Opportunities and Challenges in Steel Manufacturing: Engineering a Brighter Future

This paper was presented as the AIST J. Keith Brimacombe Memorial Lecture at AISTech 2008 in Pittsburgh, Pa.

This lecture discusses two of the major challenges and opportunities that face the steel industry today, especially in North America: attracting and keeping the best technical leaders in the steel industry, and continuing excellence in solving the steel industry's challenges in the areas of energy and the environment.

It is a great privilege and honor to present the sixth J. Keith Brimacombe Memorial Lecture. Professor Keith Brimacombe won numerous national and international awards and honors during his career and was considered one of the world's top ferrous and nonferrous process metallurgists. However, while being such a great scholar, Keith was a humble man with a sense of humor and a personality that put everyone he talked with at ease. Keith Brimacombe was loved and respected by all who knew him, whether it was corporate presidents, the world's top research scientists, his college students, or operators on the floor of the numerous steelmaking and casting shops that he visited during his career. Keith Brimacombe has been an inspiration to many steelmakers, and I am blessed to have been one of them. In the 1980s, I had the opportunity of attending one of Professor Brimacombe's continuous casting courses at the University of British Columbia and also one of the ISS short courses that he taught jointly with Professor Alex McLean, the third Brimacombe lecturer. My memories from these courses and the times I spent with Keith include intense process metallurgy discussions intertwined with times of laughter and fun that made learning an enjoyable experience. When I considered leaving my position in the steel industry to pursue teaching, it was Keith Brimacombe and Alex McLean who took the time on two different occasions to spend an evening with me. Their encouragement led me to return to graduate school and get a Ph.D. so that I could teach process metallurgy. Professor Keith Brimacombe was not only a great steelmaking and casting researcher and educator, but also a great friend and mentor to many of us in the steel industry and academia.

In considering topics for this lecture, I wanted to present issues that Professor Brimacombe would have been passionate about today if he were helping prepare this lecture. I have selected two major themes that I believe Keith Brimacombe might have chosen: people — attracting and keeping the best technical leaders in the steel industry, and research — continuing excellence in solving the industry's technical issues, especially in the areas of sustainability, energy and the environment.

During the last 25 years, there has been tremendous change in the steel industry, including consolidation and rebuilding of the industry, which brought about closure of many plants across North America, and the introduction of new technologies in steelmaking and casting that have dramatically improved productivity and economics. Redefining steel corporations and investment strategies to a global market has resulted in major foreign investment in the revitalized North American steel industry. Globally,

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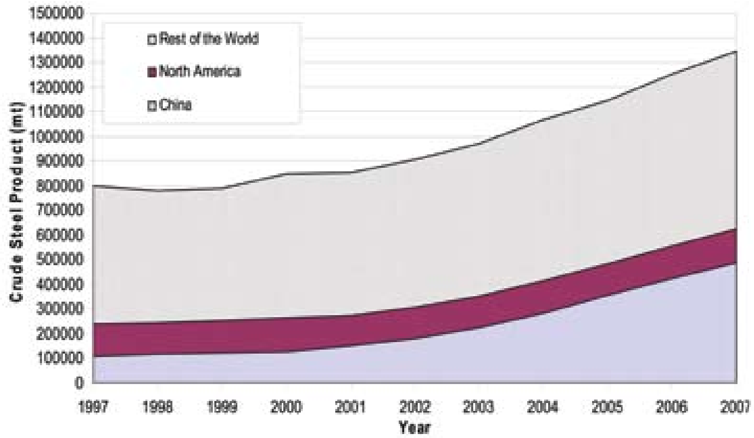
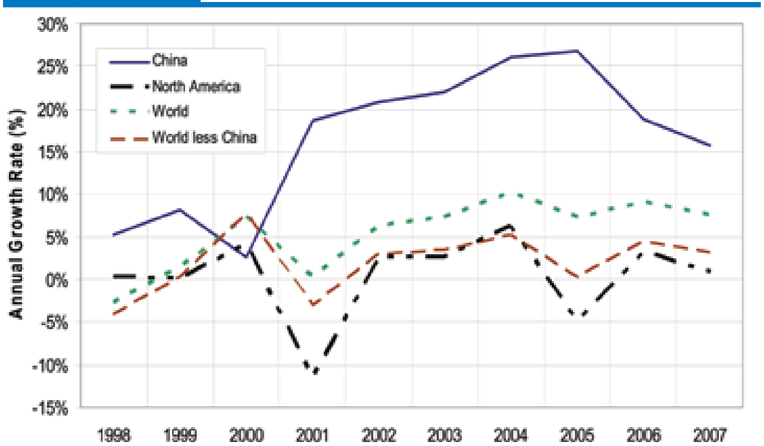
Figure 1



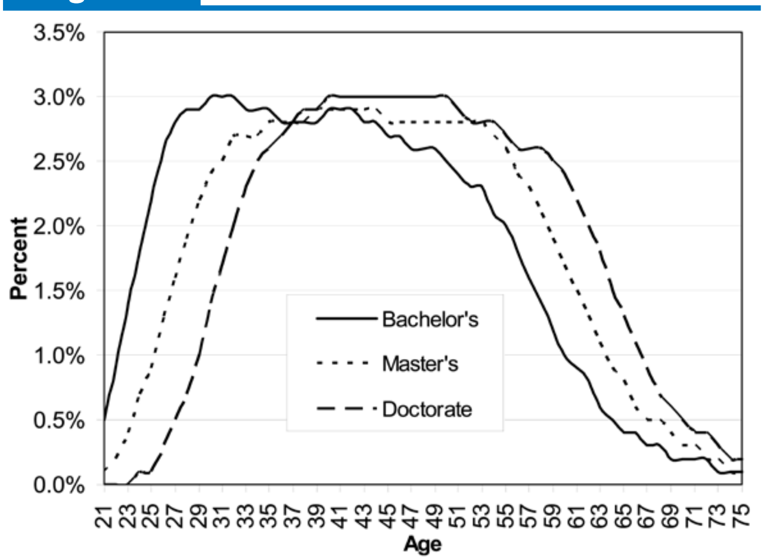
Crude steel production during the last 10 years.[1–2]

Figure 2



Annual growth rate in crude steel production in the world.[1–2]

Figure 3



Age of science and engineering workers in the U.S. in 2003.[3]

there has been tremendous growth in the steel industry due to the strong demand in developing economies such as China and the strengthening of the demand in the world. Figure 1 illustrates the growth in world steel production over the last 10 years. The steel industry in China has changed from one that produced significantly less steel than North America to the largest producer in the world today, currently producing 36% of the world's production, nearly four times the tonnage of North American steelmakers.[1–2] Figure 2 compares the growth rate of steel production in North America with China and the rest of the world. Although the steel industry in North America has been highly profitable during the last five years, steel production growth has been flat, unlike the world market driven primarily by China. In terms of opportunities and challenges, North American steel producers will need to adjust to a future steel industry dominated by forces outside of North America and work at maintaining competitiveness through continued research and development and adoption of the latest steelmaking and casting technologies.

