

The Quiet Revolution in Materials Manufacturing and Production

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INTRODUCTION

In the mid-1980s, the United States, Japan, and the European Economic Community declared their belief that three industries would drive economic growth into the next century: advanced materials, information technology, and biotechnology. Now, more than a decade later, history has proven these predictions to be at least half correct. The next decade will prove whether the remainder will come to pass.

Clearly, the information technology industry (computers and telecommunications) can point to many tens of billions of dollars of new businesses over the last 15 years. At the other extreme, the biotechnology industry is still based on promises. Although there is still great excitement about the potential of new biotechnological advances, there simply has not been a very measurable effect on the U.S. gross domestic product, unless one wishes to include the tremendous increase in health-care costs during the past decade, which represents a negative impact on the economy.

The apparent success of the materials industry lies between information technology and biotechnology. The growth of new materials businesses has not approached the prognostications of ten years ago; however, the properties, durability, and economy of traditional materials have improved dramatically over the past two decades. This is the quiet revolution. It is a quiet revolution because it represents cost avoidance rather than creation of new materials companies. The average consumer does not perceive the change due to the continuous nature of the improvements, as contrasted with discontinuous changes that are claimed and advertised by the information technology industry.

The revolution is also quiet because consumers do not "purchase" the greater materials properties of a magnetic thin-film storage device or the miniaturization of silicon transistors. The consumer does not understand such details; they

are impressed with the 200-fold increases in computer processing speed and storage capacity or the advent of cellular communications over the past ten years. These are obvious increases in functionality at no increase in overall cost. It is true that a large fraction of this improved functionality is due to improvements in materials manufacturing and processing, but these revolutions in materials performance are invisible to the consumer. The consumer is not buying the

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materials directly; they are purchasing functionality.

Another reason for the quietness of the materials revolution is that the industry has not been a creator of new jobs. This is because a large fraction of the materials revolution is based on tremendous increases in productivity. This, combined with the greater functionality and durability of materials over the past decade, means that the usage of materials, on a weight or volume basis, has not increased dramatically. With consumption roughly constant and productivity increasing at 3.5–7 percent per year, employment in the original materials industries has been decreasing by a factor of two every 10–20 years. The new materials industries have picked up some of the slack, but the overall effect is that the materials industry, although

growing dramatically by any meaningful technological measure, has not been a source of new employment.

Nonetheless, the jobs available in the materials profession are changing dramatically. Today, people are employed more for their brain than brawn. The work is safer, more pleasant, and more exciting than ever.

The productivity and performance increases of the materials industries have probably done more to improve the strength of the economy than either the information technology or biotechnology industries; but materials engineers do not receive the credit from society for these advances. The negative effect to date of biotechnology on health-care costs has already been noted. In comparison, a personal computer is not markedly less expensive today than ten years ago. Its functionality is greater, but this improved functionality is, in large part, due to the quiet revolution in the materials of construction. Thus, the predictions of 15 years ago about the future growth industries may have been most accurate with respect to jobs creation in information technology, but the materials industry has produced the most pervasive productivity improvements. In the long run, it is improvements in productivity that have the most lasting benefit on the economy.

THE MATERIALS REVOLUTION

Scientifically, and in the media, the growth in materials science and engineering is generally described in terms of advanced materials with dramatically improved properties. Nonetheless, the real revolution has been in continuous improvements in the properties and reductions in the processing costs of traditional materials. Over the past two decades, our consumption of all materials has not grown markedly, and the industrial growth of advanced composites, advanced ceramics, novel polymers, and alternatives to silicon has not come close to the claims of a decade ago. On the other hand, as seen in Figure 1, the cost

of all metals has decreased by a factor of two over the past 30 years. This is a 2.5 percent change per year—hardly dramatic on an annual basis, but truly remarkable over several decades! The cost of structural steels has decreased two-fold in the past decade—a seven percent per year improvement. The functionality of silicon computer chips has improved 10,000-fold; the useful life, fuel efficiency, and maintenance requirements of automobiles has improved dramatically; energy conversion efficiency has accelerated; materials recyclability has improved. These advances are due to continuous improvements in the technology and manufacturing of traditional materials. There are also notable examples of new materials industries such as optical fibers, flat-panel displays, compound semiconductors, hard and soft magnetic materials, oriented high-strength polymers, and so on, but none of these developments comes close to the economic size of the traditional steel, concrete, silicon, and commodity polymer industries that existed two decades ago and that continue to exist today. The cost reductions in these traditional materials industries are at least equal to the new businesses created by the advanced materials industries. There are a number of reasons why the new materials markets have not grown as predicted,¹ but these will not be repeated here; rather, the causes of the materials revolution that has occurred are highlighted.

