests. One of the oldest is the Chemical Manufacturers Association, founded in 1872; a newer but perhaps even more major player in the game is the Semiconductor Research Corporation. Generally member firms contribute an annual sum which is then allocated by a staff or by committees, either to the association's own facilities or to university-based research teams. A variant of this approach is the jointly funded research company, the most significant example being the Microelectronics and Computer Technology Corporation. Results are generally made available to all association members and research tends to be rather basic and rarely related to commercial product or process concerns.

UNIVERSITY-BASED CONSORTIA: A relatively newer model is the consortium of perhaps 10-30 firms, brought together usually at the initiative of a set of university researchers to pursue an agenda set jointly by the firms and the university department(s) in question. Companies not infrequently represent widely differing aspects of the technology in question (e.g., large-scale and small-scale applications). Research tends to be basic with little direct attention to commercialization, although there is generally an implicit or explicit assumption that there will eventually be commerical applications for the member companies to pursue independently. Industry funding of these consortia is often (although not entirely) supplemented by Federal or state government funds. Virtually all the actual research is done by the university participants, with industry playing an advisory role. Examples include NSF's University/ Industry Cooperative Research Centers and Engineering Research Centers.

"FULL SERVICE" R&D PERFORMERS: A more recent addition to the model set is this broad-gauge structure set up to span (to varying degrees) the full range from basic research to commercial applications. These organizations are often tied to explicit economic development agendas set by State governments, and usually have heavy state funding as well as industrial participation. Research performers may be drawn from universities, or set in separate not-for-profit facilities, or both. Even the basic research agenda tends to be evaluated at least in part in terms of potential relationships to commercial outcomes. Basic research results tend to be widely, even publicly, shared, but proprietary work for individual participating firms is also a major feature. There is a heavy emphasis on mechanisms for technology transfer and knowledge utilization. Examples include the Microelectronics Center of North Carolina, and some of the programs funded under Pennsylvania's Ben Franklin Partnership and Ohio's Edison Centers.

FEDERAL FACILITIES: The Federal laboratories have a long history of work by and for Federal research applications, and it is only recently that many of them have become collaborative ventures featuring extensive contracting with industry and joint industry/government dialogue shaping the research agenda. The Stevenson-Wydler Act of 1982 was a significant incentive to the development of lab-based collaborative programs, although its hopes remain largely unrealized to date. Federal labs often feature a mix of contracted-out and internal research efforts, with universities performing much of the basic research and industry the more applications-oriented development work. The missions of the labs tend to emphasize Federal requirements (defense, environment, energy, etc.) rather than commercialization as such, and where extensive commercial outcomes result it tends to be the result of some specific thrust such as NASA's Technology Utilization Program rather than a function of the labs; programs themselves.

MODELS

1. CENTERS OF EXCELLENCE
2. INFORMATION DISSEMINATION
3. PROJECT GRANTS
4. ENTREPRENEURIAL EDUCATION
5. COMPREHENSIVE CONSORTIUMS

HISTORY OF FUNDING

BEN FRANKLIN PARTNERSHIP
ADVANCED TECHNOLOGY CENTERS

YEAR	STATE FUNDS	MATCH	TOTAL
1982 - 83	$ 1M	$ 3.6M	$ 4.6M
1983 - 84	$ 9.9M	$ 29.7M	$ 39.6M
1984 - 85	$17.9M	$ 58.8M	$ 76.8M
1985 - 86	$21.3M	$ 80.9M	$102.2M
1986 - 87	$26.4M	$108.2M	$134.7M
	$76.6M	$281.4M	$358.1M

BEN FRANKLIN PARTNERSHIP
ADVANCED TECHNOLOGY CENTER RESULTS

MARCH 1, 1983 TO AUGUST 31, 1986
(42 MONTHS)

PATENT APPLICATIONS	54	
PATENTS ISSUED	26	
INDIVIDUALS, ENTREPRENEURS AND BUSINESSES COUNSELED	12,117	
WORKSHOPS HELD	886	
NUMBER OF NEW PRODUCTS, PROCESSES OR SERVICES INTRODUCED	974	
VENTURE CAPITAL COMMITTED	$49,475,035	
NUMBER OF GRADUATES OF TRAINING PROGRAMS	12,099	
NUMBER OF NEW TRAINING PROGRAMS	646	
NUMBER OF TRAINING PROGRAMS MODIFIED	390	
NUMBER OF START-UP FIRMS	369	
- NUMBER OF JOBS CREATED		2,018
- NUMBER OF JOBS RETAINED		168.5
NUMBER OF FIRMS EXPANDING	304	
- NUMBER OF JOBS CREATED		2,512.5
- NUMBER OF JOBS RETAINED		1,279.5
NUMBER OF FIRMS RETAINING JOBS	118	
- NUMBER OF JOBS RETAINED		2,022

State Funds Appropriated to Advanced Technology 1982 - 1986

Program	State Funds Appropriated (Grants, Loans, & Credits)	Match	Total
BFP Challenge Grants	$ 76,750,000 1/	$281,400,000	$358,150,000
BFP Seed Venture Capital Grants*	4,500,000	15,954,293	20,454,293
PIDA Loans	38,497,513	57,475,909 2/	95,973,422 2/
PCLF Loans	2,435,200	55,019,747	57,454,947
Community College/Voc Ed Eq Grants*	27,000,000	0	27,000,000
Pension Funds - Venture Cap Investment	138,000,000	142,354,311	280,354,311
Differential Technology Grants 3/	36,800,000	0	36,800,000
Economic Revitalization Tax Credits	25,000,000	125,000,000 4/	150,000,000
BFP Research Seed Grants	2,521,730	2,164,119	4,685,849
Community College Var Stipend Grants	11,400,000	0	11,400,000
BFP Small Business Incubator Loans*	5,029,134	5,404,134	10,433,268
BFP Engineering Equipment Grants*	3,000,000	9,769,211	12,769,211
J & L Site Improvement Grants	6,000,000	0	6,000,000
J & L Second Avenue Site Dev	8,300,000 5/	8,300,000 4/	16,600,000
DOD Software Eng Institute Grant/Loan	29,370,000	103,000,000	132,370,000
NSF Supercomputer Grant	5,250,000	66,888,818	72,138,818
Pittsburgh Univ Research Center Grant	3,000,000	3,000,000	6,000,000
Customized Job Training Grants	4,057,540 6/	--------	4,057,540
PENNTAP	900,000	0	900,000
PA Energy Development Authority	3,897,265	9,603,111	13,500,376
Technology Assessment Program 7/	2,000,000	0	2,000,000
Advanced Technology Facilities	4,000,000	0	4,000,000
Homer Research Lab	10,000,000 5/	10,000,000 4/	20,000,000
Univ of Pittsburgh Biotech Institute	14,000,000 5/	14,000,000	28,000,000
CMU Robotics Institute	20,000,000 5/	20,000,000 4/	40,000,000
Buhl Science and Technology Center	13,800,000 5/	13,800,000 4/	27,600,000
Total	$495,508,382	$943,133,653	$1,438,642,035

* Amount appropriated by PERF for three years.

1/ Includes funds appropriated through the 1986-87 Budget year. In 1986-87 $26.4 million was provided; this funding is likely to increase in future years.

2/ To avoid duplication, match and total amounts include machinery, equipment, and working capital costs due to companies receiving both PIDA and PCLF loans. These costs are not reflected under PCLF loans.

3/ This program was previously titled Higher Education Equipment and Technology Grants.

4/ Required minimum match; the actual figure will likely exceed this amount.

5/ Capital budget item.

6/ Estimated.

7/ Funds were appropriated, however, enabling legislation has not yet been passed.

September 1986

FINANCING:

- STATE CENTERS OF EXCELLENCE
- FEDERAL DESIGNATION

  --SON OF ERC
  --DOD
- CONSORTIUM OF PRIVATE FIRMS
- GIFTS/DONATIONS

CHARACTERISTICS:

- o ROLE OF PRIVATE SECTOR
  (Affiliate/Advisory, Contract/Project, Gift/Donation)
- o PRIVATE SECTOR BENEFITS
  (Knowledge, Access to Students, Seminars, Proprietory)
- o FOCUS ON R&D EFFORT
  (Fundamental, Developmental, Product Development)
- o FUNDING SUPPORT
  (Federal, State, Private)
- o COMPREHENSIVENESS OF EFFORT
  (R&D/ Entrepreneurial Development/Education & Training)

ECONOMIC DEVELOPMENT FOCUS:

1. INDUSTRIAL RECRUITING (North Carolina)

2. ENTREPRENEUR START-UPS (Boston & Silicon Valley)

3. RETENTION OF EXISTING FIRMS (Michigan, Ohio, Pennsylvania)

Dan Dimancescu

Technology & Strategy Group 50 Church Street Harvard Square Cambridge, Massachusetts 02138 (617) 497-1111

June 17, 1987 Re. TECHNOLOGY TRANSFER CONFERENCE

As chair of the Aspen conference (June 28/July 1), I want to welcome you in advance. As with any meeting held in such a beautiful setting, I hope that we can take full advantage of the surroundings to inspire some constructive and compelling thinking.

The subject -- technology transfer -- is an old one. It is clear, though, that it deserves fundamental rethinking. The reason is simple. We are lagging at the game of translating ideas into commercial products fast and effectively. Others are clearly doing it better.

The U.S. dilemma, in my view, is not in our capacity to finance or generate new ideas. Rather it is in our organizational know-how. Management practices both in our firms and in our laboratories have grown rusty. The result is that there isn't an aggressive response to a "pull" of technology exerted by the market.

I will propose that this "management" perspective be treated by the conference as a critical variable. (A) What, in short, should a well managed firm be doing differently to accelerate the commercialization of ideas? (B) And what, in turn, will laboratories (whether within firms or outside) have to do to accommodate and participate in this process? One step toward such an answer will come by attempting to agree to some common definitions of some very simple terms early in our meetings. So that we come with at least a small step forward, I would like to suggest that you consider developing working definitions of several basic terms:

Technology
    (Ex: Is it a process or a product?)
High technology:
    (Ex: Is it fundamentally different because it is 'high'?)
Technology transfer:
    (Ex: Is it a business of managing deliverables? If so, what kind? Or, is it a process of maximizing the exchange of information in a timely fashion? If so, how?)
    (Ex: How might any given view of technology transfer be affected by the structure of an institution, biases affecting allocations of resources, or tools and methods used in managing public or private entities?)

A short summary of a recent conference I co-chaired with Debra Rogers (DEC) is attached. It might jog some thoughts.

I look forwarded to meeting you and wish you good travels in getting there.

Sincerely,

Dan Dimancescu

MANAGING THE KNOWLEDGE ASSET

The Technology Transfer Process

Findings from the T2 Conference at Purdue University

(April 28/29, 1987)

Sponsored by

Technology Transfer Society

Digital Equipment Corporation

Technology Strategy Group

Co-chaired by:

Debra Rogers (DEC)

Dan Dimancescu (TSG)

The stimulus for this conference was a belief, shared by the co-chairs, that America's economic vitality is inhibited by inefficiencies in transferring new technologies to the marketplace. And although our laboratories and centers of technological innovation are strong and vibrant -- particularly those efforts exhibited in a broad array of R&D consortia, the co-chairs drew attention (a) to the need to reconceptualize the working concepts of "technology transfer, and (b) to focus more attention on the need for breakthroughs in managerial technologies without which technology transfer processes cannot be accelerated.

It was generally agreed by the seventy national leaders from industry, academe, and government, who attended the conference on R&D consortia and technology transfer that a new conceptualization was needed. This became the focus of the panel discussions and focus groups.

Four broad primary themes emerged from the ensuing conversations.

(1) The process of technology transfer is non-linear. This perspective argues the more conventional view that the root of all technology is in laboratory driven science and that it moves in a neat progression through a series of identifiable steps. One contributor (Dayne Aldridge/Auburn U)) suggested, quite to the contrary, that technology is something that happens in numerous feed-back loops throughout the stages proposed by the co-chair (Rogers) of innovation, translation, and commercialization. In this combined view science is a pool of knowledge -- to be tapped as needed -- underlying all three stages rather than a single beginning point of a linear or sequential activity labeled "technology transfer."

Old view: T2 is a linear process

New view: T2 is non-linear with numerous feedback loops

(2) A second key theme was that technology transfer is at heart a process of human interactions between what one contributor defined as "at least two consenting adults." This raised the immediate question of "who" should be involved in technology transfer, and "what" qualifications they should have. The answer was that it should be the best or most senior person required to do the job. In contrast, the conventional attitude views the T2 process as a secondary process to which the best people need not necessarily be committed or whose committtment cannot be afforded. Coupled with this understanding came the recognition that "technology" is not a deliverable that can be neatly packaged and forwarded. It is a process and it travels best in the minds of people.

Old view:	T2 consists of deliverables (papers, patents, etc).
New view:	T2 is a process of moving knowledge between people.

(3) A third theme, coupled to the prior one, was the general agreement that technology transfer must occur in a timely fashion. As one participant (Frederick Betz/NSF) suggested, it is a "real-time" process. It is something that happens by people doing and exchanging ideas rather than by creating anonymous "deliverables." Another panelist (Stotesbury/MCC) volunteered his finding that "the key is in providing a constant stream of transfer as every single point

before we can even think of calling it a technology." In short, if a firm commits resources to a laboratory (internal or external to the company) but does not commit the people to participate directly in the commissioned work as it is going on, there cannot be a timely or constant match between the source of new knowledge and the problem in need of a solution. If anything, it was proposed, the corporate infrastructure has to be better nurtured to allow this process to occur efficiently. And while there should be champions of this process there should "multi-receptors" in any one firm.

Old view:	T2, by being a sequential or linear process from a to z, does not function in "real-time."
New View:	T2 is a "real-time" process that occurs at the source, e.g. it should transfer as new knowledge is created or discovered (not after).

(4) A fourth dominant theme emerged which is central to the title of the conference: "Managing the Knowledge Asset." It was generally agreed that we have entered an era in which knowledge -- itself a volatile and perishable commodity -- is a critical competitive resource of most firms. The question of "How we are to manage our knowledge inventory?" drew attention to the growing dependence of modern economies on this "abstract commodity." If this depedence is correctly analyzed, it is incumbent on firms to focus more specifically and urgently how best to manage the creation and use of knowledge. It was

argued (Dimancescu) that Tayloristic principles are still a dominant reflex in most business enterprises and that they would have to be fundamentally altered if we are to manage knowledge (and the process of technology transfer) competitively. Defining management itself as a new technology, it was suggested, is necessary as a means of focussing creative energy on developing new principles of management. This would move us away from sequential processes that tend to serialize events (Wilson/Cincinnati Milacron) to processes that encourage parallel or concurrent events -- with numerous means for feedback.

Old view:	T2 can be managed hierarchically from the top down
New view:	T2 requires new management philosophy and tools

Follow-up

Although these themes only became obvious in retrospect as comments from panelists and participants were reviewed, it was concluded that new models (MacCordy/Washington U) were badly needed. Current ones are particularly inadequate in explaining the role of patents protection or the role of small companies in buying into consortia programs that today are largely the domain of large companies. In addition, there was a strong belief that current models offer little insight into how best to match the scientific capability of universities to the product and process needs of industry.