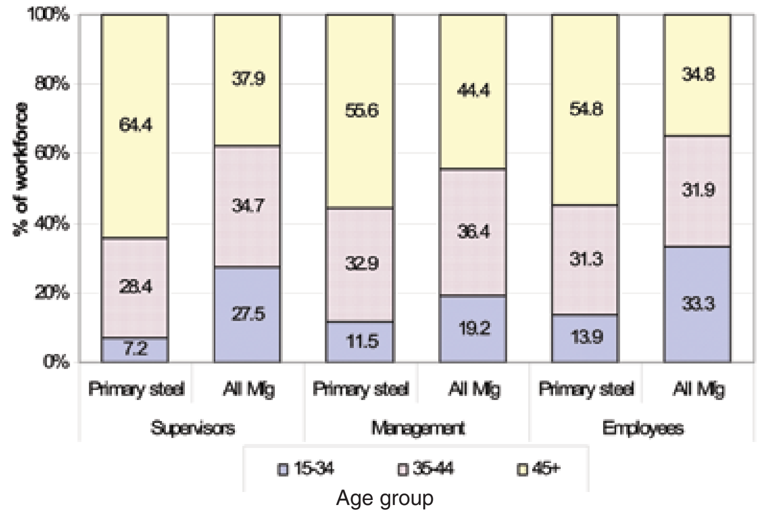
Opportunities and Challenges in Recruiting Steel Industry Leaders

One major challenge facing the steel industry of the future is recruiting the engineers and technical talent required to keep the steel industry vibrant and growing technologically. This is a challenge on numerous fronts. First, many of the engineers, technical staff and management in the steel industry are baby boomers and will be retiring in large numbers over the next 10 years. This will require an influx of new talent to replace those retiring. In addition, newer steel plants require a larger percentage of the workforce to possess technical degrees and need less unskilled labor. Figure 3 shows the demographics of the general science and engineering workforce in the United States. It is interesting that there has been some replacement of workers with bachelor's degrees during the last 10 years, but there has been a general lack of hiring of workers with graduate degrees. Although this is the demographics of the general workforce in the United States, the trends are not much different in the steel industry. During the last 10 years, with the large amount of consolidation in the industry, many of the research facilities that used to hire master's and doctoral graduates have been shut down, and workers were moved to central research or production facilities, resulting in an increase in the average age of the typical steel company researcher. The median age for the science and engineering workforce is 41 for those with a B.S., 45 for those with a master's and 48 for those with a Ph.D.[3] Although there is no comprehensive study of the average age of the engineers and managers in the North American steel industry, the Canadian steel industry recently completed a study of the demographics within their own industry.[4] Figure 4 compares the age of workers in the Canadian steel industry with other manufacturing sectors. The workforce in the steel industry is significantly older than in other manufacturing industries and will require more replacement workers over the next few years. Nearly two-thirds of the supervisors are over 45 years old, and only 7% are under 35 years old. Management in the steel industry is closer to retirement age than in other manufacturing industries. Much of this is a result of the restructuring and consolidation of the industry during the last 10 years, where steel companies combined workforces and did not recruit younger workers.

In addition to replacing those retiring, the demand for engineers has increased due to expanding technology. According to data from the National Science Foundation, during the last 20 years the number of jobs in science and engineering has risen at an average annual growth rate of 4.9%, nearly five times the average annual growth rate for all jobs, reflecting the growing trend toward technology.[3] Figure 5 shows the dramatic result of this growth rate in jobs in science and engineering, growing from 2.7% of all the jobs in the U.S. to 4.2% in 2005. Interesting enough, although the number of jobs has increased in science and engineering, the number of students majoring in engineering has not increased. When considering the majors hired most frequently by the steel industry (mechanical, electrical, chemical and metallurgical/materials engineering), the percentage of students graduating in these majors has decreased from above 5% of all college graduates 20 years ago to less than 3% today. This gap in engineering graduates to the number of engineering jobs available is resulting in a shortage of talent. This has been particularly felt in specialized fields such as metallurgical engineering. During the last 20 years, many of the metallurgical engineering programs were discontinued or replaced by materials science programs as a result of the industry's reduction in hiring of engineers and decreased spending on university-related research. Although the mining, steel, oil and transportation industries are attempting to recruit larger numbers of metallurgical engineers today, the reduction in metallurgical engineering programs and faculty makes it difficult to educate more metallurgical engineering students.

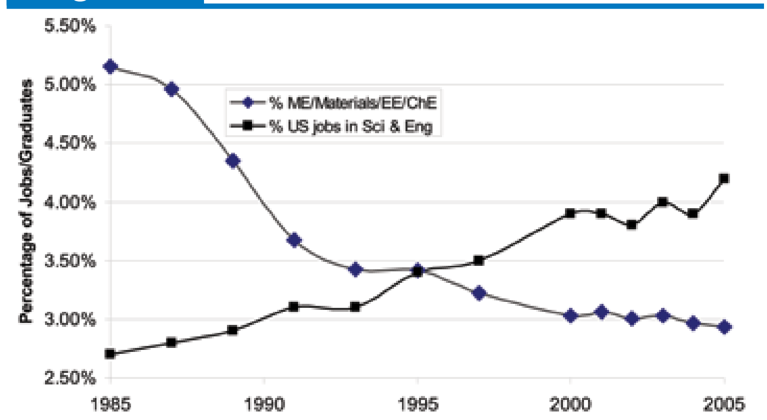
Interestingly enough, as the number of engineering degrees has been dramatically dropping in the United States, the number of degrees in many other countries has been increasing. Figure 6 compares the number of engineering degrees in the U.S. with Asia, showing that other countries have not experienced the same of type of decrease seen in the U.S. In the past, much of the gap in technical talent in the U.S. was filled by employing engineers and scientists from other countries such as India and China after they finished graduate school in the U.S. However, there has been a decline in this pool of talent since Sept. 11, 2001, because of the increased difficulty for foreign students to obtain visas to study in the U.S., which has resulted in fewer applications from abroad. In fact, 2004 represented the first time in 32 years that the number of foreign students dropped at U.S. colleges, with foreign graduate applications decreasing by 28% from 2003.[5] The drop in foreign