The great improvements in materials manufacturing productivity over the past two decades has both technological and managerial origins. The most dramatic changes have been managerial, perhaps because the managerial philoso-

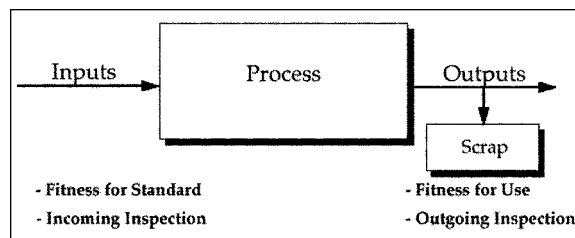
phies of two decades ago were so primitive and dysfunctional that there was considerable room for improvement. Nonetheless, the low hanging fruit of these managerial changes has already been harvested. Since management per se only reorganizes what already exists, the improvements over the next few decades are most likely to be dominated by improvements in technology, which has the potential to create new processes with greatly expanded productivity.

CHANGES IN MATERIALS MANUFACTURING MANAGEMENT

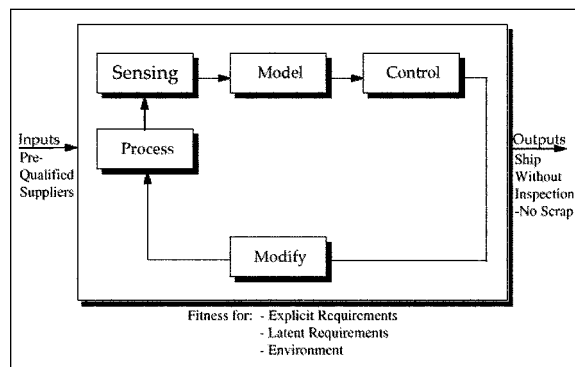
Twenty-five years ago, nearly all manufacturing organizations were compartmentalized. Managers were judged on their ability to optimize their part of the system rather than on their contribution to the overall enterprise. As a result, many decisions were made that benefited a few, while seriously damaging the overall organization. For example, bonuses were paid based on output, not on quality or yield. Not surprisingly, many tons of junk were produced and shipped, as managers and others will always respond to the way in which they are measured and rewarded. Warranty costs were not charged to production operations (such is still the policy in many organizations). Thus, there was no emphasis on quality. Waste was rampant. One tonne would be scrapped if it would get two tonnes out the door. The manufacturing process was managed on an open loop basis (Figure 2a). Incoming materials were inspected for conformance to a standard and outgoing material was fit for sale as long as it met specification.

There were two major factors that created an atmosphere for change. The first was the energy crisis of the 1970s. Overnight, energy costs that had been considered insignificant, or at least uncontrollable, increased dramatically, consuming all or nearly all of many companies' profitability.

The energy crisis changed two important managerial philosophies. The first was a realization that "fixed" costs were controllable; the second was the concept that flexibility in the use of resources added value to the organization. By 1980, most manufacturing companies were



a



b

Figure 2. (a) Old paradigm for materials manufacturing, in which quality was controlled by an outgoing inspection. The process ran open loop in the sense that information on yield and scrap rates was not received timely enough to influence the process. (b) New paradigm used in best practice materials manufacturing companies. The process is modeled, the results are sensed in real time, and the information is fed back to improve the yield and reduce the scrap.

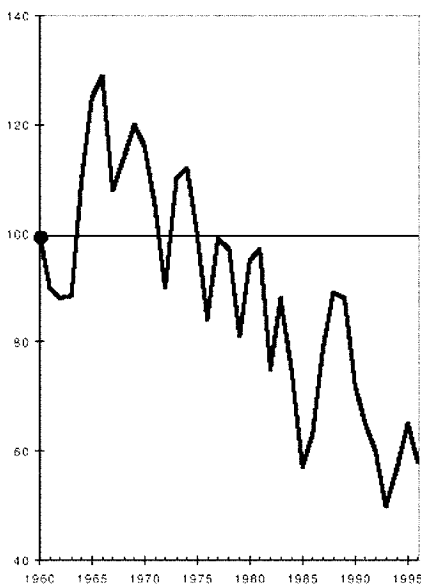


Figure 1. Metals and mineral prices as compiled by the World Bank. The value is in real terms, with 1960 = 100. The deflation factor is the dollar value index of the G5 manufacturing countries' exports.

no longer dependent solely on oil. Improvements that had been made in the fixed cost of energy caused managers to look for major reductions in other fixed costs. In the best firms, managers were no longer expected to merely maintain the operations but were asked to "continuously improve" the process.

Another factor that created changes in managerial philosophies was the demonstration by Japanese automotive companies that quality sells. This had led to a modern process control methodology (Figure 2b) that closes the loop between input and output. The process is controlled to improve the yield. Companies that had been operating with 60 percent yield and 40 percent scrap learned that they could increase capacity by more than half through process improvement alone. No capital cost was required and overall efficiency and productivity improved with consequent reductions in cost. Statistical process control, total quality management, and just-in-time inventory created improvements that were unexpected under the old management philosophies. Of course, any good thing can be turned bad when used to excess. Having been raised on the idea of compartmentalization, most managers did not really understand how the overall system interacts. Good ideas were turned into meaningless and damaging fads at many companies. Fortunately, over time, many firms have learned to balance these new operational tools.