It was also felt that there was a strong need for better or new definitions on what is exactly meant by "technology transfer" and a variety of other terms commonly associated with it. This was fittingly stated by a panelist (Telleson) in a quotation of Senecca: "If we don't know which port we are sailing to, it doesn't matter how favorable the wind is."

The short duration of the conference and the liveliness of the discussions did not allow time for the participants to define the susbtance of the new models or to tackle the dilemma of redefining terms. The co-chairs (Rogers/Dimancescu) will be taking these tasks as the departure point of a conference to be held in Aspen, Colorado, in early July 1987 under the sponsorship of the National Academy of Sience in behalf of the Jet Propulsion Laboratory.

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6/21/87

IS MANUFACTURING A SCIENCE - Some possible definitions

ENGINEERING - relates to the solution of problems usually by application of science. The "best" engineering is economical and conservative of entropy loss.

MANUFACTURING - is that activity by which materials and information are transformed into goods or services for the satisfaction of human needs.

MANUFACTURING SYSTEMS - it is the purpose of manufacturing systems to generate wealth (of the sponsoring entity, the employees, and the community).

TECHNOLOGY involves very specific application of engineering. Examples include :- ECM, EDM, lasers, ion implantation, X-ray lithography .....

TAXONOMY

A taxonomy for classifying a manufacturing system can be developed from primary components -

MATERIALS	including energy
EQUIPMENT	includes blast furnaces, computers, robots ...
FACILITIES	includes clean rooms, environments, services ...
PROCESS	information (micro) for materials transformation
LOGISTICS	information (macro), design to distribution ...
PEOPLE	personnel involved, including customers.

INTEGRATION of the manufacturing system addresses the interfaces between these primary components.

PRODUCT COST and QUALITY are second-order results of the manner in which the manufacturing system is operated, they are also a consequence of the whole product life-cycle design.

MANUFACTURING ENGINEERS, or preferably ENGINEERS ASSOCIATED WITH MANUFACTURING are architects, or facilitators, of aspects of all, or portions of the cycle from IDEA, or PROBLEM DEFINITION, through detail idea development out through implementation and the ultimate delivery of customer satisfaction with the problem solution.

This cycle can be defined as the DESIGN or MANUFACTURING CYCLE depending upon context.

Conflicting measures –

In 1985:

Japan bought $25.6 B from U.S.
& internal from "U.S." Co. 43.9 B
thus U.S. presence $69.5 B

U.S. bought $56.8 B across H_2O
& internal "Japan Co." 12.8 B
thus Japan presence $69.6 B

Individual Japanese "consumers" spend over 2x per capita on "US" products than US consumers spend on Japanese goods!

ECONOMIST 4/4 & 11, WSJ 4/1/87

6/87

File renamed DESMFGX+, developed from DESMFGX SCRIPT. 11/07/85

1985 CAD/CAM, ROBOTICS & AUTOMATION

INTERNATIONAL CONFERENCE

February 13 - 15 th., Tucson, Arizona.

POST-PUBLICATION COPY with amendments

Original version downloaded to DISPLAYWRITER and printed onto special mats with two column format and included in the conference proceedings, pp. 437-442.

DESIGN FOR MANUFACTURING

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ABSTRACT

Design must be considered as a holistic process whereby materials are transformed into goods that satisfy certain functional requirements, which represent marketplace needs. Manufacturing is the means of implementing this transformation; important aspects are the measurements systems and the organization of the enterprise, these have considerable impact upon productivity and profitability. This note discusses some concepts of design and their interaction with the manufacturing regime so as to generate products which give customer satisfaction in the marketplace.

3820 version, 8 pages - 5/15/87

1. INTRODUCTION

There is renewed emphasis on manufacturing; perhaps at no time since the late 1800's has so much attention been concentrated upon this area of human endeavor. Bankers, bureaucrats, business executives, economists, journalists, and politicians are all pressing for greater efforts and higher productivity. This attention raises many issues, and a seemingly endless barrage of popular, and fashionable cliches or buzz-words is unavoidable. Every large enterprise has to endure and survive visits from troops of consultants, and dignitaries, all verbalizing the latest rediscovery of the principles espoused by earlier industrialists, Henry Ford, Frederick Taylor and others. Their precepts are now seen in totally new light because of being reborn with new initials.

The computer is the predominant new feature in all this churning with calls for lower costs, higher output and better quality. The computer and it's acolyte microprocessors can, it is promised, bring us the industrial, or manufacturing renaissance that all economies presently seek (1). All an enterprise needs to do in order to survive and be prosperous is to install Computer Integrated Manufacturing (CIM), and Flexible Manufacturing System's (FMS), together with the application of Automation and Robotics. All these, when tied together successfully will comprise a well architected Integrated Manufacturing System (IMS). Amidst these debates only belated attention seems to be paid to the fact that the essential requirement for the survival, prosperity, and growth, of any enterprise is the provision of goods, or services, which meet the needs of the customers, and beyond this generate customer satisfaction with concomitant additional desires.

These 'good' products which generate customer satisfaction must be produced both economically and expeditiously. They must be available to the marketplace in a timely manner at some appropriate rate to avoid dissatisfied potential customers. In the final analysis the products must also be safe, user-friendly, and reliable; they must perform, at least, to the customer expectation, and meet all advertising claims. The overall quality must be adequate to impress the customer with a notion of 'value obtained'. Competition ensures heavy pressure to meet all of these requirements, and for most products today there is only slender pricing elasticity. Thus it is a requirement that costs are tightly managed to ensure an adequate return on the resource invested by the sponsoring enterprise.

It will be observed from the foregoing that the success, survival and future of the enterprise rests upon the ability to deliver satisfactory products. Thus a primary responsibility falls upon the innovators customarily considered separately, and often housed in some 'ivory tower' design department. A substantial secondary responsibility falls upon the personnel, and group, involved with implementing this design output, who are traditionally labelled as 'Manufacturing'. Hence 'Design for Manufacturing' is of extremely cogent interest for any enterprise concerned with those erstwhile intangibles productivity, progress, industrial prosperity, together with the frustration of the competition.

2. THE MANUFACTURING SYSTEM

Manufacturing is an activity which involves complex multiple transformations of materials before saleable products are realized. It is essential that this activity is viewed holistically and managed as a system (2)(3)(4)(5). In an efficient integrated system, functions are linked such that they act synergistically to offer greater total capability than the similar functions acting independently. Integration should also be associated with a smoothing of variables and greater regularity of output. A successfully integrated manufacturing system will exhibit a seamless organizational continuum from design, through the manufacturing processes, out to the marketplace and the generation of ultimate customer satisfaction. Customer satisfaction will be the result of appropriate price (cost), quality, reliability, with timeliness of delivery; these are all pervasive attributes which result from the proper operation of a well-designed system producing well-designed products. The design activity cannot exist independently it must be integrated within the whole system operation.

A system which is operated smoothly will not exhibit spikes, or disruptions, in any of the output curves, it will consume minimum energy and materiel. Overall it will conserve entropy, and this alone could be a sound theoretical measure of design effectiveness. A well-integrated, smooth-flowing manufacturing system will conform ideally to the needs of the society in which it is created, if there is incompatibility there will be inefficiencies. Hence the whole system and its raison d'etre should be viewed in both a thermodynamic and historic context (6). Design and manufacturing systems are the means by which engineers modify the environment to accomplish their prescribed objectives.

The scope of the "Integrated Manufacturing System" must deal with the nature of the whole design, or product cycle, from definition of market need, through manufacture, out to point of ultimate customer satisfaction. Today a very significant sub-set of this larger system is that of manufacturing implementation. The product design sequence should be integrated, or closely coupled, to the fabrication, manufacturing activity and subsequent marketing. To achieve this it is essential to eliminate organizational barriers, and separate departmentalized behavioral and thought patterns. In a well integrated enterprise there should be flexibility, responsiveness, and operational smoothness, as a result of the functional unity of the organization. This will lead to most efficient economical application of resources and provide great leverage with many advantages. The attributes and design of the manufacturing system are discussed by Besant and Lamming (7), and by the author (3)(4).

3. DESIGN METHODOLOGY

Design must be an activity which occurs in an unbounded environment with the objective of solving a well-defined problem. The only boundaries to the creativity and imagination of the designers should be provided by the problem, or the proposed product itself, and not by the structure of the organization. In the ideal case the organization should evolve to accommodate the requirements and technologies which develop as result of the design cycle. This idea is supported in several recently documented electronics design examples (8)(9)(10).

Ideally the design activity should commence with a 'clean sheet'. There should be no encumbrances, preconceptions or restrictions which may inhibit the initial discovery, or innovation phase. A clear and unambiguous understanding of the problem to be addressed by the design must be developed, and from this a comprehensive set of functional requirements must be devised (11). These should be assigned relative priorities. It is preferable for this activity to proceed almost without structure because the imposition of structure, or format, inhibits creativity and tends to preordain results. After some explorations of various design concepts it will usually be profitable to rethink the initial activity. This can add more precision and understanding to the problem definition, and also adjust ideas of the functional requirements. Only after this 'open minded' unstructured sequence should the notion of constraints be permitted to arise. Constraints, and their discussion are always associated with negative thought trends, and these are destructive of the creative process. Some of the constraints may have been dealt with with varying priority as functional requirements, any distinction is somewhat arbitrary. Functional requirements can be viewed as desirable objectives for the design to accomplish, whereas constraints can be construed as unavoidable imperatives resulting from the environment, or from the goals, resources, or limitations of the enterprise.

Format, organization and structure are inimical to creativity, innovation and the design activity. This is born out by the studies done by Root-Bernstein (12) into the mode of problem solving apparently favored by some of the most renowned scientists. However design for manufacturing cannot be planned to occur spontaneously whenever required, some formalization and structure is necessary (13). It may be a myth fostered by iconoclastic, or eccentric and innovative designers that good design is innovation and cannot be measured or managed. Notwithstanding these ideas there is measurement by the eventual customer, and even before this by the engineers who must implement the design in manufacturing. It is nevertheless clear that large, mature, or traditional organizational entities severely inhibit innovation and the emergence of superior new design (14). It is interesting to note that successful designs often result from the activities of small groups which develop good teamwork and integration as result of being compelled to work with limited resources in poor environments, usually against tight deadlines (8)(9)(10)(15).

Notwithstanding the apparently high success rate for anarchic design activities a methodology must be identified for accomplishing the design and thereon ensuring its successful implementation. The methodology in the final analysis becomes a part of the design and manufacturing process, and affords a constraint which must be considered, and either delimited, or evaded.

Good design for manufacturing is an essential attribute of any product which is to be widely offered. It is an obvious requirement that the design be capable of being reproduced with adequate consistency in the necessary volumes using the specified capital assets and consumable resources. The latter considerations are of prime importance to the success of the whole product program, and indeed viability of the sponsoring enterprise. If the tooling does not produce satisfactory quality, or volume, rate, and sufficient variety, with the use of planned manpower, materials and other resources, the critical costing factors rapidly go awry and market projections can shift with disastrous consequence.

The selection of manufacturing technologies is an important part of corporate strategy, and of the whole product life cycle (16). Any design and tooling plan for volume product should embody an overall strategy for eventual utilization of high capacity automated tooling. If done properly this will provide potential for greater elasticity in the economic constraints imposed upon the manufacturing operation which may result from forecasting error or imprecision. An automation strategy must not be applied piecemeal, or retrospectively, it definitely commences with initial product design (17). Manufacturing process and tooling experts must be consulted by the designers at all stages of the design cycle. It must be ensured that the product is compatible for phasing over to increasingly automated procedures as volumes increase.

Several texts are now available which offer guide-lines to design detailing for successful automation and robotics implementation; there are also sound general design texts (17)(18)(19). Nevertheless there can be no rules which axiomatically ensure good design. The best designs can only be recognized by the tests of time and many customers.

The study of industrial archeology provides many examples of successful designs. It is an old engineering saw perhaps of industrial revolution vintage (Brunel, Stephenson, Telford, et al) that if an engineering design looks right - then it is right ! Product design for manufacturing, or any of the sub-sets of automation, ease of assembly, robotics, and the like, should have similar considerations. It is important to recognize early in any prototype program that good designs engender appreciable serendipity when they enter manufacturing (20). It is prudent to avoid 'band-aid' improvements to alleviate problems of manufacturability, because poor design will cause later plagues in terms of higher costs, customer returns, or other problems of a type which cannot be forecast.

In summary, it is essential that all aspects of manufacturing be considered during the product design phase. Capability for manufacturing flexibility to accommodate future design ingenuities and growth in product complexity and/or volumes must also be a factor. It is important, however, not to drive heedlessly for objectives like automation: The requirements for quality, throughput and volume must be balanced against sound analysis of capital and resource utilization. This leads to the final cost figure which is tied to ultimate customer satisfaction with the product performance.

4. DESIGN AND THE FACTORY

For the manufacturing implementation of the design the enterprise may be better served by planning to utilize a new facility with new equipment, and fresh personnel starting from scratch on a vacant lot. This may be preferable to being compelled to design both the product and the manufacturing system to suit existing facilities and workforces. However even if this latter is an 'ab initio' requirement it should be handled as either a low priority functional requirement, or as a constraint for consideration only after first pass conceptual design studies. Additionally it is essential, if existing resource is to be utilized, that realistic financial, productivity, or efficiency measurements are imposed as a basis for resolving options (21).

Clearly if the enterprise owns foundries, and has a workforce with parallel skills it may make little sense to develop a new product family which employs injection molded plastics. However this option must be explored in any initial design cycle and eliminated by later application of the constraints, or by priorities accorded to the functional requirements. If this procedure is not followed with some rigor a wholly unsuitable 'cast iron lawn dog' may be designed. This will result in a temporarily loaded, well balanced production facility, but it may well be engaged in producing product unsuited for satisfying the latest marketplace fashions and pricing regimes. Indeed contemplation of 'going out of business' scenarios may be a preferable course of action if consistent with the long range objectives and priorities defined by the management, or stockholders of the enterprise. Rigorous comparative cost and performance analyses of potentially competitive offerings are essential for the planning of an effective manufacturing operation.

The use of computer assisted design, or drafting systems (CAD) can be a great advantage within an existing enterprise with a relatively stable product family. These systems greatly facilitate implementation of group technology (GT) techniques for design and manufacturing process commonality, and parts rationalization. The use and creation of historic data bases in this manner has value for future learning, cost reduction, design release communication, and implementation of process ground-rules. However the continuance of established proven materials, methods and techniques is ensured by the structure and format imposed by the software, and data banks; equally so by the equipment, experience, and traditions enshrined within the existing factories and management teams. This can significantly inhibit novel developments and innovation. The issue of data-base constraint to imagination has been considered by Pugh (22). Potential organizational impacts are discussed by Rubenstein (13).

These concepts of a methodology for design based upon a responsive measurement system and relying upon a structured set of functional requirements, have equal relevance not only for products, and manufacturing systems, but also for facilities, organization structures, educational activities and other human endeavors; all of which can benefit from systematic analysis.

5. MEASUREMENTS

Systems oriented measures of performance are required for effective decision making and planning. In the past measurements have been based upon traditional accounting and industrial engineering principles. These practices were developed when low single digit interest rates were common, and the capital costs of tooling were at least an order of magnitude less than today. Additionally there was a more leisurely pace in the whole marketplace. In the former environment there was more latitude, greater system elasticity, and inertia; development cycles could be longer, and product life cycles were correspondingly prolonged.