Figure 4



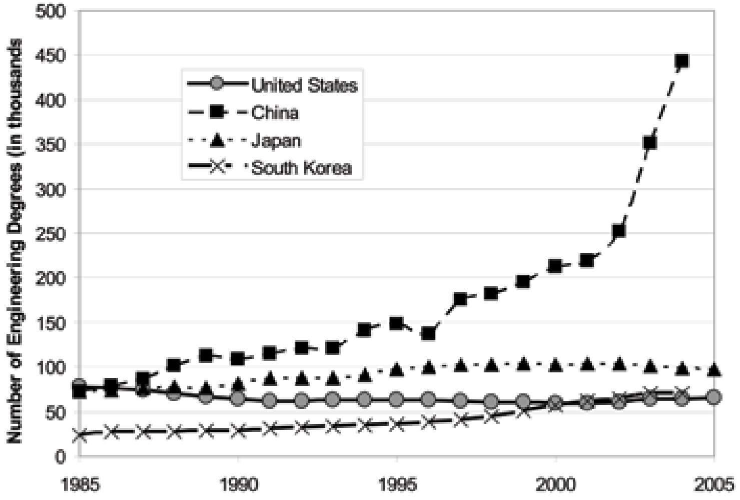
Age of workforce in the Canadian steel industry compared to other manufacturing in 2004.[4]

Figure 5



Percentage of college graduates earning a B.S. degree in mechanical electrical, chemical or materials engineering in the United States as compared to those employed in science and engineering.[3]

Figure 6



Number of students receiving engineering degrees.[3]

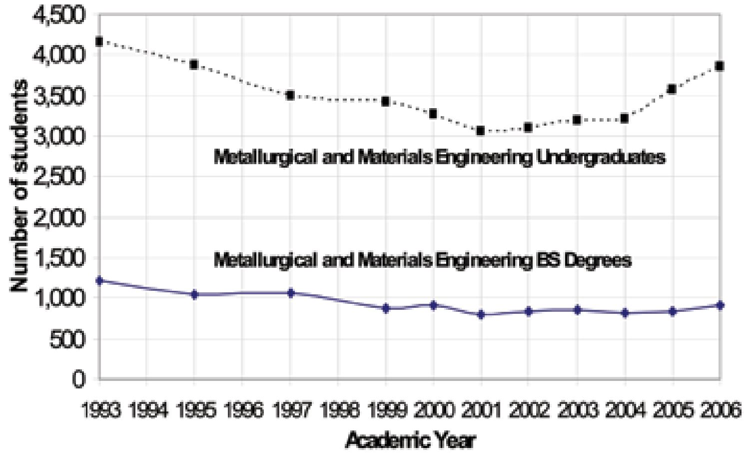
applications to engineering schools was even higher, with a 36% decrease in foreign applications in 2004 and some programs, such as the University of Florida (one of the largest materials science and engineering departments in the U.S.), seeing a 42% decrease.[5] Another factor decreasing the number of foreign students applying to graduate school in engineering is the improving higher education systems and high-technology sectors in their home countries, making it more difficult to attract and retain highly trained engineers and technical personnel from abroad. The boom in the Chinese and Indian steel industries makes it more difficult to attract foreign metallurgical engineers to North America. Therefore, it is important that the steel industry expand the number of students interested in manufacturing and increase the domestic engineering degree production to fulfill the steel industry's needs as well as support foreign engineers coming to the U.S.

One of the most important challenges to the steel industry is overcoming its poor image. Although the steel industry is proud of the contribution that its products make to modern society and its contribution to the welfare of mankind, the general population, including the future leaders of the steel industry, is ignorant of steel's contribution. This not only affects recruitment of talent, but also has a negative effect on design engineers choosing steel in new products, government decisions on public policy, and the financial market's viewpoint of the steel industry as a stable investment. Even with an increasing number of jobs in science and engineering, today's youth are less inclined to enter a career in engineering, especially one in mainstream manufacturing such as the steel industry. ACT research suggests that, even with the excellent job opportunities, students' interest in science and engineering is on the decline. Over the past 10 years, the percentage of ACT-tested students who said that they were interested in majoring in engineering has dropped steadily from 6.6% in 1997 to 3.3% in 2007.[6] Recently, the National Association of Manufacturers, the Manufacturing Institute, and Deloitte and Touche did research to determine the reasons why fewer young people are interested in entering a career in manufacturing.[7] They found that, regardless of a young person's geographic, ethnic and socioeconomic situation, the image of manufacturing is negative, typically stereotyped as an "assembly line," accompanied by other terms such as "boring," "dangerous," "dark" and "dirty," all in stark contrast to the characteristics desired in their future careers. In addition, young people generally consider manufacturing to be in a severe state of decline, requiring "hard work" and "long hours" for "low pay" with "no chance for promotion" or "benefits." Unfortunately, the same study indicated that teachers and parents universally echoed the same types of images about a career in manufacturing and therefore do not encourage the young person of today to pursue a career in manufacturing. With this perception, it is not surprising that it is difficult to attract young people to the steel industry.

Youth's lack of interest in a career in engineering, and especially manufacturing, has resulted in a decrease in the freshman enrollment in engineering fields in the U.S. associated with manufacturing. Enrollment in materials engineering dropped for several years and has only recently increased to nearly 4,000 undergraduate students presently pursuing degrees (see Figure 7).[8] Although the total number of students studying materials has slightly increased, the number of students studying metallurgical engineering has decreased. Many universities have eliminated their undergraduate metallurgical engineering degree programs, leaving only a handful of universities in North America continuing to graduate metallurgical engineers for the steel industry. Although the job opportunities are excellent for metallurgical engineering students, most Materials Science and Engineering (MSE) departments graduate few students with an emphasis in metallurgy. This is because MSE departments and professors tend to focus their efforts in the areas where research funding is available. Research funding in the area of steel has been steadily decreasing from both government and industry sources, causing most materials researchers to move into fields with more opportunities. MSE departments typically have small enrollments and therefore survive based on strong research programs. For example, 909 students graduated last year with a bachelor's degree in metallurgical or materials engineering, representing slightly more than 1% of the 74,186 engineering graduates.[8] However, the MSE departments that graduated these metallurgical and materials engineers account for nearly 10% of the total research and development funding ($644 million of the total $7.076 billion in research done in engineering).[9] In financial terms, that translates to $0.6 million in research per materials graduate with a bachelor's degree. Federal funding through agencies such as the National Science Foundation, Department of Defense, and Department of Energy (DOE) is supporting primarily fundamental research in materials areas such as nanotechnology, biomaterials, hydrogen and fuel cell technology. During the last 10 years, the largest federal program that targeted industrial-oriented research related to the steel industry (and other metals-based manufacturing) was the U.S. Department of Energy's "Industries of the Future" program. Funding for this program combined federal funds with at least an equal industrial match, and peaked in 2000 at almost $60 million in metals manufacturing research, with $20 million focused on projects for the steel industry. As summarized in Figure 8, this program has been severely cut, to where this year the U.S. DOE is funding $7 million, less than 25% of the funding just five years ago.[10] At the same time, industry consolidations have reduced the number of steel companies with research facilities that regularly support research projects at the major research universities. This explains why MSE departments and metallurgical engineering professors have moved into other research areas where there is brighter future for research funding from industry and the government. One of the major challenges to the steel industry is providing universities with the support required to continue teaching metallurgical engineering. Without professors that have an interest in the steel industry, it will be difficult to find engineers who are interested in a career in the steel industry.

