Materials Processing, from Ideas to Practice

Jiann-Yang Hwang

Abstract Dr. Jiann-Yang Hwang served as the Director of the Institute of Materials Processing at Michigan Technological University for more than 20 years. Many technologies have been developed from ideas to commercial practices in his career life. This symposium reflects his contributions in this aspect. The cycle of materials such as metals on the earth involved the steps of ore exploration (geology), mining, mineral processing, metallurgy, manufacturing, and recycling. Each step is achieved by processing materials using energy. Depending on the process and the forms of energy input, products, and by-products with various environmental impacts are generated through air, water, and solid means. To obtain the most efficient process with the minimum environmental impacts at the best economics is the driving force that continuously pushes the advances of technologies. Variables in the materials, process, and energy are common parameters facilitating the development of ideas for technology advancements. Dr. Hwang learned earth sciences, mineralogy, characterization, mineral processing, and metallurgy during his undergraduate and graduate studies. Mining, materials, and processing, and environmental and economics are mostly self-studied at postgraduate time, partly pushed by the research needs from projects he wanted to conduct. Understanding the parameters involved in the materials, energy, environment, and economics is fundamental to a systematic approach. The validity of ideas and their potential to move to practice depend on the soundness of the system. The author reviewed several cases of his research to illustrate their relations.

Keywords Mineral processing · Magnetic separation · Microwave metallurgy · Recycling · Hydrogen storage · Water treatment · Material lifecycle

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Introduction

I am deeply touched to have this symposium sponsored by TMS that honors my lifelong contributions to the society, the education, and the industry. This is a big milestone for me. This is also the time to look back, to find out what has been important to shape me, what I have contributed, and what are the experiences I can share with others.

There are many people and organizations that I appreciate. My family, my teachers, my colleagues, my students, my friends, and even those people who built barriers to me, I want to say "thank you". I have learned a lot from each of you. I will try to tell a few stories here. Some of your names will be mentioned. Most will not. This does not mean you are less important to my life. I am simply not able to name each of you, but you definitely left marks in my heart, many are deeper than those I mentioned.

Life is a continuous learning process. I am so fortunate that new things keep on hitting me that provided me the opportunity of continuous learning. The funding agencies always challenge me with new problems. The industry and friends keep on asking me if I can help finding solutions.

Teamwork is very important. Nobody knows everything. We always need assistance from others. Colleagues, friends, and students are never shy to provide their two cents and work together. The critical thing is how much one can absorb and put things together. Continuous learning is so important here. Only the person who is willing to think, to learn from the information on various aspects, to learn from others, and to put things together will be able to lead and be successful.

What Has Been Done

I was born in 1952 in Taiwan. My father was an Army General and I was the fourth son with a younger sister. His interest was to put all of us in the military since his life was one war after another. However, none of us obeyed that. My name is Jiann-Yang. All of my brothers has the "Yang" part, which is our generation name. The "Jiann" part means "build". That was my excuse not to go to the military school since that is not to build.

Like everybody in elementary school, my fifth-grade teacher asked us to write an essay on what we would like to be after we grew up. My answer was I want to be an inventor like Edison. I want to "Build" things, especially new things that can help society.

Nobody teaches how to be an inventor at my time. My only idea was to study science and engineering. My father's hometown, Daye, which means Big Smelting, was famous for its iron and copper ores and smelting. So, my first college major was Earth Science at the National Cheng Kung University. I received my B.S. degree as a top student there in 1974. After 2 years of military service as a second lieutenant in the army, I joined the Mining Research Institute in Taiwan as a mineral exploration engineer with a focus on remote sensing. In 1977, I obtained a scholarship and came to the United States to study mineralogy and geochemistry in the Earth and Atmospheric Science Department at Purdue University. Scanning electron microscope and electron microprobe analysis was new at that time and I was lucky to be one among the early generation who can look into the microstructure of materials. After completing my M.S. in 1980, I obtained support from the Electric Engineering School and began my PhD study in the mineral processing field.

I never thought I could become an inventor until my Ph.D. study at Purdue University. My Ph.D. advisor, Professor Fritz Friedlaender, was the President of the IEEE society in 1977 with a specialty in magnetics. In addition to the magnetic bubble memory area, he was also a pioneer in the High Gradient Magnetic Separation field. That was just developed to separate weakly paramagnetic material from diamagnetic materials at an ultrafine particle size and applied in the mineral industry such as clay, uranium, and rare earth. I learned Electromagnetics and Separation from him which assisted me making many unconventional breakthroughs in various fields.