Today there are competitive pressures for shorter development periods with very rapid introduction of new products. These requirements are in conflict with the increasing complexity and process-sensitivity of the newer product families, or their essential components. Huge investment is required and a very long approval, construction, and commissioning cycle before any new advanced technology manufacturing facility can be brought on stream. The cost of these investments, together with the resource development requirements, including personnel, militates against rapid transitions of major design parameters, and product types. New accounting procedures have to be developed in order to make true assessments of worth which can aid resolution of the many design, process and tooling options (21)(23).

It is now more important than ever to attribute financial, or accounting allowances which provide for the long term strategic goals of the enterprise. These should cover not only improved methods for justification of capital equipment (24), but also take account of such items as employee retraining, redeployment, re-education, or even relocation. If these measures of the financial aspects are not included inappropriate designs will be introduced which develop the resources of the enterprise in a less than optimum fashion. In this case unless any new product shows some very convincing lead, or advantages over the competition which provides a fortunate buffer, then disaster will ultimately result. The design activity carries the responsibility for conformance and delivery within these constraints and if they are not understood, measured and managed well there will be only slender prospects for the future of the enterprise.

This view of the design decision structure calls for a rethinking of the whole nature of the task of management, and structures required for its accomplishment. In an industrial society where information is both so rich and dense there are many associated questions requiring resolution. It is not apposite to consider sociotechnological aspects of our problem here, this area has been explored by Tate who gives a sound introduction to the field (25).

An integrated manufacturing system (IMS) to be thoroughly successful requires a revised management, or organizational structure, with a new measurement regime. This is equally true for the whole design activity which must be closely coupled to the fabrication, or manufacturing activities, and subsequent marketing.

6. SUMMARY

Design for manufacturing, or to satisfy the needs of any other activity, must be functional. The design process cannot commence without a thorough investigation and development of an understanding of the whole problem to be addressed, or solved by the design. This can only be undertaken in the context of a well-founded knowledge of the objectives of the enterprise, together with an appreciation of the whole environment and methods of measurement to be applied. The measurement methodology, be it accounting practices, or manufacturing equipment efficiencies must be oriented to produce measurements which relate directly to the objectives for the system. The system must be responsive to means of control adopted as result of these measurements. This applies equally to the measurement of design effectiveness. Indeed the future and prosperity of the enterprise depend upon the effectiveness of the design as it is implemented in manufacturing so as to deliver customer satisfaction in the marketplace. The measurement techniques must be sufficiently accurate and precise as to provide a means of conflict resolution to guide design decisions. Customer satisfaction is clearly the supreme objective both of the enterprise to ensure it's future, and for the sub-set of the design activity itself. To achieve this any design must be suitable for manufacturing efficiently for delivery to customers in timely manner at appropriate cost. This can only be satisfactorily accomplished when the whole activity from the design pad through to the customer accepting delivery is viewed holistically and managed as an integrated system.

The design activity carries responsibility for the success of the whole enterprise. The information interchange, management structure and the way that 'design' is organized and utilized within the enterprise must give adequate acknowledgement to the functional requirements of the total system. The design of the product itself is key for successful manufacturing. It must be basic, rugged, perhaps elegant, but certainly simple and non-fussy. The design must solve the specific problems addressed without adding others.

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MANUFACTURING FOR THE FUTURE

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MANUFACTURING FOR THE FUTURE

Keith M. Gardiner

1.0 INTRODUCTION

1.1 Following periods of growth, prosperity and relative stability of horizons, countries fall prey to introspection and pessimism (1). In America today this phenomenon is exacerbated by the reduced impedance of our communications media occasioned by modern technology. There is a surfeit of data available and this can be reduced to information which can support almost any gloomy postulate or hypothesis. It is the objective herein to highlight some of this data, examine certain indications and attempt to develop recommendations and scenarios for the 1990's and beyond which could influence the future of the United States manufacturing industries.

1.2 Our way of life is inextricably intertwined with our modes of manufacturing. "Manufacturing" of clothing, food, shelter, weapons and other items has been going on in variously organized fashion for thousands of years. There were significant changes resulting from the application of higher density power sources which brought about the industrial revolution. Subsequently attitudes, customs, mores and perceptions of the world have changed and continue to change as the evolution of manufacturing and technology proceeds. There are many issues in manufacturing particularly relating to the changing interfaces between technologies, people and the whole system from idea inception, through design to the realization of products, or services, which generate customer satisfaction. The international economic and political climate is a very key factor, but of greatest importance is a good understanding of the processes of transformation called for by the product designs and the accompanying management of the materials and resources to implement satisfactory products.

1.3 These notes will review aspects of our present situation, and thus define the central importance of manufacturing. A brief assessment of recent developments will be contrasted with some past achievements in order to suggest future directions. The nature of the ideal manufacturing system will be considered, and from this the future needs of the manufacturing arena should become recognizable.

2.0 BACKGROUND A CURRENT SCENARIO

2.1 Where are we now ?' We are in a period which could be characterised as being one which is tending to chaos, intense turbulence and wild day-to-day fluctuations in financial markets. Politically, in a global and historical sense there is remarkable, if uneasy and insecure, overall stability. Admittedly there several places where there is appreciable strife and suffering, but taking a wider historical view, there are probably greater numbers of the total population with horizons which have improved relative to the horizons of twenty, thirty or forty years ago. Times of chaos are also periods of greatest opportunity for those with the will, abilities and resource to establish new di-

3.0 BACKGROUND ADVANCED TECHNOLOGY ISSUES

3.1 A review of the 256K dynamic random access memory (DRAM) chip situation highlights some of the current difficulties with our electronics sector. In the fall of '84 industry forecasts for January '85 indicated a "street price" of $10 for the 256K chip. Manufacturing lines were being configured to implement the volume build up, and it was well known that the DRAM market could be extremely volatile. The forecasts also suggested that the price would fall to $5 by December of '85 based upon projections of manufacturing potential and market needs. Given that projection it was not surprising that silicon fabricators operating under tenuous financial circumstances elected not to join the market wholeheartedly. It is difficult to commit multi-million dollar toolsets to production of items with such a short revenue half-life, and acknowledged volatility. By fall '85 the spot price fell below $3, and went on to reach a low of $1.82 in May '86 (8). By this time a few Japanese manufacturers virtually owned the entire non-captive market, and protests from American industry were beginning to generate belated government attention and negotiations. The Japanese agreed to reduce output and restrict U.S. shipments. By August '86 our domestic electronics output was constrained by lack of 256K chips and the price rose to $8, eventually settling back to $1.90 - 2.00 in January '87. The U.S. Department of Commerce held that fair market value should be $2-3 (9). At one point in this cycle it became "economical", i.e. profitable, for other countries receiving 256K shipments from Japan to re-market into the U.S., thus evading our agreements with Japan and gaining an additional middle-man's cut ! As result of government involvement the U.S. consumer was compelled to pay more for domestically assembled electronics products.

3.2 The industries seeking shelter were sheltered too late, and by inappropriate means. In any event they chose, perhaps unconsciously, to malinger and thus not participate in the market. However, the electronics industry is often held to represent the future. The implementation of advanced technology and design is generally excellent but the industry is inhibited by the very forces that accelerated the initial growth, and give flexibility and responsiveness. There are problems of scale, financing, and short term rates of return; there are advantages to be gained from greater integration and better long range strategy development. These issues are already receiving attention at the national level (10), and it is to be hoped that the spirit of initiative, innovation and independence which has driven this "American-dream" industry can be channelled suitably without too much bureaucracy and sacrifice of proprietary advantage. The most recent announcements from IBM of a 4 Megabit DRAM chip (11), and a mention that 16 Meg. is on the horizon (12), show what lies ahead in electronics; but also vividly demonstrate the need for sustaining investments on a scale that would challenge many national economies.

3.3 Today we are eagerly applying technology to do many things the same way only faster with more precision, and more complexity; we need to develop or exploit newer fabrication technologies more thoroughly. The age of the pre-eminent machine-tool industry is clearly over; in electronics one pressure point now is the improvement of pattern replication methodologies for ever denser and faster products. Tools of these types and their supporting technologies are many orders of magnitude more expensive in terms of both the initial capital, and in the product development costs associated with their use. There is merit is paying attention to different modes of funding for developments on this scale. More particularly so because it is very likely that a multi-million dollar piece of hardware will be obsolete by the time installation and debug are complete. For example, the development of good lithographic facilities today and in the future could have the equivalent strategic importance to the facilities developed and built for the extraction/refinement of uranium 235 in the forties.

3.4 Meanwhile there are many procedures already used by our electronics sector which could be usefully carried over into other industries. In the same sense there are many factory control skills well known by our traditional industry base which could be shared with great advantage to the electronics sector. We do not communicate well between industries. There are clearly many skills

4.3 How do we produce the "best" ? The whole process from identification of need, thorough problem definition, solution implementation out to delivery of customer satisfaction has been explored at length in prior papers (2)(14)(15). Suffice it to say that the process of both product and system design must be dealt with expeditiously and in a totally consistent integrated manner. This does not necessarily mean "Computer Integrated", often, computer integrated manufacturing (CIM) systems are adopted in a technological replication of archaic hierarchical management structures. Present technologies permit the creation and leadership of multi-disciplinary teams. These can be managed and measured against the accomplishment of the final objective which must be the timely and economical satisfaction of the customer need. The implication here is that new organizations are mandatory; these must be flexible and responsive to dynamic market requirements. Drucker, in deploring the many hierarchical layers of management in America, has suggested that we need to consider running our systems in an "orchestral" mode (16). New measurements structures must accompany these redefined and restructured missions (17).

4.4 It is essential to stand back and assess our assets and resources, for they are many and vast. Nationally we are handicapped by a "frontier mentality" which encourages individualism above all else, this leads to fragmentation of efforts, and dissipates appreciable resource. However in terms of innovation and entrepreneurial activity this mentality is our greatest strength. We must recognize these and other attributes, then consciously adjust our institutionalized behaviour patterns to leverage what we have now, and turn it into more in the future. Not only must we develop a team mentality in tackling the development and exploitation of our resources to enhance the asset, we must develop more assets for our whole society. Simply expressed, the preferred cliches for emphasis should be competitiveness, excellence, productivity and cooperation in creating socially responsive systems. Clearly there are significant parts for both academia and government to play in the development and exploitation of these ideas.

5.0 HINDSIGHT LOOKING BACKWARDS AND FORWARDS

5.1 Original lathes had tool rests which acted as the fulcrum for the operator to hold the tool and control feed and depth of cut to produce exactly the required end-result. Subsequently gears were used to produce similar results; in this progression it became necessary to accumulate much data with regard to the nature of chip formation, the dynamics of the process, and the interactions of depths of cut, feed rates, tool shapes, materials, lubrication and many other variables. The researchers had field days; there were many specialized conferences which continue. There were earnest debates in the sixties that "machinability" could never be measured or controlled adequately. Machinability "Registers" were scorned as being impractical, but eventually the conservative paradigms were displaced. Computers were used to analyze machinability and calculate recommended cutting conditions for economic manufacture (18). Some of our productivity measurement discussions have a similar tenor now, but overall we have developed in many directions since the early nineteen hundreds. However most of this development has been aimed at doing the old processes in a similar manner but harnessing some new technologies. In short, in the turning process, we moved from a sound adaptive analog process to a gear driven "digital" process which is now being displaced by electronically driven digital processes (Computer Numerical Control, CNC).

5.2 In the early 1800's the Jacquard loom used new technology for lifting warp threads selectively according to a previously programmed pattern of holes punched in a roll of card which fed over a reading system (19). Rapid pattern changes with many variations were possible, and there was capability for design and set-up away from the loom. The technology enabled the process to be done so much better, faster, cheaper and with greater accuracy that totally new and original patterns became available; this changed the market opportunity, but did not change the "kind" of process which occurred. In general, today we could claim that our "new" technologies enable us to do many things better, faster, cheaper and with greater accuracy. Additionally we have the capability for

6.2 There are very few well documented success stories for the implementation of advanced technology manufacturing and control systems. The most renowned "classic" cases of "flexible" instantly responsive CIM systems are run as "utilities" with a transparent cost of availability. There is no issue of "economic" order quantity (EOQ) because the systems exist for military, or national strategic reasons. The National Bureau of Standards Automated Manufacturing Research Facility is a profoundly significant although very complex example of this genre and it is very well documented (23). All these systems function well when demonstrated, are spectacularly reported, and provide excellent learning vehicles. Reliability issues and economics questions probably make such systems irrelevant for regular commercial applications; in any event their sophistication militates against wide application.

6.3 Several enterprises have launched significant commercial systems with many accolades. These allegedly suffer many failures and disappointments but, for obvious reasons, are seldom adequately documented. Often some very elementary lessons are relearned. A frequent one is the discovery that if a product is well designed with a consciousness of process then it will be ideal for automation, or robotics assembly procedures. As a corollary, however, the product can be assembled manually, or with simple processes and tooling very readily indeed. People-based procedures also afford appreciably greater flexibility in relation to volume fluctuations or model changes and permit greater responsiveness. These systems can be implemented in much less time and for far less investment than with the creation of a "classical" CIM flexible manufacturing system (FMS) supported by automated guided vehicles (AGV's), automated storage and retrieval systems (ASRS's), and the other topical acronym technologies (20)(21).

6.4 Ultimately, however, the performance of people may not be sufficiently consistent, accurate, precise, reproducible or free of contamination for very high volume or advanced technology operations. Alternately, tasks may be dangerous, demeaning or unreasonable for direct human agency; or people of appropriate skills may not be available. In such cases there must be investment in more complex high capital cost systems which require huge resource in terms of indirect labor skills, training and maintenance support. The product volumes must be sufficient to sustain this investment. It is also mandatory that the systems be engineered for high availability, unfortunately not a customary attribute of present day complex systems. An additional difficulty lies in the financial and performance measurements of the system; our present accounting systems do not meet the needs of modern technologies (24). There is also risk of personnel and societal difficulties (25)(26).

6.5 Many analyses show that the sky is not falling, not yet, but there are indications selected by pessimists, or those who wish to stimulate action, that we do have low growth in productivity. The trends for our "smoke-stack" industries, and even for some of our(?) most significant multinationals show that we need to pay attention and be concerned. It is becoming clear that no amount of research, investment, training, or subsidies can enable industries with "smokestack" characteristics or profiles to make any significant recovery, or contribution to the national well-being. They can, at best, have ability to make local contributions, and cater to specialist markets probably of non-global nature. Archaic operations can survive, and even prosper with exceptional promotion. Even though anachronisms, they can produce significant and useful products with worthwhile market volumes. Such operations are a feature of our technological age and they are worthy of preservation, if only for their clear educational value and the utility of their products. Ironbridge, Macclesfield, Styal (in the U.K.), Stocksbridge and Williamsburg (in the U.S.) provide good examples of this style of activity; there are others at many different levels.

6.6 An analysis by Swyt shows that rather long range historical trends are continuing; there are minor perturbations for major wars, or oil embargoes (27). As a nation we are far ahead of most other groups in output. Some of the "rest" are in accelerative output mode and there are indications of convergence to some "equilibrium" status. History happens whatever we do; many of the forces are inexorable, but if we are aware we can ride the forces like a surfer rides the cresting wave instead of fighting futile battles using fiscal and social manipulations which in the long term often prove to tem information should be handled very conservatively, and held in closest possible proximity to the point of application.

