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The Great Materials Network

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A general overview of the field of Materials Science is presented. Emphasis is given to its historical evolution, its successes, and the opportunities for future exploration and exploitation.

There is an old jingle in the United States containing advice to brides regarding items to wear with their wedding dress if they are to have good luck in their marriage. Among other things, they are to wear:

> Something old, something new, something borrowed and something blue.

With the exception of "something blue" I am always reminded of this jingle when I think of the vast field of materials science and technology - or science and engineering if you prefer. The field has a rich lore stretching back to the earliest periods in the history of our species and will, as in the past, be with us as one of the centerpieces of civilization as far ahead as we have any control of our destiny. There are essentially endless requirements and prospects for new developments in the future.

Materials technology probably began with the use of wood, probably first as a club and lever, but also as a digging tool. This was broadened to the use of stone, both natural and shaped, and finally to the sequence of metals, copper, bronze, and iron. The latter apparently first came into common use in the hands of the Hittites in the 14th century B.C., although there is good evidence that meteoric iron was used for special purposes before 2000 B.C.

1. EARLY PERSONAL LINKS

My own links to the field go back some sixty years when I was a starting graduate student and a research assistant to Dr. Edward Condon, then a professor at Princeton and later head of the Bureau of Standards. He suggested that I try to speculate on the basic properties of solids and turned me over to work with Eugene Wigner, newly arrived in the United States. Through good fortune, Wigner and I were able to open up what proved to be a productive area of physics by developing a method for solving the equations of quantum mechanics for electrons in single crystals.

In those days the various components of the field of materials science and technology were fairly sharply compartmentalized. The two principal areas were devoted to metals and ceramics, with glasses occupying a special part of the latter. In fact, even the field of metals was fairly sharply divided between ferrous and non-ferrous types, with steel being king. Then there were the special areas of materials technology served by the chemists, as well as those, equally specialized, that were of interest to the electrical engineer, particularly the electronic engineer. The most commonly used semiconductor was cuprous oxide, employed in low-frequency power rectifiers. Elemental silicon was used in crude form to de-oxidize molten steel. Germanium was a chemical oddity. The great majority of polymers in practical use were of natural origin, including items such as wood, cotton, and wool. The two principal synthetic polymers in common use were celluloid with its relative cellophane, and thermo-setting

Bakelite. The dawn of the true age of synthetic polymers was still about a decade ahead. The chemists, in addition to quantifying materials standards, were everywhere in the picture providing new understanding of old areas and opening up new ones at a remarkable rate. The physicists became deeply involved in the advance of electronics and were effective not only in revolutionizing many aspects of that field but in extending our understanding of materials at the atomic level. The most basic forms of atomic science became a full partner of technology, opening up new areas of engineering.

2. DUSK?

In 1961, some thirty years after the period I have just mentioned, a very distinguished English physicist at Cambridge University gave an address in which he stated that as far as the basic science was concerned, the field of materials research had reached a terminal point and that from then onward it would be a matter for routine exploration by engineers in order to satisfy practical needs. He was undoubtedly influenced, quite strongly and perhaps understandably, by the fact that the newly formulated theory of superconductivity, developed by Bardeen, Cooper, and Schrieffer just a few years earlier, had proved to be very successful and was widely accepted. The English colleague I mentioned above had decided that the new development represented the end of the road as far as exciting fundamental discoveries in the field were concerned.

3. NEW SUPERCONDUCTORS

What has happened since? Well, for one thing, several entirely new families of superconductors have been discovered in the last decade and the discussion of the basic theory, particularly the nature of the coupling between conduction electrons and the ionic core of the material attached to the nucleus, goes on. One new family is that first found in a group of copperoxide-based compounds containing special additions. They are ceramic-like, possess a layered lattice structure, and have a transition temperature near 90° Kelvin. Another family is formed of organic polymers and still another, with a temperature range extending to near 30° Kelvin, is based upon compounds formed by the alkali metals with those remarkable cage-like polyhedral structures of carbon known as bucky-balls, or fullerenes, in honor of the architect, Buckminster Fuller. Perhaps the most exciting member of the bucky-ball family found so far contains sixty carbon atoms, but the field is still growing. In fact, the molecule having seventy carbon atoms may turn out to be interesting in its own way.