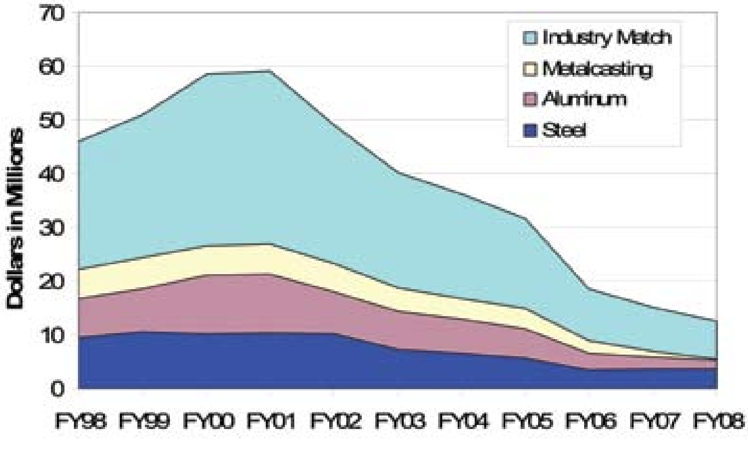
There are some excellent new programs to help in recruiting students, including the Steel Engineering Education Link (StEEL) and the Ferrous Metallurgy Education Today Initiative (FeMET), which provide scholarships to students interested in the steel industry and design grants to professors interested in developing steel-oriented curriculum and design at North American universities. Both programs are jointly sponsored by the AIST Foundation and the American Iron and Steel Institute (AISI). There are other scholarship programs supporting students interested in the steel industry from the AIST Foundation and individual steel companies. Increased efforts in university research are also important to sustaining the North American steel industry through the improvements and developments resulting from the research, linking new professors directly to the steel industry and attracting students working on the research projects to a career in steel. Efforts need to continue to make the steel industry an attractive career alternative for today's youth. More activities, such as materials camps and regular classroom demonstrations, are needed to impact students at younger ages and help them recognize that the steel industry is an exciting and vibrant career path. Industry support of metallurgical engineering programs — through gifts such as endowed professors, scholarships, research grants and equipment gifts — all help ensure the future education of engineers. The universities that have metallurgical engineering programs have seen sustained support from industry.

Figure 7



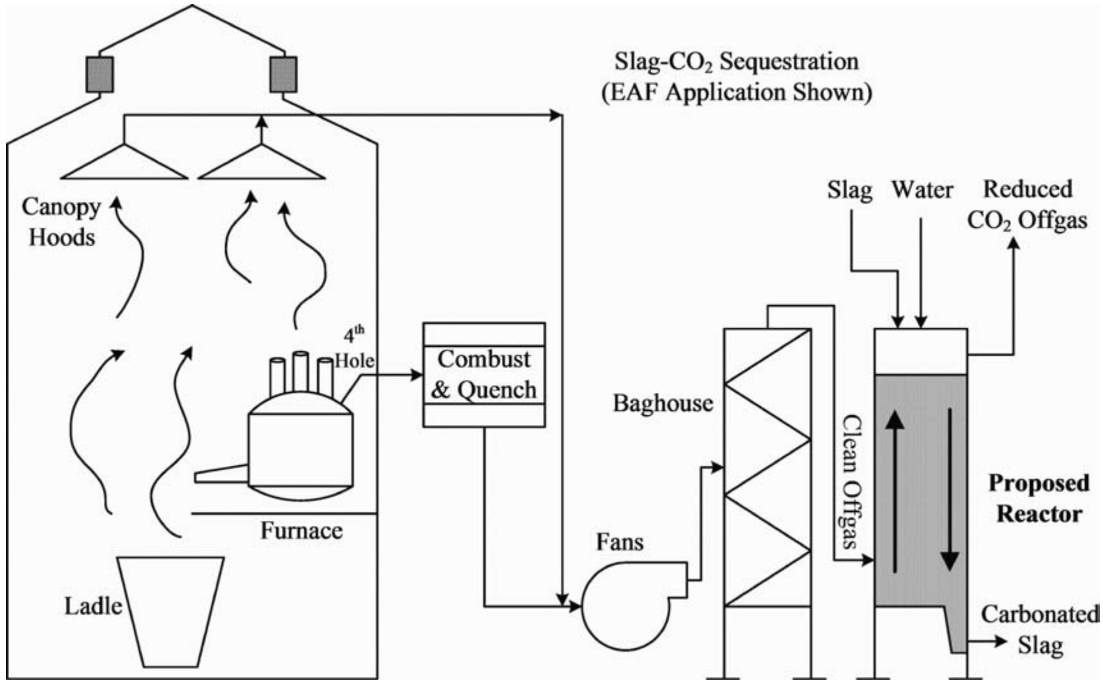
Number of students studying metallurgical or materials science and engineering in the U.S.[8]

Figure 8



Funding for metallurgy-related research through the U.S. Dept. of Energy's "Industries of the Future" program.[10]

Figure 9



Schematic of the process for capturing CO_2 from steelmaking offgas using slag (EAF application).

Technological Opportunities and Challenges to the Steel Industry

What are the top technological opportunities and challenges to the steel industry? Although there are many, one of the most important for today and years to come is reducing the environmental footprint of the steel industry. Globally, the steel industry produces 1.7 tonnes of CO_2 per tonne of steel and uses 19.1 GJ of energy per tonne of steel produced, based on figures from the International Iron and Steel Institute (IISI).[11] Reductions in these metrics require a variety of attacks. First, research and development needs to continue to develop technologies that reduce energy consumption and the carbon footprint through incremental improvements. Second, research needs to develop revolutionary new processes for ironmaking and steelmaking that completely change the use of fossil fuels through the use of renewable carbon resources or the elimination of carbon from the process. Third, the industry should adopt increased use of life cycle assessment tools to make internal company improvements and to help customers and the public realize the environmental advantages of steel products.