7.5 There are several analogies which have merit in developing the profile for the ideal system(2)(14)(15). The village blacksmith has precise control of process; he selects dies according to the shape of the piece to be worked, and the final requirement. Temperature is sensed visually by color, or by feel; the corollary, the formability of the metal can be sensed through the hammer and muscles. Reheating needs can be determined exactly by means of totally subjective judgements, and then the reheating itself controlled similarly by listening to the roar of the forge and watching the colors and sparks around the part. The interfaces between the facilities and environment, the equipment, the materials, the process and the smith are easy to comprehend and manage. The materials are pulled out of inventory and shaped to customer desire in an almost transparent logistical progression. Delivery, payment and customer satisfaction can occur almost simultaneously upon completion for the smaller forgings. The system itself is endowed with wide ranging flexibility and responsiveness; the economic order quantity for repeat orders is almost certainly one. The set-up and preparation times for small parts are minimal, if we assume that the relatively limited sets of tools are within reach, and the fire is going !

7.6 The other model which demonstrates different advanced planning and marketing strategies comes from the fast-food industry. Here we have a near-ideally configured manufacturing system prepared to offer a very limited range of products with capability for many custom options. The customer selects the particular design variation, the material flows through the process, is delivered, paid for, and there is some degree of satisfaction almost immediately. We are beginning to see applications of technology in the fast-food business, initially assisting with logistics matters. There are opportunities in the process control areas, but individual tool controllers with manual assist offer simple reliable operation. It would be foolhardy to increase complexity and require greater employee training in this particular case.

7.7 In any of our systems of manufacturing several factors need focus, these are areas that greater understanding is needed. Process is a notable area of ignorance, or mis-information; whenever we try to improve things we find out that we do not really understand the exact nature of the process. Without this understanding it becomes very difficult to manage the materials through the process. Materials management here implies not only the physical movement through the factory, but also the "chemical" management, or insertion through equipment for appropriate process. No design can be accomplished without measurement, and this is, perhaps, the area of greatest weakness. We have few effective measures for comparative equipment, materials or process selection. We have traditional engineering tools for measuring, or simulating comparative chemical, mechanical and physical performance, but our static accounting systems give us no good models for calculating the effect upon final cost of design alternatives, or materials/process substitutions. There are no sound measures which record overall design efficiencies, and thus alternative equipment, material, process or design decisions are based upon some engineering modelling, overlaid with emotionally derived financial feelings. There is an urgent need for better tools for resolving these types of issues which involve comparative productivities. The approach of Leontief which specifically contrasts input and output offers promise in this connection (33).

8.0 FINAL INDICATIONS

8.1 Many indications can be drawn; we can choose to serve any favored agenda. Many suitable agendas and initatives have been elaborated upon in recent studies (34)(35)(36)(37)(38). We can achieve little if we act singly and in isolation. Cooperation, integration and team play afford great leverage when properly managed. There is need for a nationally recognized and sponsored agenda which establishes the place of the manufacturing system in our society.

pline area. The new NSF initiatives aimed at breaking the conservatism induced by peer review cycles, the publication pressures and specializations associated with tenure issues are to be applauded and encouraged. We need new structures, and homes for new ideas to exploit our native characteristics for "undisciplined", "structure-free" creativity, innovation and entrepreneurship. The design of this workshop is certainly a useful step towards our brighter futures.

9.0 ACKNOWLEDGEMENTS

This survey around the manufacturing arena owes much to the ideas explored by students and visiting speakers in classes on the Philosophy of Manufacturing Systems, and Design at the IBM Manufacturing Technology Institute. Contributions of colleagues associated with these activities and committees of both the American Society of Mechanical Engineers and the Society of Manufacturing Engineers are also acknowledged with gratitude.

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ADDENDA - to accompany notes for talk "MANUFACTURING FOR THE FUTURE"

NEW SYSTEMS

> **"IT MUST BE REMEMBERED THAT THERE IS NOTHING MORE DIFFICULT TO PLAN, MORE DOUBTFUL OF SUCCESS, NOR MORE DANGEROUS TO MANAGE, THAN THE CREATION OF A NEW SYSTEM FOR THE INITIATOR HAS THE ENMITY OF ALL WHO WOULD PROFIT BY THE PRESERVATION OF THE OLD INSTITUTIONS AND MERELY LUKEWARM DEFENDERS IN THOSE WHO WOULD GAIN BY THE NEW ONES."**
>
> Machiavelli (1513)

COMPONENTS OF THE MANUFACTURING SYSTEM

0 PEOPLE |
>---> RESOURCE (A)
0 MATERIALS |

0 EQUIPMENT |
>---> RESOURCE (B)
0 FACILITIES |

0 LOGISTICS |
>---> INFORMATION
0 PROCESS |

MANUFACTURING SYSTEM NEEDS

0 Recognition of place in society
0 Adequate measures of performance
0 Suitable infrastructure and resources
0 Utility - design & customer satisfaction

RESEARCH ACTIVITIES

0 Societal factors, costs, retraining, redeployment ...
0 Accounting, taxation, and tariffs; productivity ...
0 Comparative measures - material, process, technology
0 Understanding of processes, adaptive control ...
  (materials & process innovation)
0 Management of materials through the processes ...
  (design implementation)

NATIONAL REQUIREMENTS

0 Manufacturing imperative
0 Improved measures
0 Infrastructure and resources
0 Global markets / Designs

M.C.C. NOT PRIVATE
NOT PUBLIC

1983 - PEOPLE AS CARRIERS -
LIAISON CARRIER 2 years M.C.C. →
TOO LONG

→ CORP. CHAMPIONS

HAD TO "CREATE CHAMPIONS"
(single CHAMP. vulnerable)
not in Corp. bowels yet)
(continuity)

Shifted listening post / mkt. arm

1. assigned employees

2. -transfer when "tech" is ready?
/standard packages

-transfer when licenceable

vs

continuing flow of tech/
workshop + user document,
+ onsite/demo

3. tech transfer + res. plan
needed / brought
Shareholder production
people in through panels

4. – "New" visitor program
(short-term)
(mid – SR. engineer)

– on-site (appl.) eng.
+ res. eng. interface

- people
- trad'l media not enough

4

- NASA decision-making
  Fed lab at lab level

- Knowledge Network (K-N)
  How far does it extend?

- contractual understanding vital
  Take the $ and run ... (VS)

- gift/affiliate to contract
  (deliverables)

- $ only 1st step / want access to
  people

- Joint resource commitments
  ($/people) KEY

- need deal-maker(s):
  univ/ind/govt
  (ex.: patents, other) to commit
  at "creating" organizations

- NASA - decision making
Fed lab at lab level
→ today: deals c low level
tomorrow: deals c high level
thru lab director

- TECH. DEALS (3 kinds)
  1. "Overhanging" need (ex.: disease)/ easiest
  2. Replace existing Provider (new product/process)
  3. No need established (hardest "deal" to make)

"Not all deal makers are equal"

ARGONNE $280M for tech dev
DOE

ex: schitzophrenic deal maker (lab dir)
responsive to DOE/DOD program
managers, VS
responsive to lab T^2 focus on industry
ex: need money to cover distance
from concept to "reality"
for industry

ARCH → "something can be done"

- "Throw services over the fence"
  ex: Dayton (Wright-Patterson)
  Gould - med. instrumentation
  W. Dayton lab staff
  instrumentation maint./repair
  - "privatize service activities"
  - maintain bond with "inside" lab people

Anticipate Serendipity/proactive

ex: → co. people into lab
(industry view often too narrow in expectations)
Lab people into co...

ex: networking (computer/communic.)
(labs could be threatened by it)

Networking (DEC)

- added value communication system
  1 massive data
  2 electronic bulletin board
    -- Who is Who in research projects
    -- programs
    -- competition
    -- catalogue all tech. reports abstracts / Key words
  3 teleconf. capability
- STILL NOT WORKING

- Knowledge asset
- – " – networking
- – " – engineering

LAB → gap ← Ind

- ✓ domestic application not legitimate
- ✓ control of programs (no industry)
- ✓ Staying out of trouble

~~~

IND → gap ← Lab

- ✓ Short mind-set
- ✓ government not responsive

~~~

(NO rewards)

(No major initiatives w. all participants)

2

Tech Transfer Act ? / Institutional structure ? / FLC ? / scope
graduated scales

The Real Challenge in Materials Engineering

BY THOMAS W. EAGAR

Scientists can now design and build amazing new materials from scratch. But what is possible in the laboratory is not always practical in large-scale production.

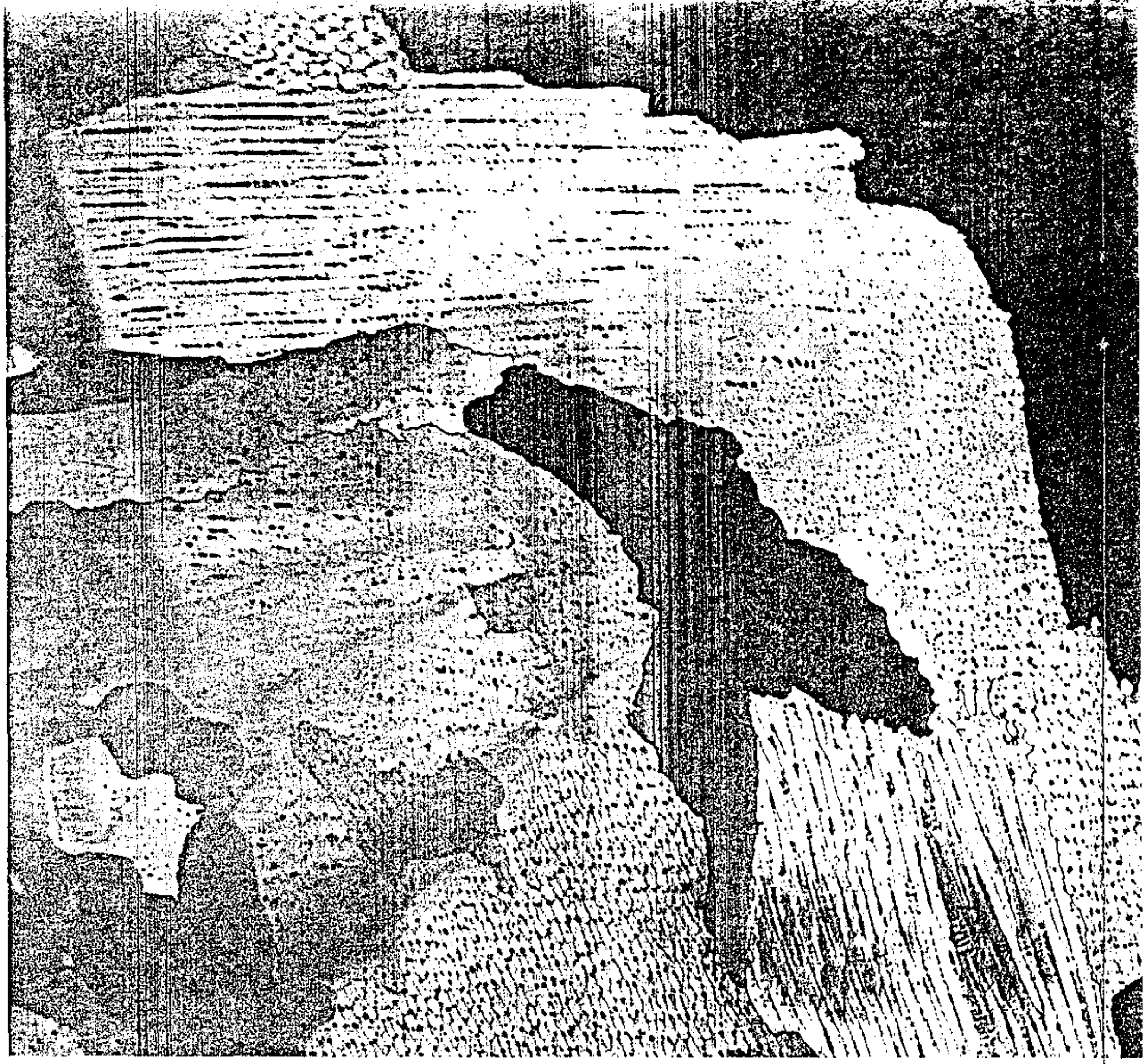
In the early 1960s the United States decided to put someone on the moon by the end of the decade. To the non-scientists and engineers of the world, this was a remarkable goal. In hindsight, however, we can see that the basic knowledge needed to achieve it was available in 1960. The only thing lacking were the resources and commitment to make it happen. In contrast, researchers still have not found a cure for cancer despite huge financial expenditures over the last 10 years. That's because progress in the war on cancer requires fundamental new knowledge.

Like the moon landing, the development and processing of new materials today is a problem limited mainly by the available resources. Materials used to be developed through trial and error. Researchers would make a series of alloys whose chemical composition varied slightly, and then they would try to correlate the properties of those alloys with their different atomic structures.

Today, materials scientists and engineers possess enough basic knowledge about the bonding of atoms to predict and design new materials. In many cases, we can decide what properties we want in a material and then make a material that has those properties. We can turn lead into gold or carbon into diamonds. We can create polymers and ceramics as strong as the strongest steel. We can perform such seemingly miraculous feats largely because we have a better understanding of quantum mechanics—the physics of how electrons behave in solids—and a clearer idea of how the structure of materials relates to their properties. New technological advances in the analysis and fabrication of materials have also contributed to this new era of materials science and engineering.

Creating new materials became a recognized science near the end of the nineteenth century after a geologist discovered a way to see the crystalline structure of steel. He used acid to wear off certain parts of the surface so that a distinct pattern would be visible through a microscope. This photo shows the surface structure of stainless steel. The material has been exposed to a corrosive, high-temperature atmosphere and then magnified 28 times. The raised, razor-sharp shapes reveal the boundaries of separate crystals. The bright spots are impurities.

PHOTOGRAPH:
RICHARD LEE/NIKON, INC.



Decades ago, materials scientists realized they could change the properties of a specific material by modifying its chemical composition or exposing it to heat. For instance, they learned that adding chromium to nickel could create a strong, heat-resistant alloy not susceptible to corrosion. Today's improved nickel-chromium alloys are used to make the turbine blades inside jet engines. The photo at right shows the weld of two such alloys. Scientists at Lawrence Livermore Laboratory have magnified it 100 times to reveal its exquisite crystalline structure.

mines all the chemical reactions in a solid. Therefore, quantum theory can tell physicists why materials behave as they do.

Quantum mechanics has shown, for instance, that electrons in solids absorb light only at specific energies. Compared with electrons in many other solids, electrons in metals can absorb light at very small energies. That's why metals are considered good conductors of electricity. Quantum theory also explains that glass is transparent because its electrons cannot absorb photons of visible light. The photons pass through the glass as if it did not exist.

Insights such as these have led to major technological breakthroughs. For instance, before quantum theory was developed, scientists realized that some materials, which had bands of energy completely filled with electrons, were electrical insulators. It was widely known that since the electrons had no room to jump around or pass from band to band, they only would respond to enormous voltages. But quantum theory revealed that other materials such as silicon and germanium are versatile: they can perform as either insulators or conductors. Under normal conditions, these semiconductor (or semi-insulator) materials behaved like insulators with completely full bands of electrons.