I was also advised by Prof. Reinhardt Schuhmann, Jr., from Chemical and Metallurgical Engineering. Prof. Schuhmann was a colleague of Prof. Antoine Gaudin at the Massachusetts Institute of Technology in ore dressing (mineral processing) before he moved to Purdue. The famous Gaudin–Schuhmann Model on particle size distribution was given by them. I was also co-advised by Prof. Phillip Wanket in Chemical and Metallurgical Engineering and Prof. Gunnar Kullerud in Earth Science. Prof. Wanket is well known for his book "Separation Process Engineering: Includes Mass Transfer Analysis". Prof. Kullerud was famous in the sulfide mineralogy, who established many phase diagrams of sulfides and advised mining companies on their applications to mineral exploration. I build my knowledge in various areas from them.

My Ph.D. thesis was my first challenge on innovation. I need to separate alunite from quartz in a Colorado ore after grinding the ore to an average particle size of 5 μ when ultrafine particle processing technology was lacking or nonexisting. Alunite is a potassium aluminum sulfate mineral. It is diamagnetic (or non-magnetic) and so does the quartz. To separate them by magnetic separation is nearly impossible, but it has to be done. I could not graduate unless I solve the problem, as my advisor told me. I have to detour from conventional physics and make alunite pseudo-magnetic. I initiated the magnetic seeding concept to selectively co-flocculate alunite and magnetite since I found an article from Prof. Kitchener in Empire College of England talking about selective flocculation of ultrafine particles for their separation. If one can selectively flocculate a mineral, then it might be possible to flocculate two minerals together. After I learned and was able to control the surface chemistry of various minerals and their behavior in water, I made the magnetic separation of alunite and quartz [1, 2] and got my Ph.D. degree.

I was a postdoc in the School of Electric Engineering at Purdue University from 1982 to 1984 to assist Prof. Friedlaender in continuing the development of the theory and application of high gradient magnetic separation technology. In this period, I had my first patent, "Magnetic Separation Method Utilizing a Colloid of Magnetic Particles" (US Patent 4,526,681). My colleague, Dr. Makoto Takayasu, who moved to

MIT later, and I were playing ferrofluid or called magnetic fluid at that time. Ferrofluid was a new material found applications in seal, magnetic levitation, etc. It is composed of magnetite particles of about 100 angstroms homogeneously dispersed in water by lignosulfonate-type coating on the nanoparticles [3]. Most people use ferrofluid based on their bulk property. However, we found that the diffusion of the magnetic particles under the magnetic force can yield a magnetite concentration gradient. Then particles of different materials possessing different magnetic susceptibilities placed in the fluid with magnetite nanoparticle concentration gradient under a magnetic field can move to positions where their magnetic susceptibility equals to the magnetic susceptibility of the colloid with corresponding concentration. This is the first time one can separate materials purely based on their magnetic susceptibility without worrying about other physical properties such as particle size and density [4].

Magnetic fluid is composed of nanomagnetic material coated with charged organics such as lignosulfonate, a paper pulping by-product, to provide sufficient repulsive force between the nanomagnetic particles. Learned from that concept, I combined it with the flotation collector concept to create a new kind of mineral processing technology. Froth flotation is the most commonly utilized separation technology in mineral processing. This technology was invented and developed by Prof. Gaudin of MIT, a colleague of one of my advisor, Professor Reinhardt Schuhmann, Jr. Froth flotation uses the selective adsorption of surfactant on a mineral particle through the functional group of the surfactant (surfactant has one end of functional group with hydrophilic property and the other end of hydrocarbon chain with hydrophobic property) to render the mineral particle hydrophobic and hence make the particle possessing the ability to attach to an air bubble for its flotation so the separation of different minerals can be achieved. Through the years of development, the chemical system for the selective adsorption of different minerals has been established and applied in the industry. However, froth flotation has problems to apply to particles of microns and below. Ultrafine particles generally cannot be made hydrophobic enough in water to facilitate efficient particle–bubble attachment. For example, kaolin clay is a major ingredient for paper coating to make the paper white and easy to write. Kaolin clay has impurities such as anatase TiO_2 that makes clay not white enough and has to be removed after mined. Since the anatase particles in clay are microns and less, froth flotation was difficult to be applied and High Gradient Magnetic Separation was utilized by the clay industry. Anatase is only feebly magnetic, this gives a big headache to the clay industry. They have to increase the magnetic field intensity at very high cost to enhance the separability.