Geological Sequestration of CO_2 Using Steelmaking Slag — One example of research and development aimed at improving the carbon footprint for steelmaking plants is the work at the Missouri University of Science and Technology (Missouri S&T) in geological sequestration of CO_2 using steelmaking slag. In this process, specially prepared steelmaking slag from either the basic oxygen furnace (BOF), electric arc furnace (EAF) or ladle metallurgy furnace (LMF) is allowed to contact the steelmaking furnace exhaust gases to react and create carbonates, thus capturing and storing the CO_2. Production of a ton of steel generates, on the average, 519 kg CO_2 carbon equivalent (CE) for BOFs and 119 kg CO_2 CE for EAFs.[12] BOF and EAF slags typically average 30–50 wt. % CaO and 10–12 wt. % MgO, and LMF slags typically contain 50–60 wt. % CaO and 10–12 wt. % MgO. With slag production per ton of 75–150 kg for BOFs, 65–80 kg for EAFs, and 15–20 kg for LMFs, and assuming full stoichiometric conversion of CaO and MgO to carbonate, steelmaking slag has the potential to sequester 6–11% of the CO_2 generated from BOF production and 35–45% of the CO_2 generated from EAF production.[13]

Steelmakers have realized that slag reacts with the atmosphere, and it is a common practice to allow aging time for steelmaking slag before shipment to stabilize the volume changes that occur during the hydration and carbonation reactions within the slag. In this work, the objective was to develop a process for sequestering CO_2 from steelmaking offgas by forming carbonates with the alkaline earth oxide–containing phases in slag, based on improving the kinetics of the carbonate formation reaction to allow the design of a commercially feasible reactor, as illustrated in Figure 9. Work considering a "dry" solid-gas contactor, in which stack offgas is directed through an atmospheric pressure-rated vessel containing slag particles, has proved to be technically difficult due to the kinetics involved with the gas reactions. Although work is still in progress to investigate catalysts, chances of developing this type of reactor are not promising. However, a more promising reactor is a “wet” design, in which slag is mixed with water and continuously bubbled with the offgas — very similar in function to a mechanical flotation cell, which allows for intimate gas-solid contact in a water-dispersed system. This design has been improved through use of a two-vessel reactor system, illustrated in Figure 10, in which fine slag is fed into the first reactor, where it contacts carbonic acid pumped from the second reactor. The carbon acid is formed by bubbling offgas through water, stripping the gas of the CO_2. While a slurry reactor system is more complicated for operations, the water addition greatly improves the kinetics of reactions. The following equations summarize the possible reactions that can occur. For simplicity’s sake, the reactions are for calcium, but similar reactions occur with magnesium and other alkali metals.

Ca leaching

$$CaO_{(s)} + H_2O_{(l)} = Ca_{(aq)}^{2+} + 2\,(OH^-) \quad \text{(Eq. 1)}$$

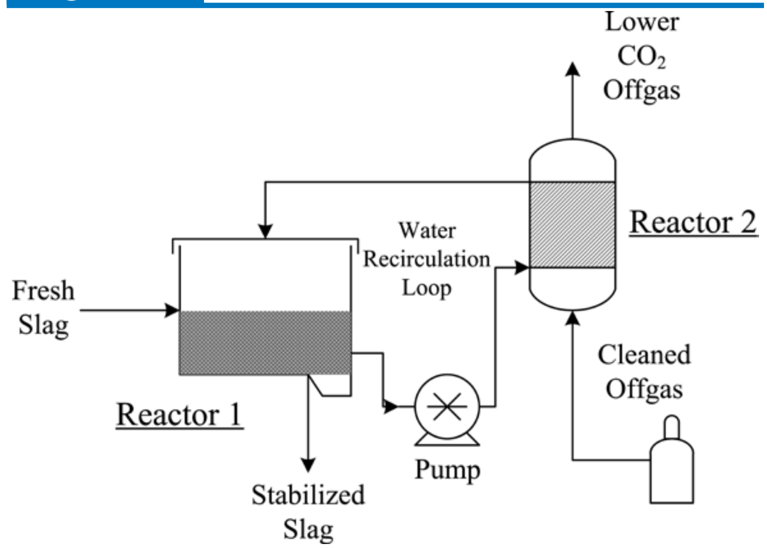
CO_2 dissolution (carbonic acid formation)

$$CO_{2(g)} + H_2O_{(l)} = 2H^+ + CO_{3(aq)}^{2-} \quad \text{(Eq. 2)}$$

Carbonate precipitation

$$Ca_{(aq)}^{2+} + CO_{3(aq)}^{2-} = CaCO_{3(s)} \quad \text{(Eq. 3)}$$

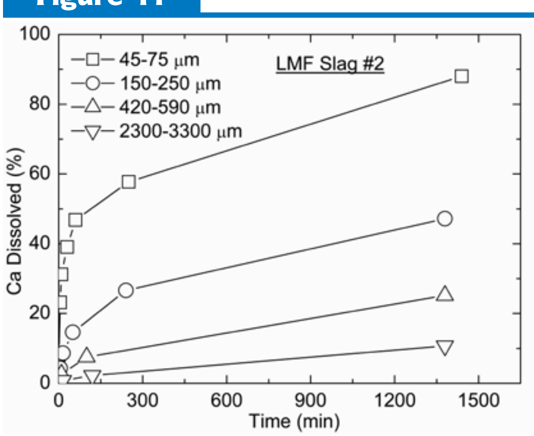
Figure 10



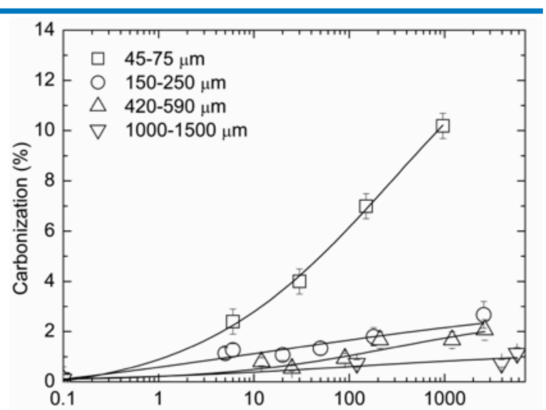
Schematic of two-stage slurry reactor for contact of slag with water and CO_2.