But if a certain number of electrons are injected into a silicon crystal, some of the electrons already present are kicked out of their original energy band into another, making the material a conductor. By regulating the number of electrons injected, we can turn the flow of electricity on and off much as a faucet turns on and off water. It was this ability to transform and control the electrical resistance of silicon that produced the transistor—the forerunner of today's semiconductor chip.

The history of the transistor demonstrates how important processing is to the success of materials development. The first transistors produced had extremely high rejection rates because the silicon and germanium crystals contained impurities that disrupted their electronic structures. Large-scale manufacturing didn't become feasible until William Pfann at Bell Laboratories showed that silicon and germanium of extremely high purity could be produced by alternately melting and freezing the materials in a process called zone refining. Later, researchers at Texas Instruments took advantage of

PHOTOGRAPH: ROBERT KERSHAW

Quantum mechanics showed scientists how to manipulate electricity in semiconducting materials.

However, what is possible in the laboratory is not always practical in large-scale production—at least not yet. Some observers claim that the transition from possible to practical is only a detail, but history tells us that this detail can require decades of time and vast quantities of capital. Indeed, the processing of new materials is the most significant problem materials scientists and engineers face. U.S. industry should be devoting its considerable resources and engineering talent to learning how to process these materials for commercial use on a large scale, rather than inventing still newer ones.

The Beginnings of Materials Science

The development of new materials became a recognized science near the end of the nineteenth century after British geologist Henry Clifton Sorby discovered that he could see the crystalline structure of steel by polishing the surface and etching it with acid. The acid selectively wore away certain parts of the structure so that the structure as a whole became more distinct when viewed through a microscope.

After repeating this procedure with steels of different chemistry and heat treatments, Sorby and others were able to correlate the structure of each steel with its mechanical properties. They noted that the low-strength steels had large amounts of light gray crystals—made up primarily of iron atoms. They called these crystals ferrite (from the Latin for iron). Strong, wear-resistant higher-carbon steels had darker, somewhat shiny areas, which the researchers called pearlite. Pearlite was a mixture of pure iron crystals and of carbon-rich iron crystals. Thanks to Sorby's work, scientists began to understand the relationship between properties, structure, and processing. This relationship still forms the basis for materials science and engineering.

In the 1920s, scientists found that x-rays could be used to discern structures even more refined than those visible through an optical microscope. By bombarding a material with x-rays and observing the angles at which they reflected off different planes of atoms, a researcher could measure the distance between the atoms in a particular crystal and determine how those atoms were arranged in space. X-rays determine the three-dimensional crystal structure of a solid from a series of two-dimensional measurements in much the same way that CAT scans measure cross-sections in human body tissue, revealing three-dimensional abnormalities that are indiscernible to the naked eye.

Using x-rays, scientists finally figured out why an alloy of aluminum and copper known as duraluminum could be made much stronger than the original aluminum or copper alloy. They knew that duraluminum became weak when heated and cooled suddenly from a high temperature. They also knew that heating it again later to an intermediate temperature made it five times stronger than it had been originally. The x-rays showed that when duraluminum was heated and then cooled suddenly, tiny particles formed inside the crystal. When the alloy was reheated at an intermediate temperature, those particles separated from the rest of the structure and distributed themselves throughout the metal as copper-rich areas surrounded by aluminum. That "precipitation" gave the alloy its extra strength.

This was the first explanation of how precipitation hardens metals, and it is still the basis for most of our high-strength aluminum alloys today. But precipitation theory did not explain the hardening of steel, and a decade later, Edgar Bain at U.S. Steel discovered why. While the hardening of aluminum involves the formation of fine particles, steel hardens because of a distortion in the crystal itself: the atoms themselves are rearranged when steel is heated and then suddenly cooled.

A Quantum Advance

The next major gain for materials science and engineering came in the 1930s when quantum mechanics began to explain how electrons behave in solids. In a gas, the electrons orbiting around the nucleus of an atom possess certain fixed energies. For instance, there are 23 separate energies for electrons in a sodium atom.

However, when the gas condenses and the atoms are reorganized into a solid crystalline structure, some of these energies become "smeared," according to quantum theory. What this means is that they are no longer fixed. Unlike electrons in a gas, electrons in a solid can exist only over a limited range or band of energies. These energies indicate how they are clustered around the nucleus of each atom and how the atoms bond. The bonding between atoms deter-

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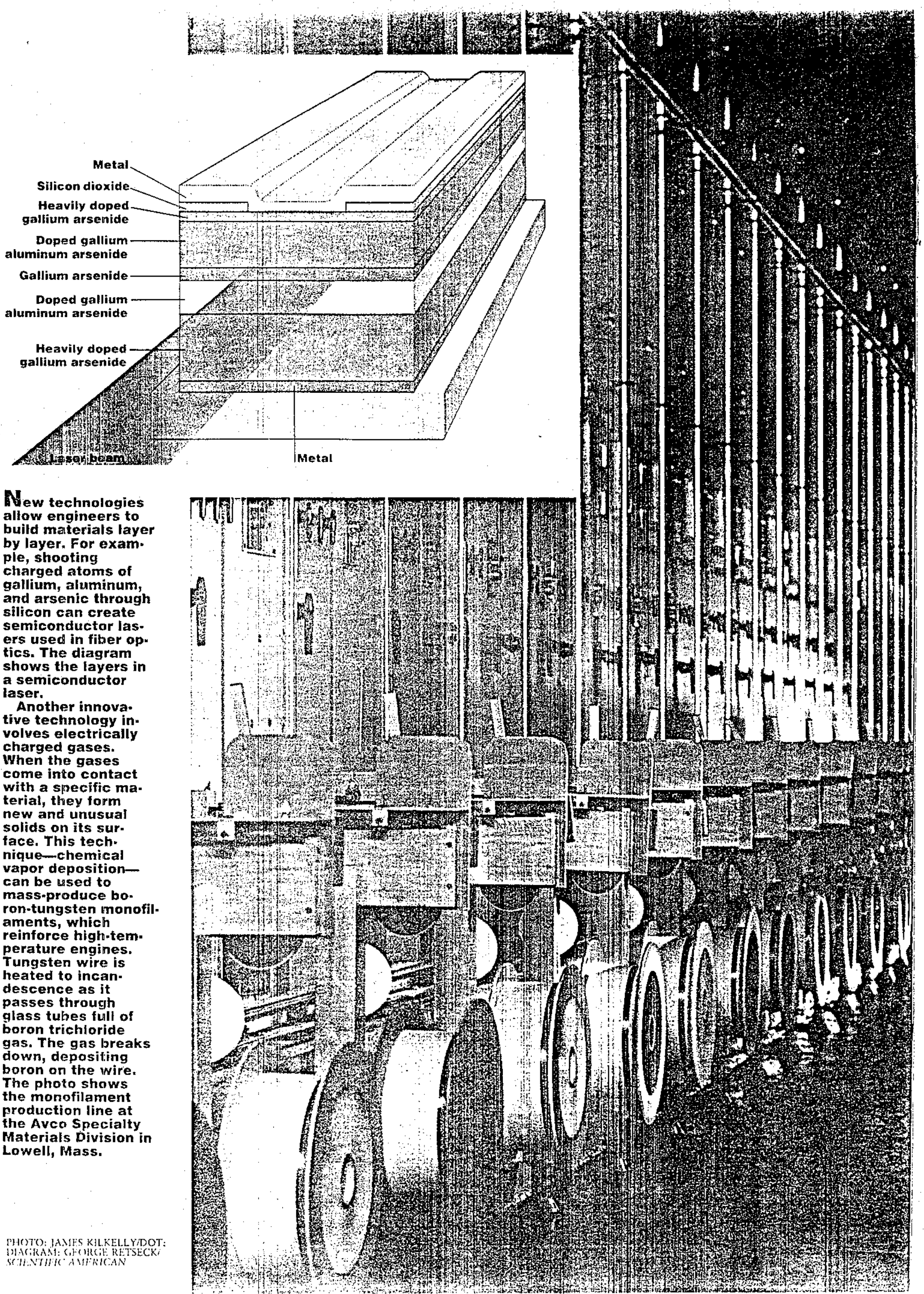
Quantum theory helped scientists understand that they could regulate the flow of electricity in silicon simply by injecting different numbers of electrons. The result was the transistor, the forerunner of today's semiconductor chip. Many of the first transistors never left the factory because the silicon contained impurities that disrupted its electronic properties. The silicon wafer in the photo at left is magnified 50 times to show the major triangular defects in its surface structure.

PHOTOGRAPH:
GORDON P. LEE/NIKON,
INC.



New technologies allow engineers to build materials layer by layer. For example, shooting charged atoms of gallium, aluminum, and arsenic through silicon can create semiconductor lasers used in fiber optics. The diagram shows the layers in a semiconductor laser.

Another innovative technology involves electrically charged gases. When the gases come into contact with a specific material, they form new and unusual solids on its surface. This technique—chemical vapor deposition—can be used to mass-produce boron-tungsten monofilaments, which reinforce high-temperature engines. Tungsten wire is heated to incandescence as it passes through glass tubes full of boron trichloride gas. The gas breaks down, depositing boron on the wire. The photo shows the monofilament production line at the Avco Specialty Materials Division in Lowell, Mass.

PHOTO: JAMES KILKELLY/DOT; DIAGRAM: GEORGE RETSECK/ *SCIENTIFIC AMERICAN*

Just because we can produce new materials on a large scale does not mean we can convert them into viable products.

glamour of biotechnology has faded. Investment in that industry peaked at $850 million in 1983, and dropped to $200 million in 1986. Materials science, on the other hand, has both the theory and the technological means to make good on its promises. Thus, it may be more commercially successful.

A Dose of Reality

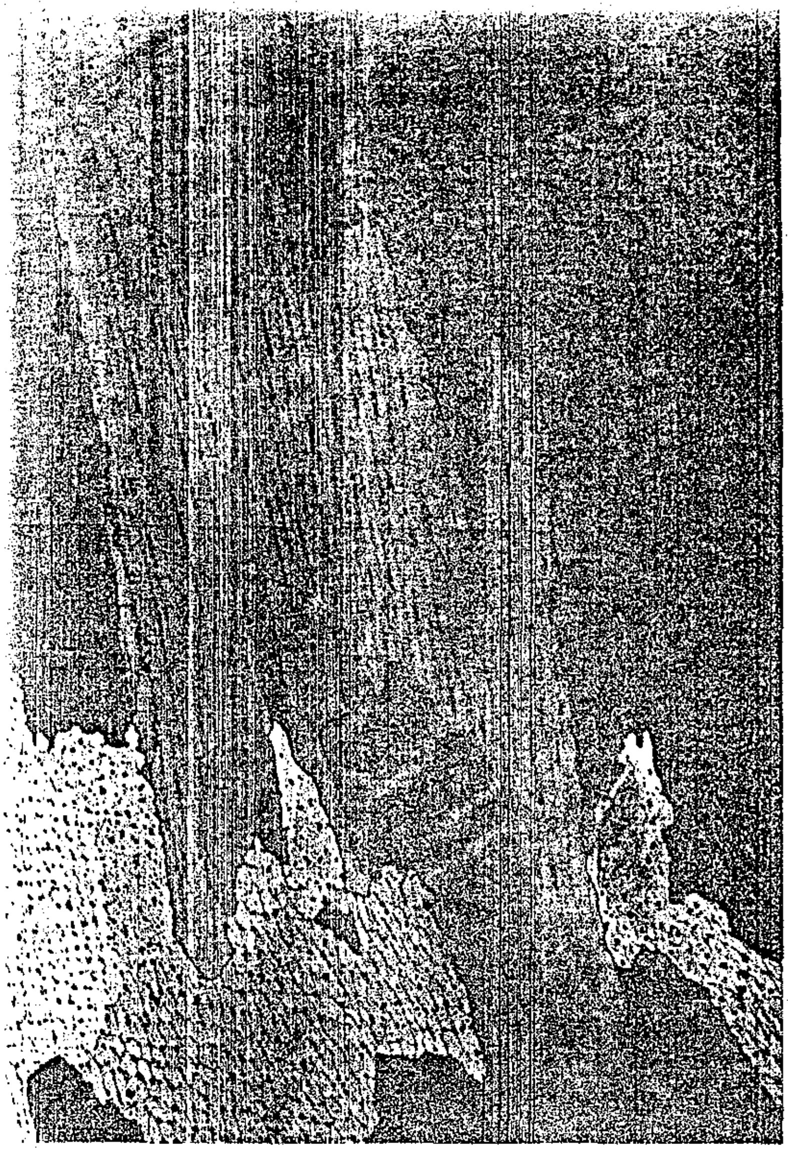
Nonetheless, there are limits to what we can achieve in materials science. Some of the limits are dictated by physical laws. For example, the elasticity, stiffness, and melting temperature of a material depend on the strength of its atomic bonds. Carbon-carbon bonds are the strongest, so diamond, which consists solely of carbon-carbon bonds, is the strongest material known. Diamond has the highest melting temperature as well. But even though polymer molecules also have a carbon-carbon bond, they do not have as great strength or as high a melting temperature. That's because these two physical properties are controlled in polymers by the weaker intermolecular bonds that link the carbon-carbon chain. Thus, there are inherent physical limits to the strength and melting temperature of polymers, and materials science can not alter that fact.

Scientists and engineers can now predict or explain many such differences among various materials and determine their practical limits. The problem is that not all researchers agree on what those limits are. In some cases, there is honest disagreement about the proper assumptions. However, all too often the confusion stems from the distinction between what is possible in the lab and what is practical in mass production. Furthermore, just because we have the capability to produce new materials on a large scale does not necessarily mean we can convert them into usable, cost-effective products.

Take, for example, high-technology ceramics and composites. They are projected to command $10 billion in annual worldwide markets by the year 2000. This is only one-fiftieth of what the world's present steel industry commands, yet government and industry are spending much more on fine-ceramics R&D each year than they are on steel R&D. The justification is that the market for high-temperature structural ceramics is forecast to constitute up to $300 billion of the automotive industry by the end of the century. The forecast is based on the prediction that once ceramics are used in car engines, car owners can expect a 30 percent increase in fuel economy.

This is a very impressive claim, but one that many insiders question. First of all, to achieve such improved fuel economy, an engine would have to operate at a higher temperature than is now possible, and as the temperature increases, other energy losses would become greater. After all, one can hardly expect to exhaust gases from the tailpipe at 1,80 Fahrenheit. And very few people will want to d

PHOTOGRAPH: DAVID PEARSON/SCIENTIFIC



We can now decide exactly what properties we want in a material and then make it.

both the conducting and insulating properties of silicon by writing entire circuits of conducting silicon on a single chip, thereby producing the first integrated chip.

Looking Inside Solids

The invention of techniques that analyze crystalline structures at the microscopic and even atomic level gave materials science and engineering yet another major boost. The transmission electron microscope of the 1950s enabled researchers to measure distinctions in crystalline structure 1,000 times finer than those visible through the optical microscope. In the 1960s, the scanning electron microscope magnified surfaces to a degree that had never been possible before, while the electron microprobe provided a microchemical analysis of those surfaces. The Auger spectrometer was developed in the 1970s, providing an even more precise instrument for microchemical analysis of surfaces.