4. OTHER FIELDS

Beyond this, a number of other new fields of speculation have opened up. Let me mention a few.

4.1. Laser Optics

The field of laser optics, which was in its infancy thirty years ago, has opened up a vast area of exploratory research both for the study of materials and for the generation of special forms of laser light. Laser radiation, as you will recall, is phase locked or synchronized much like radio or radar radiation and provides a powerful tool for research and application. It has made possible exciting studies in gases, liquids, and crystals.

4.2. Low Temperatures

It is now possible to reach temperatures within a few millionths of a degree of the absolute zero. This makes it possible to study some very interesting properties of materials such as their magnetic behavior in a very unusual environment.

4.3. High Pressures

Similarly, the behavior of materials at very high pressures is proving to provide a great deal of information on how materials act when the constituent atoms are squeezed very closely together.

4.4. Miniaturization

The miniaturizing of electrical circuits, which was still an abstraction thirty years ago, has proceeded to the point at which one is already fabricating components in integrated circuits that are well below one micron in size. We can expect this work to open up an entirely new and exciting area for fundamental study of the property of materials, not least the properties of metals and semiconductors.

4.5. High Magnetic Fields

The techniques for generating high magnetic fields are extending research to the range of one million gauss for routine investigation. We can anticipate important new discoveries regarding our understanding of electronic structures which will have an influence upon technology in the long if not the short range.

5. NEW ENGINEERING MATERIALS

The areas devoted to new applications of materials - matters of immediate interest to the engineer - are no less exciting. Here again we can list some of the fields being studied for exploitation.

5.1. Polymers

The areas once dominated by metals and ceramics are now being invaded and indeed extended by the advances in polymer technology. We now have aramid polymers such as Kevlar, and high density polyethylene types such as Dyneema, which have the intrinsic strength of steel and offer many opportunities for new structural systems both alone and in composite materials.

5.2. Glass fibers

Glass fibers, which were introduced in the 1930's to provide various forms of insulation, both thermal and electrical, turn out to be remarkable conductors of light. The potentialities for extending and improving the current communication systems, which already stretch across the Atlantic and Pacific oceans, is great. It is perhaps worth reminding you on this occasion that, because of the great bandwidth of fiber optic systems, it is now possible to send in a single day more messages across the Atlantic than were previously sent in total since the dawn of electric communications - a multi-quantum jump.

5.3. Composites

It seems clear that the study and development of composite materials of many types for many purposes are still in their infancy. It is a pleasure to note that experiments are being carried out on novel methods of incorporating the matrix into fiber systems. For example, vapor phase reaction techniques are being used to permeate carbon fiber structures with silicon carbide in order to avoid a high temperature sintering step which may degrade the system. The incorporation of the matrix by such methods can be done on a continuing basis.

5.4. New high temperature alloys

Similarly, it is interesting to see that investigators are now considering new high temperature materials such as rhenium and its alloys. These high temperature materials have properties compensatory to those of neighboring tungsten in the periodic chart and may open up new areas for utilization.

5.5. Amorphous semiconductors

At one time the principal amorphous materials in common use were glass and some polymeric substances. We now realize that amorphous metals and semiconductors can have significant useful properties either alone or as coatings. The amorphous semiconductors may, indeed, prove to be very useful in the conversion of solar energy for generating electric power.

5.6. Synthetic diamonds

Once the feasibility of making synthetic diamonds was revealed in the 1950's, diamond and diamond-like materials were removed from the exotic list. Many new and exceedingly useful applications of diamonds and diamond coatings to improve tool life and to serve as optical windows are now apparent. Others will come.

I note evidence that diamond coated machine tool bits that are operated at high speed have a much longer tool life if they are maintained at low temperatures during the cutting operation. This suggests that there may be room for substantial innovation with corresponding benefits by redesigning such machine tools with appropriate, even cryogenic, cooling systems.

5.7. New magnetic materials

The field of useful magnetic materials has been expanded appreciably with the discovery of the magnetic properties of rare earth compounds. In my student days, the study of the magnetic properties of the rare earth was regarded to be one of the most exotic aspects of the field.

5.8. Superconducting magnets

The traditional low temperature Type II superconductors which can entrap the magnetic field have found specialized uses in steady state magnets employed in scientific equipment. They offer great savings in electric power. The materials community is now being challenged to find uses for the high temperature families in even more traditional areas.