Figure 11a shows the effect of particle size on the rate of calcium leaching from slag. The particle size (i.e., surface area) had a significant influence on the amount of calcium leached. Leaching of Ca^{2+} starts at the slag surface, which includes many deep, interconnected pores throughout the slag particle. During carbonation, the interconnected channels within the highly porous slag allow surface reactions to take place deep inside slag particles. A cross-sectional sample of a particle showed that, after 48 hours, carbonization treatment, a 10- to 20-µm-thick carbonate layer on the external surface extended into the pores and consisted of plate-like crystals in a random high-porosity structure, as observed in Figure 12a. Pores connected to the slag surface through channels exhibited a reaction layer made of overlapping calcium carbonate plates packed very close together (see Figure

Figure 11



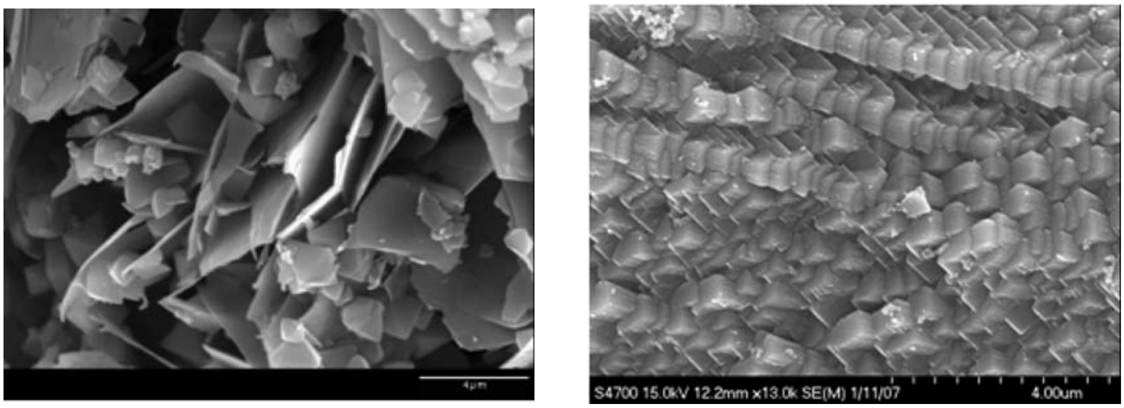
(a)



(b)

Calcium leaching from slag (a) and direct carbonization of slag in CO_2-saturated aqueous solutions (b).

Figure 12



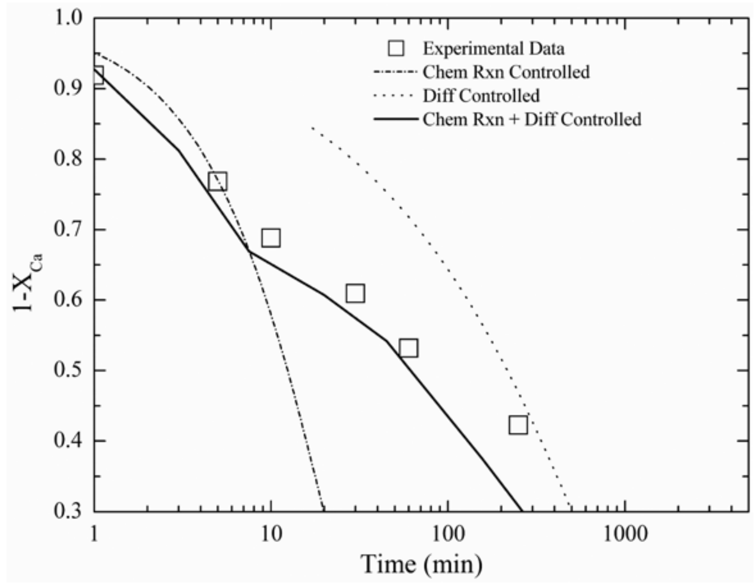
(a) (b)

SEM image showing external surface carbonate layer (a) and internal surface carbonate layer (b).

12b) and thus having a high bulk density. The shrinking core model was used for analysis of heterogeneous (particulate) solid-fluid reactions to determine the rate-limiting mechanism. During the initial stage, the reaction time follows the chemical reaction controlled model, whereby solid CaO dissolves into Ca^{2+} ions in the water. As the dissolution reaction progresses, a porous surface structure develops, resulting in a tortuous path for the ions to travel. Subsequent diffusion through this structure became the rate-limiting step, as indicated by the data closely fitting the diffusion mechanism of the shrinking core model (Figure 13).

Direct carbonization was performed in a batch-type reactor using slag mixed with deionized water through which CO_2 was continuously bubbled. The degree of carbonization versus time for four different slag size fractions is shown in Figure 11b. Particle size has a significant controlling influence on the resultant amount of carbonization, with a particle size of < 100 µm needed to achieve any appreciable level of reaction. In summary, the sequestration of CO_2 using steelmaking slag is promising, based on improving the kinetics of the reaction through reduction in size and use of catalysts. Reducing the size of the slag not only improves the kinetics of carbonation, but it also improves the recovery of the iron units currently being lost to the slag.

Figure 13



Comparison of calcium leaching data for (45–75 µm) particles with chemical and diffusion reaction control mechanisms.[14]

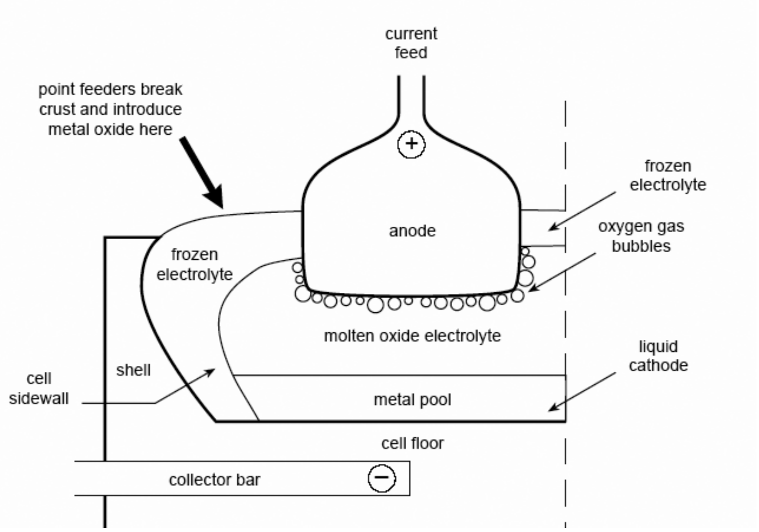
Research in Carbonless Ironmaking — One interesting research topic that could change the way the steel industry makes iron in the future is Molten Oxide Electrolysis (MOE), being developed at Massachusetts Institute of Technology. MOE is a form of molten salt electrolysis, the technology that has been producing aluminum for over 100 years. However, unlike aluminum production, the new process for iron will use carbon-free anodes, which results in the production of oxygen gas instead of carbon dioxide at the anode, as illustrated in Figure 14.[15] Unlike conventional ironmaking, this process is totally carbon-free and hence produces no CO or CO_2, and therefore offers powerful environmental advantages over conventional technology. Iron oxide is fed into a molten oxide electrolyte, which through an electrochemical reaction results in the following net reaction:

$$(FeO_x) = Fe_{(l)} + x/2\ O_2 \qquad \text{(Eq. 4)}$$

Initial results from the process have proved that deposition of iron is feasible at fairly high current densities, making this technology promising for the future. Although this process in itself does not generate CO_2, in today's world, much of the electricity generation is carbon-based, resulting in significant CO_2 emissions to generate the electrical energy required to drive the iron reduction process. This process becomes more favorable on a life cycle basis once more carbon-free electrical generation becomes available.