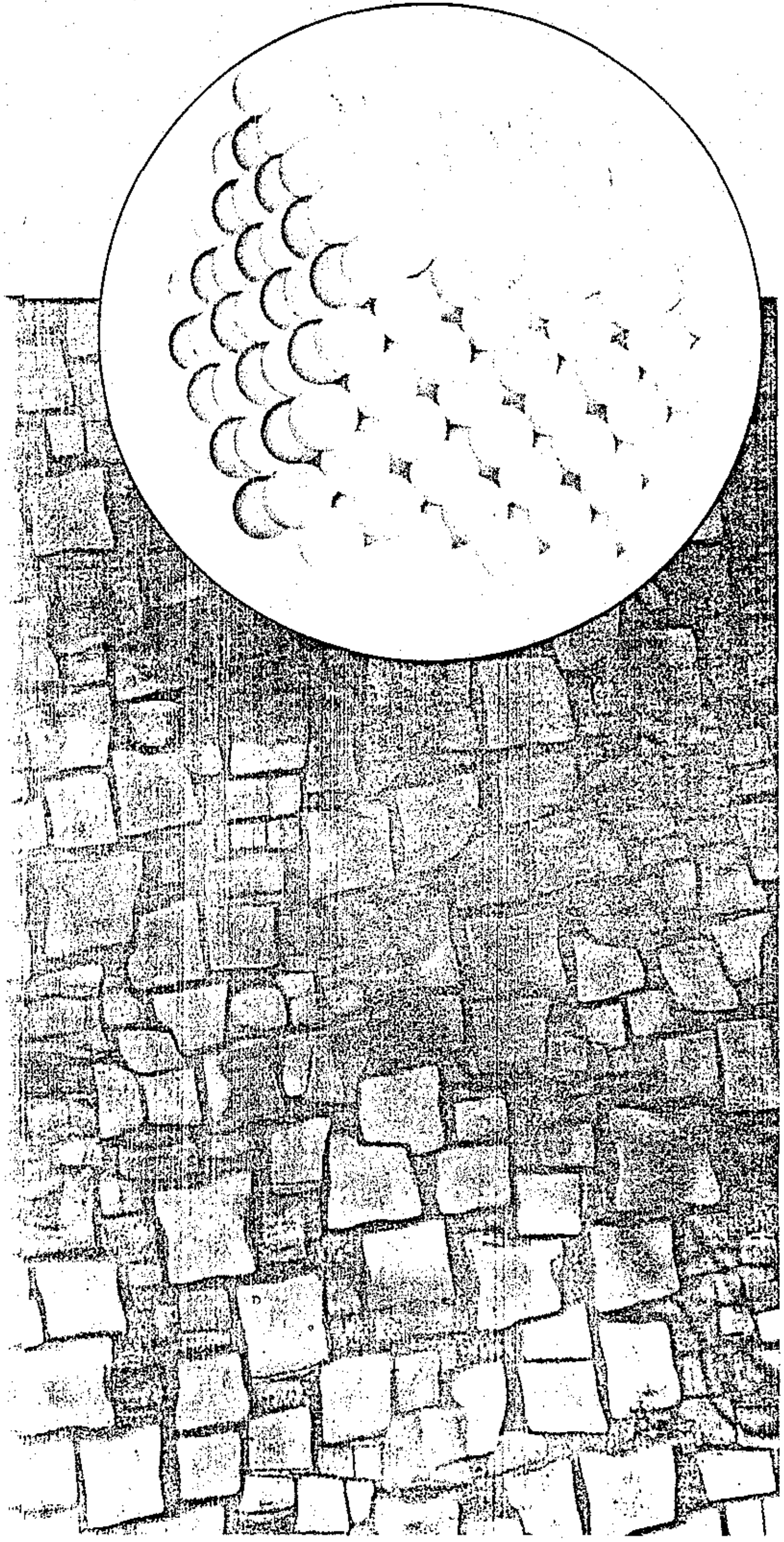
The latest technology—the scanning tunneling microscope—places a probe within a few atom distances of a crystal and measures the rate at which electrons jump across the gap between the probe and the crystal. That reveals both the electronic structure of the atoms and their geometric structure—how far apart they are from one another. The scanning tunneling microscope is the first instrument that can measure both these structures simultaneously.

With these and other new technologies, materials scientists can correlate structure with an expanding number of properties ranging from mechanical, electrical, and optical to magnetic, surface, and interfacial (the boundaries between crystals packed together in a material). The more we know about how different atomic structures relate to particular properties, the more precisely we can design the materials we want.

But there is more to the new era of materials science and engineering than improved characterization technologies. Materials science is no longer a knowledge-limited discipline in large part because of our ability to theoretically predict properties and then make the different materials that we conceive theoretically. The development of high-speed computers has permitted materials scientists and engineers to take full advantage of quantum theory. Now we can do more than just calculate the electron densities and properties of a hydrogen atom (which contains only one proton and one electron). We can determine the electron densities and properties of hundreds or thousands of atoms clustered together in crystals.

Such calculations involve an extraordinary amount of number crunching, which would be impossible without a computer. A sodium atom, for instance, contains a nucleus and 23 electrons; in order to figure out the properties of even one atom, we need to solve hundreds of quantum mechanical equations. We must solve a first equation for the nucleus and electron one, a second equation for the nucleus and electron two, and so on on up to the nucleus and electron twenty-three. Then we must solve equations for the different combinations of electrons. To figure out the properties of the most microscopic crystal requires trillions of calculations.

Such calculations yield exciting new insights into the properties of the electrons that lie on the surface of small crystals. For example, experiments have shown that an alloy in which platinum and nickel are mixed randomly is 99 percent platinum on the outer atomic layer and only 30 percent platinum on the second layer from the surface. Now that we have



A new nickel-aluminum superalloy is well suited for use in engines that function at extremely high temperatures. A sample of this alloy is magnified about 140,000 times in the photo at left. The inset illustration shows how constellations of nickel atoms (white) and aluminum atoms (color) interpenetrate in individual crystals. High-temperature engines made of the alloy are more fuel-efficient than those operating at standard temperatures.

a vehicle with a 10-foot-high smokestack. To cool down exhaust gases, car manufacturers would have to install a radiator, thus adding to the weight of the car and decreasing the efficiency with which it burns fuel. When the entire engine system is considered, estimates show that high-temperature ceramics will improve fuel economy by only 3 percent.

At this point, ceramists cannot even produce a reliable high-temperature ceramic for less than five times the cost of a metal part. They claim that their raw materials—which include silicon, aluminum, oxygen, and nitrogen—are abundant. Yet they spend a tremendous amount of money purifying and inspecting the final product. And even so, finished ceramic parts can have rejection rates of 90 percent or more because of imperfections in their structure.

Another problem with ceramics is their brittleness. One recent technical paper on silicon-dioxide glass claimed that its resistance to fracture has doubled. However, the paper failed to note that this means the material is still more than twice as brittle as the poorest grade of cast iron. Brittle car engines, of course, are not very economical. If your engine cracks, you have no choice but to buy a new one.

Furthermore, what if researchers make the internal-combustion engine obsolete by developing an efficient, low-cost way to produce electricity directly from fuels? What will be the advantage of high-temperature ceramics then? Ceramics have much to offer in automotive applications. But to tie the future of this industry to the growth of a single material is both premature and naive.

The Complexity of Composites

Composites have problems similar to those of ceramics. Composites are materials such as fiberglass, in which a glass and a polymer are mixed to exploit the benefits of both the strength of glass and the flexibility of plastic. However, it is unlikely that the cost of composites will ever compete with the cost of metals or plastics in high-volume uses. Producing composites simply involves more steps. In addition, parts made of a composite are much more difficult to join in a complex assembly.

Composites often consist of materials with vastly different types of chemical bonding. In any joining process other than putting in a simple screw, the chemical bonds of the materials being joined must match. This greatly restricts the number of joining methods available. The joint where the composite meets the larger structure must also have properties equal to those of that structure. Yet it is unlikely that the material that glues the composite to the rest of the assembly (being a non-composite in nature) can match the properties of the composite. As a result, it is very difficult to join complex composite materials together.

In a sense, composites are to aircraft as aluminum is to automobile bodies. Car manufacturers could

INSET: GEORGE V. KELVIN/*SCIENTIFIC AMERICAN*

A true competitive advantage often comes from better-quality processing, not from a technologically superior material.

reduce vehicle weight and increase fuel efficiency by bolting aluminum hoods and fenders onto auto bodies. Airplane builders could do the same by attaching composite rudders and wing flaps to airplanes. But no one is mass-producing autobodies with aluminum or aircraft frames with composites because of the difficulties of joining these materials. Despite the claims of materials enthusiasts, most composites will remain high-performance, high-cost materials for limited markets such as the military.

The Secret Is Processing

If we look closely at the information revolution, we find that it has depended primarily on the ability to make silicon chips faster, cheaper, and smaller. While other developments in electronic materials are very exciting scientifically, advances in silicon processing have provided the economic and technological basis for the information revolution.

Materials processing has also been crucial to the growth of the steel industry. Today Japan is readily acknowledged as the world's leading steel producer, but its secret does not lie in any special knowledge of how to make the material. Rather, Japan leads the world in steel production because it has invested more heavily in materials-processing equipment. As a result, it produces steel of equivalent or higher quality at significantly lower costs than any other country.

For example, Japanese blast furnaces are more than twice the size of older U.S. furnaces, on average. With a lower surface-to-volume ratio, large furnaces lose less heat per ton of iron, which allows them to burn fuel more efficiently. In addition, the amount of labor required to operate a large furnace is not very different from that required to operate a small furnace. However, as the Japanese are now learning, nations such as Korea, Brazil, and Romania can also invest in this resource-limited industry and, with even lower labor costs, compete very effectively.

In industries such as aerospace and defense, where competition is limited, companies that focus on new materials and cutting-edge technology are most successful. But in industries such as semiconductors, steel, and automobiles, where the competition is severe, companies that put more resources into materials processing have the lowest costs and are thus the most profitable.

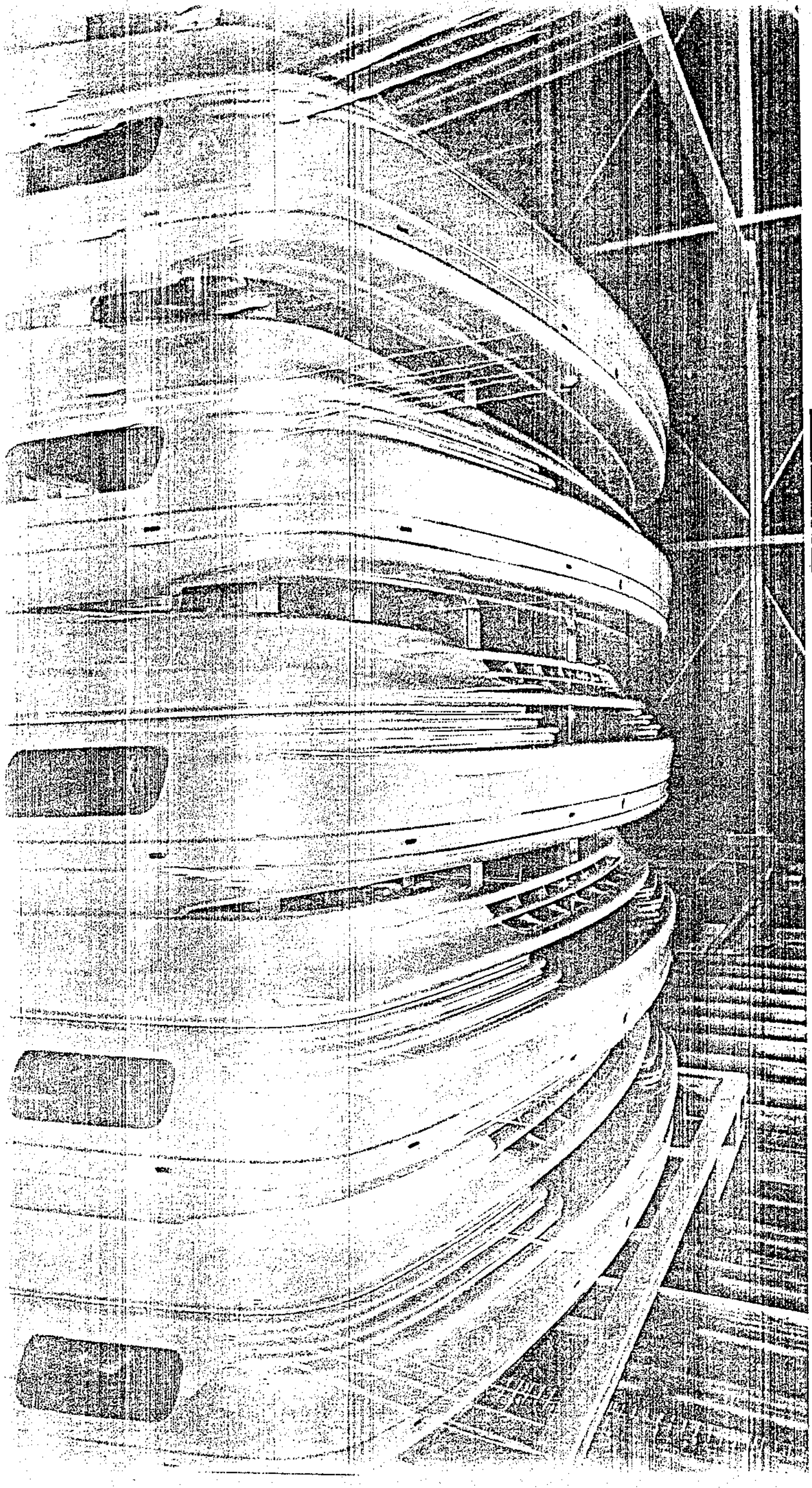
The story of Lincoln Electric Co. shows how important processing is in maintaining a competitive edge. More than 15 years ago, Lincoln Electric, the largest U.S. welding-electrode company, shocked the industry by introducing an electrode that did not require a shielding gas to protect the steel from the nitrogen in air. Once the shielding gas was eliminated, welding equipment became smaller and easier to use. Also, since the gas had been a major expense, materials costs dropped.

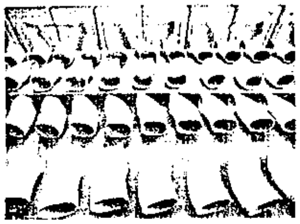
Within two or three years, Lincoln Electric's competitors had successfully copied the new electrode in the laboratory. Yet even today, they still have not made a dent in the market. Lincoln Electric now controls the entire world's use of this type of welding electrode—not because it has a technological advantage, but because it can make and sell its product for less.

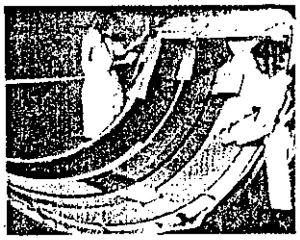
How did the company accomplish this? First, it developed methods to reduce the cost of producing the alloy powder that gives the electrode its special characteristics. Second, it refined its electrode-forming equipment and quality-control procedures to produce welding wire that was of consistent quality. As Lincoln Electric's success shows, the true competitive advantage for many companies today comes from better-quality and lower-cost processing—and not from a technologically superior material.