5.9. Electronic video systems

The chemists who once dominated the field of photography must now share the field with electrical engineers as electronic video systems become evermore sophisticated and useful.

6. THE VIEW AHEAD

Fully as important as recognizing current opportunities for explorations at the frontier of materials research is the problem of trying to guess what may be ahead. Technical people are usually not very good at this, being grounded in what is definitely known or reasonably feasible in their area of technology. Nevertheless, we should at least make the attempt. In this connection, one is reminded of the turn of the century New York newspaper reporter who, on hearing that the Wright brothers were making routine flights around Dayton, Ohio soon after the flight at Kittyhawk, went to interview both them and several other individuals. When asked what possible practical use the airplane might have, the brothers suggested that it might have military use as a complement to the bicycle and motorcycle for carrying messages during military actions. The great French-American engineer Octave Chanute, a close friend of the Wright brothers, thought that the use of the airplane would be severely limited at best because he had estimated that the heaviest airplane possible could weigh no more than three or four tons at the outside. A New York financier who had made much money by investing in the railroad systems showed better vision. He stated in contrast that in about fifty years commercial airplanes would be travelling at speeds of several hundred miles an hour and carry several hundred passengers.

7. ISSUES

Let us at least try to raise some issues.

7.1. Extraction and fabrication

Many of the greatest advances in materials technology have arisen from new methods of extraction and fabrication. Zone refining, for example, raised the level of purity of semiconducting materials to a new high level when it was introduced in the 1950's. At the present time, we are greatly constrained in the use of metals such as titanium, not because of high intrinsic costs of the elements in their natural ores, but because the cost of extracting, refining, and fabricating these materials is exceedingly expensive. It is very important that the attention of talented investigators continue to be directed to issues such as this. The results could be expected to yield great dividends as such materials become more economically useful.

7.2. Information processing

The advance of our present civilization is now intimately tied to advances in the rapid generation, processing and transmitting of information. The latest gains have been linked to the development of integrated circuits, electro-optics, including fiberoptic transmission, and satellites. Practical innovations in the production and fabrication of materials have been very close to the heart of all of this. Since most of the technically advanced countries are giving serious attention to the evolution of materials technology, we can expect a great deal of advance at a pace that matches what has happened in the forty odd years since the development of the transistor. One may ask if silicon is unquestionably to remain king in this field as we go to the submicron range or if an entirely new system, for example, one based on other semiconductors or superconducting materials, will emerge and replace present systems. The gains would obviously have to be very significant because of the high fixed investment we already have in the type of technology in use today. Nevertheless, a remarkable new advance could lead us to scrap old systems as the advance of fiberoptics demonstrates.

Will fluorescent screens and liquid crystals with their advantages and disadvantages retain their place in the area of displays? Will the use of fiberoptics replace the needs for satellite communications in most of the present applications of the latter, or will there be great reductions in the cost of satellites by a factor of ten or more as a result of new technology that will give them new competitive advantage?

7.3. Space technology

Where will we go with space technology? Will the Apollo program and the planetary explorers represent the limit of our serious adventures into space and will we, in the future, remain relatively earthbound? Or will our societies regain the type of momentum that launched the exciting programs that began with the challenge of Sputnik? Will we, before long, plan some form of serious scientific activity on the moon and eventually on Mars on a realistic time scale? Research and development in the field of materials could do much to make such programs realistic and practical by helping to improve space technology, not least by lowering costs.

7.4. Commercial air transportation

Subsonic commercial air travel is now as routine on a worldwide basis as railroad and passenger ship transportation was prior to World War II. Does this mark the highwater point of the development of air transportation or will new technology open up the transonic area to everyday long distance travel air travel at an economical level?

7.5. Medical Diagnostics

Many of the advances in medicine both diagnostic and surgical have been related to the development of new materials in conjunction with other techniques. One thinks again of fiber optic probes, laser scalpels, magnets for nuclear magnetic resonance and of countless other devices from computers to protheses. It is clear that the materials scientists and engineers will play a prominent and even a leading role in the period ahead in some of the most important advances in the practice of medicine by helping to introduce simpler, safer techniques and lower costs.