In the materials industries, the improvements have been dramatic. Yields in the steel industry, as measured by tonnes shipped divided by tonnes poured, increased from less than 70 percent to considerably more than 90 percent. Semiconductor chip yields improved from 25 percent to more than 90 percent. Of course, technology had a large influence on these yields—continuous casting replaced ingot casting and semiconductor manufacturing went through three or four generations of process equipment and process control technology. Nonetheless, the basic manufacturing philosophy at most successful firms had changed. Quality was valued, fitness for explicit and latent requirements replaced conformance to specification, inventory was reduced, delivery time was reduced, and customer satisfaction was measured. Productivity soared. But there are limits to growth driven by managerial change. If one starts at 70 percent yield, there is great room for improvement, but at 99 percent yield, there is little room to improve yield. As companies have become more efficient, the need for technological change to increase productivity is ever greater.

CHANGES IN MATERIALS MANUFACTURING TECHNOLOGY

Just as yield cannot exceed 100 percent, energy costs cannot be reduced to zero. At the same time, society requires environmental improvements in process technology. Capital costs must be controlled. For example, many people have heard of Moore's first law that the number of transistors on an integrated circuit doubles every 18 months, but few know Moore's second law: The capital cost of a semiconductor fabrication plant doubles with each generation of process technology. By 2010, one semiconductor fabrication facility may equal ten percent of the world's annual semiconductor sales. Similar problems exist in the commercial airframe industry. The next newly

designed airliner will cost \$10 billion to bring to market. A new commercial jet engine will cost \$5 billion to design. There are few companies large enough to generate such capital and even fewer capable of assuming the risk.

Such capital requirements are not new to the steel industry. The last green-field steel mill in the United States was built in the late 1960s. Its construction nearly bankrupted the world's second largest steel company. Since that time, no company has built an integrated steel mill without the financial backing of an entire nation! The risk is simply too great for an individual company. In the aerospace industry, future aircraft and engines will be built by consortia of companies willing to share the risks.

Overall, the materials manufacturing industry has been phenomenally successful in reducing costs and improving quality and productivity over the past two decades.

The steel industry led the way in defining the solution to the problem of huge capital requirements. Steel mini-mills (Figure 3) have dramatically reduced the risk necessary to add production capacity. New technology was required, but it has been developed. It is likely that new process technologies, which take a fresh look at materials processing, will reduce the size of investment required in other industries as well.

PROSPECTS FOR THE FUTURE

Improvements in technology will be the likely driver for improved productivity in the materials industries of the future. Managerial improvements will continue, mostly because there are still many firms that have not yet developed the focus on quality that is required.

Advanced materials will continue to find niche markets, but it is not obvious

that replacements for steel, silicon, polyethylene, and concrete are on the horizon. In these relatively huge and traditional industries, cost reductions and continuous improvements in properties will predominate. Yields are already approaching practical limits; hence, reductions in capital cost, improvements in environmental controls, and better transportation and distribution are the areas of

promise. Unfortunately, the tremendous productivity improvements in these industries over the past decade have created worldwide overcapacity. This overcapacity has battered profitability. Surprisingly, the loss of profitability has not stifled the development of technology, as new technology has been one of the only means of maintaining profitability. What has suffered is industrial sponsorship of long-term science. Since this science is the foundation for future technological change, it remains to be seen if technology can keep ahead of the competition in the long run. Again, the steel industry may be the trend leader. The reduction of investment in the science of steel 25 years ago is now beginning to stifle the development of technology in that area.

Most firms that perform materials research still seek a breakthrough in the properties of an advanced material in hopes of creating a large and highly profitable new industry. History shows that the more likely route to financial success is by reducing the manufacturing cost and improving the quality of an existing material to create greater profitability.

Overall, the materials manufacturing industry has been phenomenally successful in reducing costs and improving quality and productivity over the past two decades. It is likely that these trends will continue for the next decade, although it would be helpful if profitability could increase as well. Too much of the materials industry has become a commodity business. If this trend is not reversed, many entrepreneurs will leave the materials community for other industries, such as information technology, biotechnology, or investment banking, where the financial rewards are greater. The tremendous productivity success of materials science and engineering could be the factor that ultimately causes some of the most talented people in the field to choose other professions.

Reference

1. T.W. Eagar, "Bringing New Materials to Market," *Technology Review*, 42, February / March (1995).

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Thomas W. Eagar earned his Sc.D. in metallurgy at the Massachusetts Institute of Technology in 1975. He is currently head of the Department of Materials Science and Engineering and POSCO Professor of Materials Engineering at the Massachusetts Institute of Technology. Dr. Eagar is also a member of TMS.

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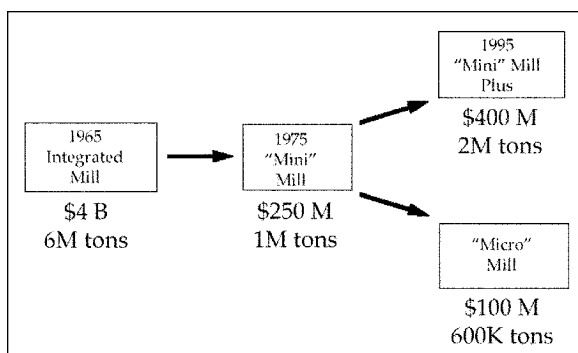


Figure 3. The 30 year evolution of economic plant capacity and required capital costs for steelmaking.