For this reason, the hunt for new materials should remain primarily the province of academic and government laboratories. And those labs should continue to receive federal funding. However, once new materials are conceived, U.S. companies should step in and decide which are the most practical for commercial exploitation. The companies should also supply the resources necessary to develop low-cost, high-quality methods of processing these materials. After all, the successful industrial development of new materials is often driven more by market pull than by technological push.

Designing materials with curious properties is fun for the materials scientist and engineer, but it does not often yield results of major commercial or social benefit. American companies must spend their resources learning how to manufacture existing materials economically, not searching for exciting new materials. Otherwise, we will only be creating gold that is more expensive than the gold we dig out of the ground. The promise of new materials will fade and both the materials scientists and the general public will suffer. But if we spend our resources o cessing selected new products of high reliabili low cost, we will all be winners. ☐







Dramatic growth is predicted in the markets for advanced ceramics, composites, and plastics. Some materials enthusiasts even claim that ceramic parts (top) could be used in automobile engines to effect a 30 percent increase in fuel economy. But engineers still cannot produce a reliable high-temperature ceramic for less than five times the cost of a metal part.

Similarly, high-temperature composites cost so much to manufacture that they are limited to custom applications such as military jet engines and spacecraft. Above, two technicians at Martin Marietta Aerospace assemble a jet engine from composite parts.

Plastics may have a brighter future. Ford already manufactures a plastic bumper for its Taurus sedan (left), and GM has installed plastic body panels in the Corvette and Pontiac Fiero. Since plastics are light, they improve mileage. Also, they don't rust, and they resist minor damage, exter the life of th mobile.

PHOTOS: JAMES KI
DOT; ASMINT/*ADVA*
MATERIALS & PROCE

The Promise of New Materials — Real or Imaginary?

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INTRODUCTION

Materials science and engineering (MSE) is currently experiencing a great deal of international attention. A September 1986 Office of Technology Assessment report ranked advanced materials with information technology and biotechnology as the three most important "high-tech" industries of the future. Over half of the 13 projects identified in the Japanese Ministry of International Trade and Industry's Program of Basic Technologies for Future Industries are materials related, and three others have a strong materials component. Further, the leaders of the European community, the United States and Japan have organized an international program entitled the Versailles Agreement on Materials and Standards (VAMAS) in recognition of the growing complexity of new materials and of their growing importance in international trade.

From the Metallurgraphics entry "Advanced Ceramics" in the August 1986 *Journal of Metals*. Shown are (clockwise) ultra-pure alumina powder; a medical hip joint replacement; a tundish nozzel for the continuous casting of steel; a silicidized resistor; and a ceramic multilayer substrate for electronics.

At times, the trend to new materials seems to be a hysteria—many major industrial laboratories in both the U.S. and Japan are converting 20 to 50% of their research and development efforts to this field.

WHY THE INTEREST?

Why is there such a strong interest in new materials? One answer lies with technical and non-technical magazines and newspapers which are constantly emphasizing new application potentials—plastics to reduce weight and cost of autobodies; ceramics for engines to improve efficiency and service life; composites for aircraft to reduce weight and provide electronic invisibility; electronic materials for faster and larger computers, higher speed communications, etc. The reports invariably include an admonition that the nation that does not pioneer these developments and applications may ultimately lose entire industries and be relegated to the list of underdeveloped countries.

A second answer lies with the many truly exciting developments taking place within the materials field. Indeed, seven of the past 14 Nobel Prizes in Physics have been awarded for materials-related research.

For example, low-loss optical fibers and semi-conductor lasers have been developed over the past decade to the extent that the use of copper conductors or microwaves for long range communications will decrease dramatically in the future. The high rates of information transfer with these new materials have lowered the costs of communication by orders of magnitude, thus providing a boon to the information industry. The development of high strength concretes over the past five years may alter the construction industry as dramatically as did the introduction of structural steel one hundred years ago.

Another reason for the interest in new materials is that materials are tangible. It is easier to demonstrate or describe the properties of a new material than it is to explain the utility of a new axiom of mathematics. Further, in the past, materials were developed through a rather serendipitious process. Today, however, the structure of matter can be engineered to provide the required physical properties. Simply put, materials science and engineering has embarked upon a new era.

AN HISTORICAL PERSPECTIVE

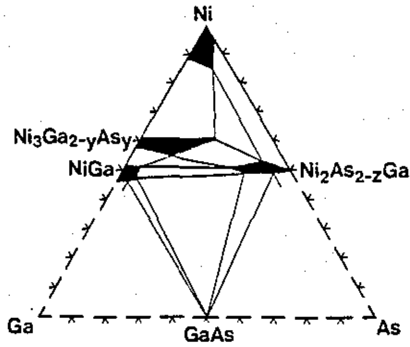
Materials science began to grow rapidly in the latter part of the nineteenth century after a British geologist, Henry Clifton Sorby, discovered that he could see the crystalline structure of steel by polishing its surface, etching it with acid and viewing it through a microscope. By repeating this procedure with steels which had differing compositions and heat treatments, Sorby and others were able to empirically correlate the microstructure of the steel with the bulk mechanical properties. They noted that the low strength steels had large amounts of pure iron crystals which they called ferrite, while higher carbon steels achieved their strength and wear resistance due to an iron carbide which they called cementite. This was the beginning of the processing-structure-property relationship which still forms the basis for MSE. It was soon found that further chemical modification or heat treatment of the steel would change its structure and properties. For example, a low strength ferritic steel could be heated and quenched to produce a new structure of exceptional hardness, or chromium and nickel could be added to produce a steel of greater density, different structure and excellent corrosion resistance.

In the 1920's, x-rays were used to determine even more refined structures than could be seen in the optical microscope. One of the major early successes of x-rays was an explanation of the hardening of duraluminum, an alloy of aluminum and copper, which, when heated and quenched from a high temperature, produces a soft structure. This was the opposite of steel which produced a harder structure when heated and quenched. A later, intermediate temperature treatment would strengthen the aluminum but would soften the steel. The x-rays showed that the strength of the duraluminum was controlled by dissolution of the copper in the aluminum at high temperatures and the solid state precipitation of copper-aluminum particles at subsequent intermediate temperatures. This was the first explanation of precipitation hardening in metals and is still the basis for most high strength aluminum alloys. Subsequent attempts to use x-rays to find a precipitate responsible for the hardening of steel were unsuccessful. It was not until a decade later that E.C. Bain at U.S. Steel explained the hardening of steel as a hard crystallographic modification of the ferrite rather than a solid state precipitation process as with duraluminum.

The next major gain in MSE came in the 1930's when quantum mechanics began to explain, at least generally, some of the electronic and optical properties of materials. Spectroscopists had shown in the late nineteenth century that the electrons in gas molecules existed in discrete energy levels, but when such ideas were transferred to solids, it was impossible to explain even the simplest properties such as electrical conductivity or transparency. Quantum mechanics treated the solid as a single giant molecule and showed that the discrete energy levels of the gaseous electrons were distributed over a band of permissable energy levels. This insight permitted materials scientists and physicists to explain qualitatively, the behavior of electrons in solids. This ultimately led to the demonstration of the transistor in 1947.

It was known that some materials had bands completely filled with electrons and hence were electrical insulators and were transparent to light. Quantum theory explained that some materials, such as silicon or germanium, lie halfway between metals and insulators in their electronic band structure. Under normal conditions, these semiconductor (or semi-insulator) materials behaved like insulators. By injecting electrons into the crystal in a certain manner, however, the insulator could be switched to a conductor. The number of injected electrons controlled the overall resistance of the material making it a variable resistor.

It was this ability to transform the resistance of the materials from an insulator to a conductor that produced the transistor. Nonetheless, materials scientists quickly found that it was easier to demonstrate a principal in the laboratory than it was to commercialize it in large scale production. The history of the transistor splendidly illustrates the importance of processing as another component in the structure-property relationship.



From the article "Contacts to Compound Semiconductors" by T. Sands in the October 1986 *Journal of Metals*. Shown is an isothermal section (T<600°C) of the thin-film Ni-Ga-As phase diagram as determined for 45 nm Ni deposited on (100) GaAs and annealed in forming gas.

The first transistor consisted of two large crystals touching each other at a point. The leads were crudely formed copper wires. One of today's integrated circuits built in this manner would weigh several tons and would occupy the area of a football field. The first production transistors had extremely high rejection rates until Pfann at Bell Laboratories showed that silicon and germanium of uniform purity could be made by alternately freezing and solidifying the materials by zone refining. Later, developers at Texas Instruments took advantage of both the conducting and insulating properties of silicon by writing entire circuits of conducting silicon on an insulating silicon chip, thereby producing the first integrated chip.

Another major gain in MSE has been the growth of structural analysis techniques. The transmission electron microscope of the 1950's married the structures measured in the optical microscope with those measured by x-ray diffraction. The electron microprobe of the 1960's provided chemical composition on a microscale. The scanning electron microscope of the 1960's provided exciting new magnifications of surfaces, while the Auger microprobe and secondary ion mass spectrometer of the 1970's provided microchemical analysis of the surface. The scanning tunneling microscope of the 1980's will provide measurements of both the electronic and geometric arrangement of individual atoms on the surface of the material. Indeed, it may be argued that these improvements in materials characterization methods are the catalyst for the new era of MSE. It has become possible to measure structure in entirely new ways, allowing the materials scientist to improve his empirical correlation of structure with properties. With these new methods, the number of properties of interest have expanded from primarily mechanical or electrical or optical to magnetic, surface, interfacial, etc.

But there is more to the new era of MSE than improved characterization technologies. The other two major gains of the past two decades are theoretical predictions of properties and an ability to make the materials which we conceive theoretically.

THEORETICAL PREDICTIONS AND MATERIALS PROCESSING

On the theoretical side, the growth of high speed computers has permitted full utilization of the principles of quantum mechanics which were developed fifty years previous. It is now possible to calculate not just the electron densities and properties of hydrogen, but of clusters of hundreds or thousands of atoms, permitting the materials scientist to understand the transition from atomic properties of gases to the properties of bulk materials. This transition is providing some very exciting new insights into the properties of surfaces and the mechanisms of catalysis.

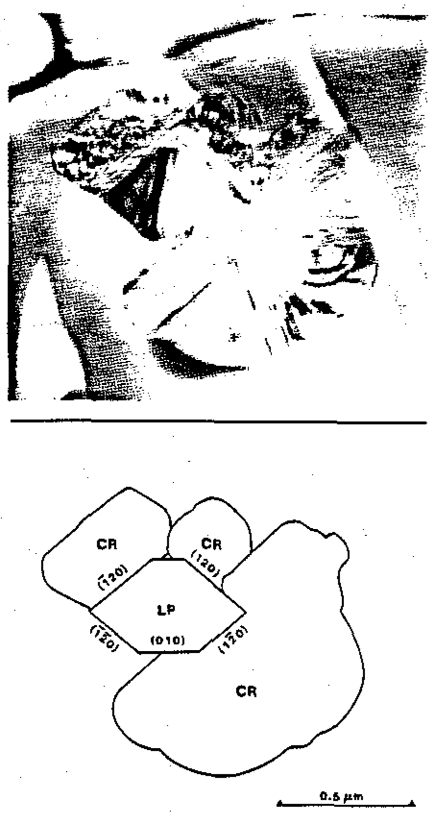
For example, a platinum-nickel alloy which mixes randomly in the bulk has been shown to be 99 percent platinum on the outer atomic layer and only 30 percent platinum on the second layer from the surface. The surface of silicon has been found to order in a different crystal unit than the bulk silicon. Such insights into surface composition and structure can be combined with quantum mechanical calculations to predict the energy states of surface electrons. In this way, new catalysts can be designed to enhance production of chemicals and pharmaceuticals. Such information on the composition and geometry of surfaces will also explain deviation from bulk properties as ultra-miniature electronic circuits are produced.

The combination of the new characterization instruments and the theoretical predictive capability of MSE is creating an explosion in the century-old study of structure/property relationships. However, these two factors alone could not create the new era of MSE. The final area of progress has been materials processing. Through methods such as molecular beam epitaxy or ion implantation, wherein streams of atoms are accelerated toward a surface and condense in the pattern and structure desired, materials engineers are able to build up structures atom by atom. For example, semiconductor lasers may begin as mixtures of gallium and arsenic, but ultimately feature a composition which is changed atom layer by atom layer to a mixture of gallium, aluminum and arsenic to produce the desired optical and electronic properties. Thus, materials scientists are now creating the materials conceived by the theoreticians.

Many processes are enabling bulk production of materials which possess a chemical and structural uniformity which approaches atomic dimensions. These processes include plasma deposition wherein an ionized gas condenses on a surface, and chemical vapor deposition wherein a mixture of gases reacts on a surface to deposit a solid; sol-gel chemistry wherein metallo-organic molecules are mixed and subsequently decomposed at relatively low processing temperatures to produce a mixture of atoms that otherwise would separate into a more stable form; and rapid solidification wherein liquid atomic structures are frozen into the material by cooling at rates of 10^6 degrees per second.

KNOWLEDGE LIMITATIONS VS. RESOURCE LIMITATIONS

In the early 1960's, the United States set a goal to put a man on the moon within ten years. To the non-scientists and engineers of the world, this was a remarkable goal. Looking back today, however, it is apparent that all of the basic knowledge for doing this was available in 1960. All that was lacking was resources and committment. As we all know, the resources were committed and the first man stepped on the moon in 1969. Subsequently, many non-scientists and non-engineers in the American government felt that there was no technical goal which was out of reach. Thus, in the early 1970's, the United States Congress declared war on cancer and stuffed the war chest with financial resources equal to that spent in getting to the moon.



From the FORUM article "Glass Ceramics from Hermetic Metal-Insulator Seals" in the December 1986 *Journal of Metals*. Shown is epitaxial growth of cristobalite (CR) on {120} faces of Li_3PO_4 (LP). Micrograph by T.J. Headley of Sandia National Laboratories.

Unlike the Apollo mission—a *resource-limited* problem—the study of cancer is *knowledge-limited.* Regardless of the resources expended, progress requires fundamental new knowledge. As a result, some progress has been made in the war on cancer, but victory is not yet at hand. In a resource-limited problem, goals, objectives and methodology can be outlined from beginning to end. In a knowledge-limited problem, it is often difficult to know how to begin the outline. From a practical viewpoint, a resource-limited problem can be solved relatively easily by new investment. A knowledge-limited problem is not so easily reduced to dollars and cents.

In most cases, MSE is now resource-limited. We can turn lead into gold or carbon into diamonds. We can extrude Kevlar (trademark of DuPont) polymer fibers with the strength of steel. We can design crystals which produce large mechanical displacements when small voltages are applied for use as acoustic transmitters, or we can produce crystals which produce large voltages for small displacements for use as acoustic receivers. We can make glass and ceramics as strong as the strongest steel. We can modify the composition of semiconductors lasers to tune the light to a desired frequency by changing the energy levels of the electrons in the solids. We can then transmit, without amplification, the light more than a thousand miles over a fluoride glass of exceptional purity which is exceedingly transparent. We can modify the composition of brittle metallic compounds to make them ductile, thus expanding the upper temperature limit of engines by ten percent or more. This can produce a 20 to 30 percent increase in fuel efficiency since the thermodynamic efficiency of a heat engine is related to its maximum operating temperature.

With sufficient resources, it seems that we can do anything that we want. Unfortunately, such a view is unrealistic, yet many hope it is true.