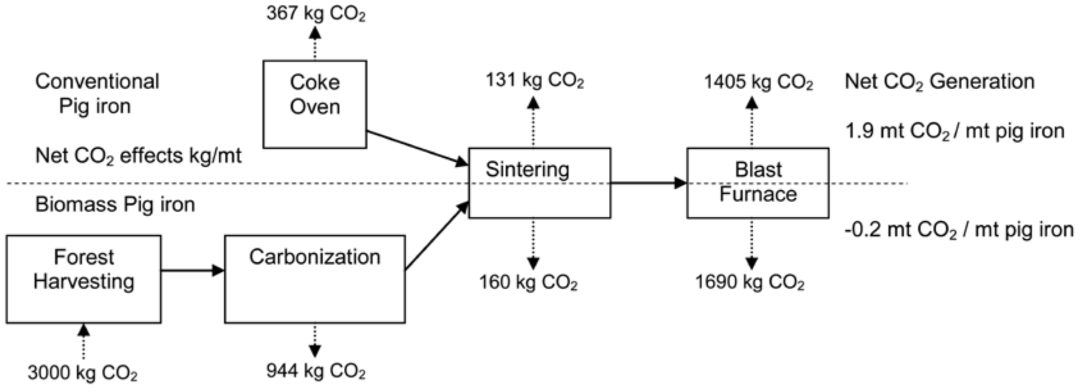
Use of Biomass in Ironmaking — Another area of research that could gain importance in the near future is the use of biomass in place of other carbon sources. Nucor announced a joint project to produce environmentally friendly pig iron with the Brazilian mining company Companhia Vale do Rio Doce (VALE). This project is especially attractive because the production of pig iron results in the net effect of actually removing carbon dioxide from the atmosphere rather than increasing it.[11] The carbon source is fast-growing hybrid eucalyptus trees that reach a height of approximately 21 m and are harvested every seven years and replanted every 21 years. During the growth phase of the trees, carbon dioxide is taken from the atmosphere and "sequestered" as biomass. The wood is harvested and carbonized to create charcoal and used to reduce the iron oxide. Some of the biomass returns to the soil as leaves and twigs. Although carbon is released into the atmosphere during carbonization, sintering and the blast furnace processes, the amount is less than that of the carbon originally removed by eucalyptus trees during photosynthesis. Therefore, instead of resulting in an overall increase in the amount of atmospheric carbon, as is the case with conventional pig iron production, the amount actually decreases. This is not a n ew concept in Brazil, as steel has been produced using charcoal from eucalyptus trees for many years. The challenge with large tonnages will be to sustain sufficient forests to manufacture the charcoal required for this project. Producing 500,000 tonnes of pig iron per year will require over 40,000 hectares of eucalyptus forest, which must by Brazilian law be doubled because of previous abuses to the forest. An equal amount of forest must be restored to its original condition, thus increasing the required size of forest to over 80,000 hectares, the equivalent of more than 200,000 acres or about 312 square miles of forest. It is estimated that these huge forests will remove 2 million tonnes of carbon dioxide annually and will in total remove 1.1 tonnes of carbon dioxide from the atmosphere for every ton of pig iron produced, as compared to conventional pig iron production, which increases the carbon dioxide released to the atmosphere by 1.9 tonnes per tonne of steel produced.[11] Figure 15 illustrates the carbon

Figure 14



Molten oxide electrolysis for iron production.[15]

Figure 15



Comparison of carbon dioxide production/sequestered for conventional coke versus eucalyptus iron production.[16]

dioxide emissions from current operations in Brazil using eucalyptus charcoal to manufacture pig iron.[16]

Other similar types of projects should be investigated in the future to determine how much biomass could be implemented in traditional types of ironmaking and steelmaking in the blast furnace, cupolas, and in place of coke additions in steelmaking furnaces. There has been limited research in the past, but more is required. Additional research topics for the future include investigating the adaptation of eucalyptus trees and other similar types of plants for green energy production in regions where they presently cannot be grown, such as the United States, providing additional opportunities for renewable carbon sources.

Life Cycle Assessment Use in the Steel Industry — Life cycle assessment (LCA) is a valuable tool that could help the steel industry evaluate new processes and steel products. The theory of life cycle assessment originated as a study to reduce the cost and emissions (i.e., greenhouse gases, carbon dioxide emissions and energy consumption) associated with various production processes. LCA refers to the "cradle to grave" assessment of the energy requirements and environmental impacts of a given product design. All assessments of the total life cycle of the product are considered, including raw-material extraction from the earth and product manufacture, use, recycling (including design for recycling) and disposal. Life cycle assessments and life cycle inventories (LCIs) are a part of the International Organization for Standardization (ISO) 14000 family classification designated as ISO 14040–14043, which specifically delineate LCAs and LCIs. The intention of these standards is to give companies a methodology to minimize the overall environmental impact of their products. To perform an LCA, the scope, including the purpose and the expected outcomes, must first be defined. Then an LCI is performed to quantify the various inputs and outputs (i.e., energy, wastes and resources) required for each phase of the life cycle. Based on the LCI, an impact analysis is completed to consider the effects of the inputs and outputs on health and environmental issues. Once the impact has been analyzed, improvement analysis can be used to evaluate reductions, such as minimizing cost and harm to the environment.

For example, there is considerable concern about the greenhouse gases emitted from vehicles. Quite often, the emissions discussions focus on the use portion of the automobile life, not taking into consideration the amount of greenhouse gases created during the manufacturing and disposal phases of the automobile. To fully assess a vehicle's carbon footprint, all phases of a vehicle's life must be considered. Therefore, using a life cycle assessment technique is critical for material selection and design decisions to achieve vehicle mass reduction because changes in the product system, such as using aluminum instead of steel structure applications, may decrease the use phase global warming potential at the expense of increasing the material production phase global warming potential.

In an LCA, proving that one product or process is superior to the other is difficult because process parameters cannot be simplified to the same extent when using different materials. The main purpose of an LCA is to make manufacturers aware of the environmental impacts of their products and to improve a specific process by making the product less harmful to the environment. Furthermore, a consumer can be more informed on which process is more efficient, thus allowing for a personal choice on which product to purchase.