I invented a new technology (“Reagents for Magnetizing Nonmagnetic Materials”, US Patent 4,834,898 (1989), 4,906,382 (1990), and 5,043,070 (1991)) that opens the door for the treatment of ultrafine particles. In this technology, nanomagnetic particles are coated with two layers of surfactants like a Michelle structure. The first (inner) layer has a functional group with an affinity to the magnetic particle. The second (outer) layer has an affinity to the particle we want to separate. Through this arrangement, nanomagnetic particles can be selectively adsorbed on the particles of interest [5, 6]. Cytec Industries, a billion-dollar revenue major specialty chemical company that has business in froth flotation chemicals has commercialized this technology.

I have applied the concept of high electric charge/polarization to enhance the adsorption of hydrogen for hydrogen storage materials [7–11]. My hydrogen storage material concept received one of the Grand Challenge awards of the US Department of Energy.

Electrosorption technology was a water treatment technology that has gone all the way to the full commercial practice [12]. In its operation, water flows in between the electrodes. Ions and charged molecules are attracted to the electrodes of opposite charge. Once they reach the electrodes, they are adsorbed and stored there. Thus, they are separated from clean water. When the adsorption is saturated, the circuit is shorted to release the ions and flush them out. In addition to various operational parameters of the system, such as the voltage, flow velocity, retention time, etc., electrode material is the key to the electrosorb technology. Porosity, pore structures, and chemical stability are some of the important factors.

The water treatment technology was further considered in a system that treats the electroplating wastewater using a variety of technologies including membranes and electrodialysis [13]. The electroplating wastewater is one of the most complicated industrial wastewaters that contains chemicals and wastes generated from various plating operations such as copper, nickel, chrome, zinc, and others. Many organic and inorganic materials are involved for the quality of the plating. Futianbao is a leading company in China for electroplating wastewater treatment and there are several papers in this symposium discussing the advances on recent developments.

Development of copper-based antimicrobial coating material that can inactivate bacterial and virus on the surface of products to avoid sickness through contact [14]. Its commercial development was carried out by Dr. Bowen Li under the QTEK Inc.

I have conducted research on materials recycling where I combine separation technology, materials processing technology, market analysis, and re-manufacturing and re-utilization technologies with a life cycle analysis to obtain the most logical approach. Fly ash, automobile shredding residue, steelmaking slags, foundry sands, grinding swarfs, blasting media, aluminum smelting slags and saltcakes, are a few examples of the projects he directed [15–21]. Cemex, one of the world largest cement and constructional material company with 18 billion in revenue, has licensed the flyash separation and utilization technologies I developed (US Patent 4,834,898 (1989); 4,906,382 (1990); 5,047,145 (1991); 5,249,688 (1992); 5,096,572 (1993); 5,277,047 (1993); 6,068,131 (2000)), which makes millions tons of coal combustion by-products generated from power plants to quality products that can be utilized in constructions, plastic fillers, and others.

One of the biggest challenges to me is the microwave metallurgy technology, which I have spent the last 20 years to advance the theory, mechanisms, equipment, and operations for its industrial applications [22–33]. The environmental problems are the biggest challenge to the smelting operations of all metal industries. When I was young, I observed the closure of one of the largest copper ore smelters in my neighborhood at White Pine, Michigan. In the 1990s, the bankruptcy of more than

30 of the world's largest and most famous iron and steel companies, such as Inland, Bethlehem, LTV, etc., astonished me and my generation. I began to think about what I can do in my life to change that, making the industry and environment more friendly to each other.

The fundamental problem is all the smelting technologies are basically combustion-oriented. Combustion inevitably resulted in various air pollutants such as NOx, SOx, CO_2, dust, etc., that are very burdensome to the smelting operations. To avoid combustion, air-free heating and reaction are required. Since carbohydrates, carbon, water, iron oxides, and many other minerals are microwave absorbing materials, I began to investigate the possibility of microwave metallurgy. It is easy to understand that CO_2 and H_2O react with carbon at high temperature to generate CO and H_2 gases (Boudouard reaction). CO and H_2 gases are excellent reductants to reduce metal oxides to metals and generate CO_2 and H_2O again. As long as carbon and microwave heating exist, the reaction will continue until all oxides reduced and the final products are only metal, CO, and H_2. In a sealed microwave furnace, no air is present so NOx is prevented. No blast air and hence no dust. Sulfur is converted mostly to CaS instead of SOx. The reaction can be on–off controlled, enabling the use of cheap energy available off the peak, such as nights. Electric energy is clean and can be generated from all kinds of technologies. Smelters will only need to pay without worrying about environmental emission punishing tickets and lawsuits. CO and H_2 are the Syngas components that can be the raw material for the production of all kinds of chemicals and fuels. Not only coal but biomass wastes can also a good carbohydrate source in this approach, solving another environmental problem.