FINDING THE LIMITS

As noted earlier, the rate of MSE's advancement has accelerated in recent years. Consider aluminum alloys—tensile strength has grown from 20,000 psi in 1890 to 60,000 psi in 1920 to 80,000 psi in the 1970's and to 100,000 psi in 1985. The maximum operating temperatures of nickel-base superalloys display a similar trend, albeit on a different time scale. Most significantly, new materials development in the past decade has accelerated from the previous rate of advancement.

Despite the many breakthroughs, there are limits to what is achievable in MSE. Some of the limits are dictated by physical laws. For example, both the elastic stiffness and melting temperature of a material are fundamentally limited by the strength of the interatomic bonds (i.e., carbon-carbon bonds are the strongest, and thus, diamond has the highest elastic modulus and melting temperature). In polymers, these two physical properties are controlled not by the strong carbon-carbon bonds along the chain but by the weaker interchain bonds between the individual molecules. In similar ways, materials scientists and engineers are able to predict or explain many of the measured differences between various materials and to predict their practical limits.

Unfortunately, not all materials scientists and engineers agree on what these limits are. In some cases, it is an honest disagreement as to the proper assumptions. It seems that all too often, however, that the confusion is over the difference between what is possible and what is practical. Many things are possible in the laboratory that are not practical in large scale production—at least not yet. Some claim that the transition from possible to practical is only a detail, but history tells us that this detail can require decades of time and vast quantities of capital to accomplish. For example, the weight of cars could be reduced by using aluminum sheet metal. It is not practical, however, to resistance weld aluminum on the large scale of the automotive industry even though it is possible to weld the aluminum in the higher value aerospace industry. It is possible to make high quality ceramics for demonstration in engines but mass production of such ceramics is not presently economical.

Because of the great promise of new materials, many people are very enthusiastic about their potential. Unfortunately, many of the production trials result in disappointment because the possibility of the laboratory is not practical in production. It is possible that the glamour of new materials will fade within a few years just as it did with biotechnology. In 1983, investment in biotechnology peaked at $850 million and dropped to $200 million in 1986. As the president of one research laboratory stated, "Most investors now recognize that (biotechnology) is nothing but a tool to dissect biology. Anyone who knew anything about it as early as 1976 could have predicted all that has happened." So it is with MSE. The insiders know the true story and the outsiders are still trying to differentiate between what is possible and what is practical.

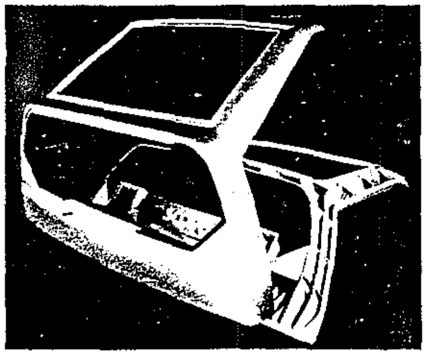
There is a very significant difference between the progress in biotechnology and the progress in MSE during the past decade. Recombinant DNA gave biotechnology the characterization and fabrication techniques necessary to measure and to make new genes, but biotechnology still lacks the theory between structure and properties. As a result, it is a knowledge-limited discipline, and progress is slow. MSE, on the other hand, has all three components and hence, may be more successful in realizing its promises on a short term basis.

ECONOMICAL PRODUCTION

Since MSE is less knowledge-limited than in the past, the development or demonstration of our ability to create new materials in the laboratory is no longer a problem. Today's most significant problem involves materials processing—the economical production of new materials on a large scale.

Looking closely at the information revolution, it is apparent that it has primarily depended on how we have learned to process silicon faster, cheaper, and smaller. This is primarily due to miniaturization, which may increase the cost per pound, but has decreased the cost per circuit element by many orders of magnitude. While other developments in electronic materials such as GaAs with high switching speed, or higher temperature superconductors are very exciting scientifically, it is the ability to economically process silicon that has had the greatest economic and technological impact on the information revolution.

Looking at another, less glamorous industry such as steel, we also find that materials processing has been the major factor in leading the growth of this industry. Today, Japan is readily acknowledged as the leading steelmaker in the world, at least in quality. The secret of Japan's success in steel is not due to any fundamentally different knowledge, but rather to heavy investment. Japan now produces steel of equivalent or higher quality, but at significantly lower processing costs, than anyone else. The technology is not vastly different, it is mostly a matter of size. On average, Japanese blast furnaces are more than twice the size of older U.S. furnaces, and hence possess a lower surface to volume ratio, producing less heat loss per ton of iron and resulting in greater fuel efficiency. Additionally, the labor required to operate a larger furnace is not very different from that required to operate a small furnace. But, as the Japanese are now learning, others can invest in this resource-limited industry and, with lower labor costs, can compete very effectively.



From the FORUM article "Automotive Plastic Use Increases" in the March 1986 *Journal of Metals*. Shown is an all-plastic liftgate with an outer skin assembly molded in NORYL GTX resin.

In materials intensive industries where there is limited competition, and costs are not the primary concern, the high technology, new materials companies (aerospace, defense, etc.) are most successful. In materials intensive industries where competition is very severe (semiconductors, steel, automobiles, etc.), the companies which invest most heavily in processing, feature the lowest costs, are the most competitive, and are the most profitable. Clearly, research into exciting new materials is important, but we are also learning that materials processing research is as important, if not more so, especially in our most competitive industries.

For example, the Lincoln Electric Company, the largest welding electrode company in the United States, shocked the industry a number of years ago by introducing an electrode that did not require a shielding gas to protect the steel from the nitrogen in air. By eliminating the gas, the equipment became smaller and easier to use and the fabricator eliminated a major material cost which had previously gone up, literally, as smoke. Within two or three years, their competitors had successfully copied this new product in the laboratory, but even today, some 15 years later, the competitors still have not successfully penetrated this market. The original company controls the world's use of this material, not because they have a technological advantage, others copied the technology in a few years, but because they can fabricate and sell this electrode for less than the production costs of their competitors.

There are several ways that Lincoln Electric accomplished this feat. First, they developed methods of producing the alloy powder which were much lower than the industry standard. They still hold some proprietary advantage in this area. Second, they refined their fabricating equipment and quality control procedures to produce uniform quality wire reliably.

The lesson from this example is that high technology can create exciting new products, but these are often easily copied. The United States complains that Japan does this to the United States, and Japan complains that Korea and Taiwan are doing this to Japan. The true competitive advantage comes from better quality and lower cost processing, and this advantage can last much longer than a high technology product advantage.

MARKET MYTHOLOGY

We read much about the properties of new materials, and we hear much about the several fold growth in the ceramics, composites and polymer industries over the next few years. Annual growth rates of 20 to 40 percent are predicted for ceramics and polymers alone. While each of these industries may have already achieved such growth over a short period of time, one must be careful in extrapolating such growth over 15 or 20 years. Some materials have very limited markets. Both the high technology ceramics and the composites markets are projected to grow to $10 billion annually worldwide by the year 2000. These figures represent 1/50 of the world's present steel industry, yet both the government and industrial sectors are spending more on fine ceramics research and development each year than on steel research and development. The most frequently cited justification for this disparity of investment says that the high temperature structural ceramics market will control up to $300 billion of the automotive industry by the end of the century—an impressive, though questionable claim. What if there is a breakthrough in the development of fuel cells for electrically driven cars? What will be the advantage of heat engine ceramics then?

A theoretical thermodynamic efficiency for a heat engine based on a higher maximum operating temperature predicts a 30-percent increase in fuel economy as a result of ceramic applications. These figures have been re-analyzed more completely by considering the entire engine system efficiency not just the thermal efficiency. The results show only a three percent improvement. It all depends upon the assumptions used in making projections. For example, one can hardly expect to exhaust gases from the tailpipe at 1000°C. Very few people will want to drive vehicles carrying a ten-foot high smokestack.

Ceramics have much to offer in the way of new structural applications and electronics, but to tie the future of these two industries to the growth of a single material is both premature and naive. It presumes that there will not be any major breakthroughs in these industries or in the properties of competitive materials. Even today, ceramists cannot produce a reliable structural ceramic for less than ten times the cost of a metal part. They claim that their raw materials are abundant, but they spend a tremendous amount of money purifying the material and inspecting the final parts which can have rejection rates of 90 percent or more.

The problem with ceramics is their low fracture toughness or brittleness. The abstract of one recent technical paper on glass claimed a doubling of the resistance of the material to brittle fracture. The paper failed, however, to note that the produced material was still more than twice as brittle as the poorest grade of cast iron. New high temperature polymers are being introduced that will operate at 500°F, but this is a laughable goal to a metallurgist. Clearly, part of the excitement over new materials can be traced to similar examples of major advances in properties that were not very exciting from the start. It is always easier to produce a major gain if one compares a ratio of new vs. old and the old value was small.

Composites have similar problems, and it is unlikely that their costs will ever be able to compete with metals or plastics in high volume applications. Thus, most composites will remain high performance, high cost materials for limited markets.

Further, wider spread composite utilization will continue to be limited by its inferior joining technology. The problem is twofold. First, composites often consist of two materials with vastly different types of chemical bonding. Since any joining process other than a simple screw fastener must match the chemical bonds of the material, the complex composite material greatly restricts the available joining methods. Second, since the joint usually must have properties equal to the bulk composite, it is unlikely that a non-composite joint filler can produce the enhanced properties designed into the composite.

No matter how exciting the properties of composites are as monolithic shapes, their widespread use will be limited by the ability to integrate them into complex structures. Composites are to aircraft as aluminum is to automotive bodies. One can reduce weight and increase efficiency by bolting on hoods or fenders or rudders or ailerons, but no one is mass producing total aluminum autobodies or composite aircraft due to the difficulties in joining these materials into complex structures. This integration of many new materials into a complete system is another problem which is often ignored by the enthusiasts.

CONCLUSION

While it is true that MSE is a dynamic discipline with many exciting new materials, we must not lose sight of the fact that an exciting technical accomplishment does not mean a successful commercial product. There must be sufficient market and sufficient manufacturing economy to make a reasonable profit. Academic research can search out new materials with exciting properties, but industry must learn to exploit these materials through inexpensive processing.

Academia is well qualified to develop new materials, but it is not capable of producing them on a large scale. Industry is also capable of developing new materials, but if it only demonstrates such new materials and does not emphasize their economical and reliable manufacture, resources will be wasted. Academia cannot work on these manufacturing processes on their own. They must have a close interaction with industry to distinguish the practical from the possible. Academia can develop axioms of processing science but cannot operate a true processing factory without a partnership with industry.

If we spend our resources searching for new materials rather than learning how to manufacture our current materials economically, we will be successful—but we will only be learning to turn lead into gold that is more expensive than the gold we dig out of the ground.

The search for new materials is exciting, but there are many old materials, such as concrete or plastics, which have yet to be exploited fully. Industry should not develop new materials for their own sake—such work is the province of not-for-profit private and government laboratories. Industry should, however, select the key materials necessary for new and improved products. If a material already exists, industry must learn to produce it reliably and economically. If it does not exist, industry or academia can invent it, and industry can then develop reliable and economical processing methods.

Generally, successful industrial development of new materials should be driven by market pull rather than technology push. The high strength, low density aluminum-lithium alloys for aircraft are an excellent example of how market pull forced the rapid development of a material that is difficult to produce reliably and economically. It is only in this way that the promise of new materials becomes a reality for a large number of people.

Constantly designing materials with curious new properties is a satisfying pursuit for the materials scientist or engineer, but it will not yield the ultimate social benefit if it cannot be made economically and in large quantities. If we spend our resources demonstrating curiosities, the promise of new materials will be imaginary, the enthusiasm will fade, and materials scientists and the general public will suffer.

If we direct our resources toward processing selected new products of high reliability and low cost, we will all be winners.

If you want more information on this subject, please circle reader service card number 64.

The excitement over new materials is reminiscent of the flurry over biotechnology in the early 1980s.

this information, we can perform quantum mechanical calculations to predict—with an accuracy never before possible—the properties of the electrons on the surface of the alloy.

This information is important for a number of reasons. Surface electrons control the ability of catalysts to accelerate chemical reactions. Moreover, as we design smaller and smaller electronic circuits, their surface-to-volume ratio increases, and the properties of the surface electrons begin to dictate the properties of the entire circuit.

Building Materials Atom by Atom

There is one more essential ingredient to progress in materials science: the ability to manufacture the materials that we can theoretically predict. In the last two decades, engineers have devised methods to build materials with the desired properties atom by atom. Such methods include molecular beam epitaxy, in which streams of atoms are shot at the surface of a crystal and condense on the surface in a specific pattern. Another method, ion implantation, accelerates charged atoms to such high energies that they become embedded beneath the surface.

Furthermore, engineers can now produce new materials in bulk quantities through technologies such as plasma deposition and chemical vapor deposition. In plasma deposition, an electrically charged gas (as opposed to a chemical) is deposited on the surface of a material in layers to build an integrated circuit. In chemical vapor deposition, a mixture of gases reacts on the surface of a material to form a solid. These processes can build up materials faster than molecular beam epitaxy or ion implantation because the gases involved put many more atoms on the surface of the materials.

Yet another innovative technology is sol-gel chemistry, which enables scientists to mix organic compounds with metals in ways that could never be done before. Chemists can "hide" a metal in an organic compound and then bake the mixture at lower temperatures than would be possible for pure metal. During this process, the organic compound evaporates in much the same way that water evaporates in the baking of bread. The result is a controlled mixture of atoms that high-temperature processing could never have produced. For instance, sol-gel chemistry is responsible for high-strength ceramics that have unique properties.

What can be achieved in materials science and engineering today seems almost miraculous. We can extrude polymer fibers as strong as steel for use in bullet-proof vests and helicopter blades. We can create acoustical transmitters by designing crystals that produce sound vibrations when small voltages are applied. We can build semiconductor lasers atom layer by atom layer. The mixture of gallium, aluminum, and arsenic in such a laser gives it the properties required for fiber-optic communications. By changing the energy levels of electrons in the laser, we can tune its light to a desired frequency, and we can then transmit that frequency more than 1,000 miles without amplification through an exceptionally pure glass. In a few years, fiber-optic lasers will almost completely replace copper conductors or microwaves for long-range communications.

Given such extraordinary advances, there is much talk about dramatic growth in the markets for advanced ceramics, composites, and polymers over the next few years. The ceramics and composites markets are expected to grow 20 to 40 percent annually. Many industrial leaders are excited about the potential of these materials. Technical and non-technical magazines and newspapers herald plastics that could reduce the weight and cost of cars, ceramics that could improve fuel efficiency and lengthen the life of car engines, and electronic materials that could mean faster and larger computers.

The international community is also enthusiastic. More than half of the 13 projects that Japan's Ministry of International Trade and Industry has identified as priorities involve materials science. I have visited major industrial labs in both Japan and the United States that are devoting 20 to 50 percent of their R&D efforts to new materials.

In some ways, the excitement is reminiscent of the flurry over biotechnology in the early 1980s. And indeed, the developments in materials science do bear some resemblance to those in biotechnology. Like scanning electron microscopy, the new recombinant DNA techniques allow scientists to measure genetic structure, correlate it with genetic properties, and fabricate new structures.

But even a few years ago, any biologist would have freely admitted that it would be a long time before we could predict the relationship between the structure and properties of engineered DNA. Biotechnology still lacks the theory that explains that correlation. As a result, progress is slow and the

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