7.6. Refrigeration

Refrigeration is an important part of modern life and yet we are in the midst of a, perhaps dubious, movement to eliminate the use of halogen-containing materials such as freon which have been so effective as thermodynamic working substances in the past. Moreover, some of the compounds such as halon have become indispensable in fighting fires, saving many lives. Finding practical substitute systems represents a great challenge since a multi-billion dollar business and human lives are involved. Suggested alternatives for refrigeration have been to use systems based on the thermo-electric effect and chemisorption of ammonia gas on inorganic salts. What will be the final solution?

8. MONEY AND WILL

At the end of World War II, one of my wise and philosophical friends who had witnessed the technical miracles that had been accomplished in six years from a standing start made the observation that, provided we do not run counter to the basic laws of the natural world, we can accomplish any goal we wish. All that is needed is the will and the means. The materials scientist and engineer will continue to play a crucial role in achieving whatever dreams mankind sets its mind to.

9. ESTABLISHED TECHNOLOGIES

When looking to the future, it is equally important to review the well-established technologies to see if we can accomplish the types of ends achieved with them by improvements, or by other means which are cheaper and otherwise more efficient with respect to time, labor, and convenience. One cannot but be impressed with the speed with which the European countries rebuilt their damaged cities with the use of new construction technology once their economies were placed in reasonable order. Only a decade or so was needed to achieve miracles. It took the Central European countries well over a century to recover reasonably well from the comparably great destruction it experienced in the Thirty Years War that occurred between 1618 and 1648. A comparable period was required for the complete recovery of our own southern states from the set-backs of the Civil War.

9.1. Railroads

By 1950, one might have thought the evolution of railroads was at an end, as indeed seemed to be the case in the United States. Other countries, such as Japan, France, and Germany, however, having denser populations and possessing major cities that are closer to one another than most of those in the United States, felt otherwise. As a result we witness in Europe and parts of Asia an entirely new era of innovation in railroad equipment and systems, all being guided in part by what might be called a technology race.

9.2. Mining

Some aspects of mining and extraction are undergoing significant changes as new methods are introduced to deal with leaner ores. A great deal is being done with the use of new earth-moving and handling equipment and new methods of refinement. Gold mining, for example, has experienced a great renaissance as a result of the working of open pit systems and modifications of methods of extraction. The metal is presently selling at prices very close to production costs, as if it were a commodity rather than a material whose price is carefully controlled as the basis for the monetary system as was once the case.

9.3. Papermaking

Papermaking is an ancient art that can be traced back to the Egyptians who based their technology on the papyrus reed. Subsequently the Chinese encouraged much wider use of paper by developing a cheaper and more commonly usable form employing wood fiber, although they also used more expensive natural fibers for special high-grade papers. As usual, Western technology, interested in mass production, carried the process of papermaking several steps further and by the middle of the last century had focussed on an acid-based wood fiber product that has been in wide use internationally ever since. As we all know, ordinary paper used in books, magazines and newspapers suffers from degradation over time at a rate that depends upon the care with which it is made. In recent decades, new alkaline-based processes have emerged in which pigmentary calcium carbonate is used as a filler. It turns out that the new product is not only far more stable but is also cheaper to produce, showing that no technical system is too old to be reviewed and possibly supplemented.

9.4. Paints

When the use of paints based on the use of white lead were barred by law because they caused death through the disease known as painter's colic, the chemists were forced to look for practical replacements. The first choice on the basis of quality and hiding power was titanium dioxide which was relatively expensively produced by a wet sulfate process. The Dupont company set to work and developed an entirely new, less expensive process based upon the controlled combustion of titanium chloride. It has remained the dominant process for forty years. Recently a competitor has suggested that even better and less expensive results can be obtained by passing the ingredients through a plasma arc.

9.5. Solders

In this connection, we note that there is a strong movement to replace common lead-based solders with alloys that are less toxic. This issue provides a major challenge to the materials community.

9.6. Steel

The United States was once the major steel producer in the world. For example, during World War II it produced over one hundred million tons per year. The great bulk of this business has gone elsewhere for reasons which are complex in origin. It now imports about a third of the steel it uses in manufacturing. Both what was the Soviet Union and Japan took the lead for a period, but even they find leadership moving elsewhere. The transition resulted in part from general shortsightedness of management, labor and government in the United States in the two decades after World War II when it possessed an essential monopoly position. To some individuals in the United States the situation has aspects of a disaster but it also offers a very great challenge to imaginative entrepreneurs. One such group in the U.S. is now producing about a million tons of sheet steel per year from scrap in a continuous flow system.