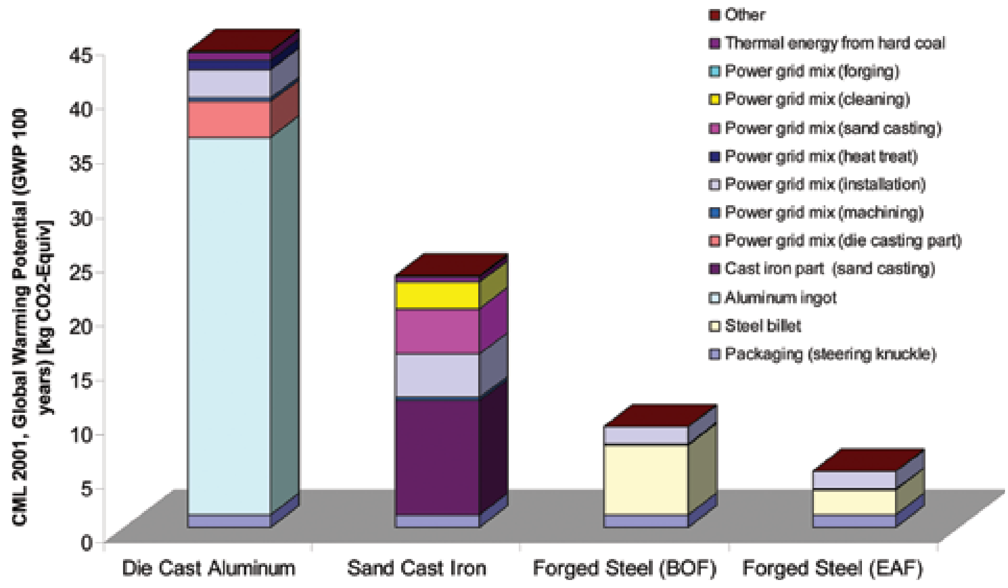
To illustrate, a senior design team at Missouri S&T, supported under a FeMET design grant, compared steering knuckles manufactured from three materials: cast aluminum, cast iron and forged steel. The steering knuckle includes a spindle that supports the inner and outer wheel bearings and is the pivot point for the wheel and the vehicle's suspension system. The three knuckles selected were the subject of a previous AISI study comparing the difference in properties based on materials and manufacturing.[17] The forged SAE grade 11V37 steel knuckle (2.4 kg) was from the rear suspension of a 4-cylinder sedan, the die-cast aluminum ASTM A356-T6 knuckle (2.4 kg) was from the front suspension of a 6-cylinder minivan and the sand cast 65-45-12 cast-iron knuckle (4.7 kg) was from the front suspension of a 4-cylinder sedan. The scope of the study was "cradle to grave" for each of the steering knuckles. Each LCA began with a cast part or billet, using emission data tabulated in a commercial software database, and ended with the steering knuckles being transported back for recycling or to a landfill. Commercial LCA modeling software, GaBi version 4.2 developed by PE Group GmbH and IKP University of Stuttgart, was used to organize the data, produce flow diagrams and evaluate the possible environmental impact statistics. The tabulated database is determined by industry averages and standard industry calculations. The forged steel steering knuckle was the only part that included a spindle portion. During the use phase, the same vehicle was used to compare the environmental impact attributed to the processes. The environmental impact of the steering knuckles use phase will differ only by the effect of weight differences, as the vehicle life was assumed to be the same for each part (125,000 miles) and the parts will not fail during their life. The aluminum considered was virgin, and the steel was a mixture of virgin and recycled, depending on the process.

Figure 16 compares the carbon dioxide emissions from the different steering knuckles during the production phase. The production of the aluminum ingot created the largest amount of carbon dioxide of the three steering knuckles due to the electrical requirement for alumina reduction. In North America, electrical generation has a large fossil fuel component. Furthermore, the production of the sand cast-iron part (before machining and cleaning) was the major contributor of carbon dioxide emissions for the cast-iron steering knuckle. For the forged steel billet, the EAF forging resulted in less carbon dioxide production because it melts recycled steel scrap rather than a combination of scrap and hot metal in the BOF billet. Figure 17 compares the carbon dioxide emissions from the different steering knuckles during production, use and recycling — the entire life cycle. The amount of greenhouse gases during the use phase is directly proportional to the weight of the part. As indicated in this example, material and manufacturing processes in many cases result in significantly more greenhouse gas emissions than the use phase.

Summary and Conclusions

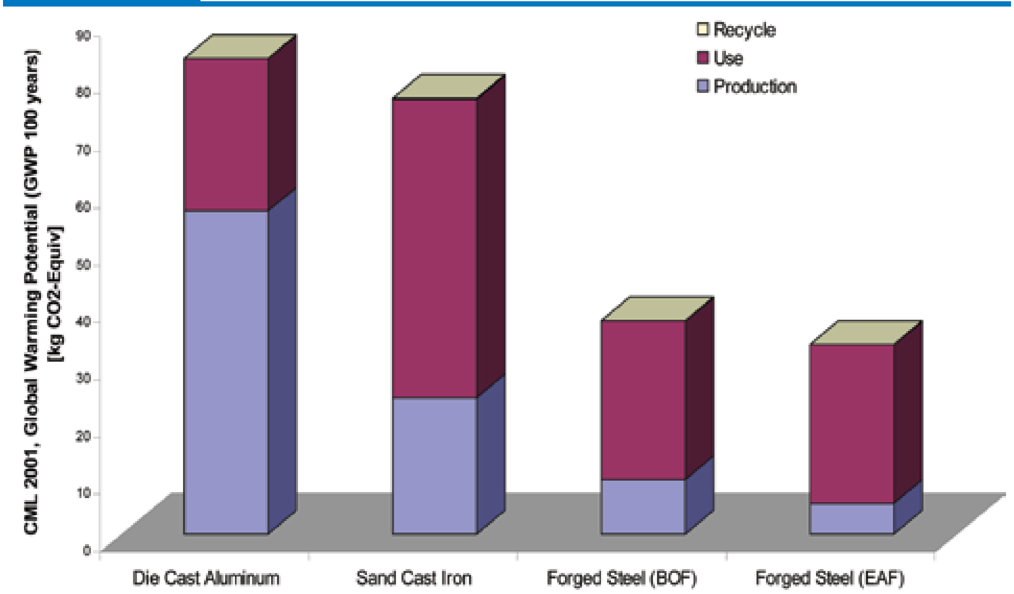
Today's steel industry faces a number of opportunities and challenges, especially in North America. Two in particular are critical to the future of the industry: (1) attracting and keeping the best technical leaders in the steel industry and (2) research and development in solving the steel industry's challenges, especially in the areas of energy and the environment. A primary goal of the industry is to recruit the best and brightest college graduates in engineering to the steel industry. This will require improvements in the steel industry's image and increased interaction and industrial support of the universities that supply the engineers and technical research. Process metallurgy research needs to continue, especially in the areas of energy savings and greenhouse gas reductions. This will require an increased level of research funding from the steel industry based on the major reductions in federal government funding for steel-related research.

Figure 16



CO_2 emissions during production of a steering knuckle from different materials.

Figure 17



CO_2 emissions during entire life cycle of steering knuckles from different materials (1,500 kg weight car, 24 mpg, 125,000 miles).

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