Development of microwave metallurgy is a long and difficult road. The chemical reactions are easy to prove. Through even a household microwave, I have proved that metal can be produced using this new concept. An early patent, "Method for Direct Metal Making by Microwave Energy", US Patent 6,277,168, 2001, demonstrated that. However, it is far away from industrial practice. How to transport the microwave from its generator at a distance, how to design a furnace that can meet the needs to distribute the microwave to materials evenly and efficiently, what are the interactions between microwave and materials under various physical and chemical conditions, how to obtain the highest heating efficiency, what are the mass transfer and heat transfer phenomena and how to control them for the reaction uniformity, etc. There are numerous problems associated with it that are not traditionally encountered by metallurgists. Dr. Zhiwei Peng, Dr. Xiaodi, and I have tried to solve many fundamental and operational problems but much more work is still needed.

Career Development

After my postdoc research at Purdue from 1982 to 1984, I joined Michigan Technological University in 1984 and stayed there all the time. I started as a Research Scientist at the Institute of Mineral Research and had the adjunct assistant professor appointment in the Department of Electrical Engineering and the Department of

Geological Engineering in the university. The university was established in 1885 as the Michigan School of Mines because of the rich copper and iron ores in the area. Mineral related technologies were the emphasis of the research and education programs in the university and the Institute of Mineral Research was the focus of all mineral programs and was the center of mining research of Michigan state government before it was transferred to the university. In the Institute, I was able to broaden my knowledge to many other mineral technologies ranging from exploration, mining, mineral processing, metallurgy, and related environmental issues. In 1989, the Institute was renamed as the Institute of Materials Processing to bring in several materials programs such Plasma Coating, Hot and Cold Isostatic Press, Ceramics, and Powder Metallurgy and I was promoted as the Senior Research Scientist and the Research Manager to lead to the original mineral program of the Institute. In 1992, I was further promoted as the Director of the Institute of Materials Processing and oversaw all the mineral and material programs. Through this opportunity, I was able to learn many material processing technologies and expand my capacity of expertise. I was asked to join the Mining Engineering Department in 1996 for an academic appointment and served as the Chair of that department in 1997 while still serving as the Director of the Institute. Because of my research accomplishment expanded greatly into the metallurgical and materials side and the merge of the Institute with the Materials Science and Engineering Department, I was transferred to the Materials Department in 2004 and continued my Director position until 2012. The Department of Chemical Engineering and the Department of Civil and Environmental Engineering have also recruited me as their adjunct professor for my research overlap and achievements in their areas.

I am a continuous learner and have never feared to face the challenges of new research topics. I am able to combine my knowledge in mineral, mining, mineral processing, metallurgy, materials, electrical engineering, and environment to create new concepts for solving problems in the complicated world. I am able to put together a team composed of various disciplines to conduct a problem-oriented research.

I have been involved with many professional societies, especially TMS and SME. I have served as the chair of the Process Mineralogy Committee and the Secondary Materials and Environmental Committee of MPD in SME and the chair of the Materials Characterization Committee and the Pyrometallurgy Committee of EPD in TMS. I have initiated and organized or co-organized many international symposia for the two societies and edited or co-edited more than 20 books, especially the series of Materials Characterization proceedings and the International High-Temperature Metallurgical Process proceedings.

The prestigious AIME/TMS/SME James Douglas Gold Medal Award, the TMS EPD Technology Award, the TMS EPD Distinguish Service Award, the 1000 Talents Award of China, the China Non-Ferrous Society Award, and the MTU Bhakta Rath Research Award are some of the awards I received. I have also brought my graduate student team to win the Championship of the International Automotive Solutions Competition on Plastics Recycling, jointly sponsored by American Plastics Council (the major plastic companies), Vehicle Recycling Partnership (the big three), and Society of Automotive Engineers. My undergraduate senior design team is also the winner of the university-wide Champion. In addition to more than hundreds of industrial and government research projects, my research team won the US DOE Grand Challenge on Hydrogen Storage and the US DOE Grand Challenge on Steel Production of the Next Generation. My consulting activities included the Chief Energy and Environment Adviser for Wuhan Iron and Steel Corp, a Global Fortune 500 company, the Chief Technical Adviser of EST Technology Co., and the Chief Science Adviser of Futianbao Environmental Protection Technology Company. I understand what industry needs and can bridge the academic and industry well.

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