9.7. New approaches to ceramics

Recently several imaginative groups have demonstrated that ceramics fabricated with the use of constituent powders that are submicron in size can have very special properties which can improve old products and yield new ones. One is reminded of changes in the utilization of glassware which occurred with the invention of Pyrex which has a very low thermal expansion coefficient at normal usable temperatures.

9.8. Construction Cements

The invention of Portland cement nearly two hundred years ago generated a revolution in the construction industry, reducing hand labor and extending the range of practical architectural design enormously. Moreover, the development of techniques of reinforcement, such as the addition of steel bars or other agents, and the invention of methods of pre-stressing have added substantially to the usefulness of the material under a variety of circumstances. Nevertheless, serious drawbacks remain. In most applications, Portland cements are of greatest use if they can be employed in relatively fluid form, requiring the addition of more water than is desirable for obtaining optimum strength and minimum porosity. At present such optimum conditions can usually be achieved only in small applications and are not economical in large ones.

Since Portland cements are the most widely used of all fabricating agents and will continue to represent the backbone of the construction industry in the foreseeable future, the research community should regard it as a challenge to find ways of improving the quality of such materials while retaining the advantages of convenience and low cost.

10. EDUCATION

10.1. Routes for Engineering

Finally, let me say a few words with respect to technical education. The engineer has three prominent career routes open, namely, the innovative technical, the managerial and the entrepreneurial pathways. The number of good opportunities in each of these categories decreases sequentially. Moreover, the entrepreneurial pathway is a very special one, frequently tied to personal gifts that extend beyond matters of formal education. Throughout much of the 19th century, most native-born American engineers were self-taught through one form of apprenticeship or another. Thomas Edison was perhaps the idealized prototype. Among other remarkable things, he covered the range of all three pathways.

10.2. Five year program

In this century the four year, or in some cases five year, college program has become the norm for engineers in the United States and to a degree it has served the profession well. It is notable, however, that those engineers who have added a graduate research program to their educational career, particularly one leading to a Ph.D. degree, have a longer effective professional life at the technical or managerial levels. This is the case not only because of the specific knowledge they have gained but because they are better prepared for the unexpected. Unless they have taken special steps to broaden their educational background from the workplace, most four year engineers seem to peak in usefulness by age fifty if not earlier. The advantages of the more extended period of education and the things that go with it showed up clearly within the U.S. in the technology competitions of World War II. The traditional four year electrical engineers did not have a strong background in the basic science of electromagnetic theory as represented by Maxwell's equations. The Ph.D. physicists did and took the lead in the field of radar. Much the same thing occurred on a broader scale in the field of semiconductor electronics in the post-war period.

It is notable that for complex reasons, including economic ones, most native American engineering students still follow the four to five year college route to their possible ultimate disadvantage. The graduate engineering departments tend to be tenanted principally by foreign born students who are prepared to pay short term penalties for longer term gains. Incidentally, far two few native American students enter the field.

10.3. Continuing education

Second, it is necessary in all countries that we continue to expand our vision of education so that those who for one reason or another limit their college education to a short period have abundant opportunity to extend it either from the workplace through special educational programs or through a scheduled leave of absence with company support. When Patrick Haggerty, who turned Texas Instruments into a leading semiconductor company, was Chief Executive of the corporation he made certain that particularly talented young engineers had an opportunity for continuing education either in the plant, at a local university or, in some cases, for full-time study at a leading institution elsewhere. Such farsightedness can pay major dividends everywhere for all concerned.

The field of materials research, development, and application is becoming ever more sophisticated. Those working in it must remain informed of new concepts as they arise and have the capacity to adjust to changing times and requirements. A strong educational background in the fundamentals obtained in whatever way is feasible is very important for those engaged in such work.

11. EPILOGUE

Ancient civilizations revered the technical professions and gave them a personal god of their own - Haiphistos in Greek and Vulcan in Roman mythology. Both were given beautiful, highly prized brides as a just reward - Aphrodite in the first case and Venus in the second. Both gods were masters of all aspects of the arts and practices of materials fabrication.

Our own civilization would do well to re-emphasize the importance of the technical professions.

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