The Evolution of Engineering Materials

Dr. Amber L. Genau, University of Alabama at Birmingham

Dr. Amber Genau is an assistant professor in the Materials Science and Engineering Department at the University of Alabama at Birmingham. She received her B.S. and M.S. from Iowa State University and Ph.D. from Northwestern University, all in materials engineering. Before coming to UAB, Dr. Genau spent two years as a guest scientist at the German Aerospace Center in Cologne, Germany, working on metal solidification and microstructural characterization. She is particularly interested in broadening participation in engineering and providing international experiences and perspectives to undergraduate students.

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Abstract

This paper describes the development of an upper level engineering elective entitled “The Evolution of Engineering Materials.” The course considers how the discovery of new materials and the ability of process materials in new ways has influenced the course of history, shaping both human societies and their surrounding environments, from the Stone Age to the Modern Era. Students become familiar with a variety of still-relevant technical content through the consideration of historical activity, from smelting and coking to polymerization reactions and cross linking. The course addresses a variety of ABET outcomes while also supporting the development of global competency through an increased appreciation of world history. Although this course was developed for and taught in the context of a three-week study abroad trip to Europe, the engaging and accessible nature of the content could also make it valuable as a service course for non-engineering majors. The course is currently serving as the inspiration for a new collaborative effort between the School of Engineering and the history department at the University of Alabama at Birmingham.

Motivation

Participation in study abroad programs is generally low among engineering students. Although study abroad participation by STEM students has increased over the last decade, during the 2009/10 academic year, only 3.9% of study abroad came from engineering majors [1]. This is attributed to the heavy course loads required in engineering programs and the highly-structured, sequential curriculum that makes missing a semester problematic, in addition to difficulties in finding equivalent technical courses which can be transferred back to American institutions.

When I started teaching at UAB, study abroad options for engineering students were few and far between. Because of the transformative role that studying abroad played in my own undergraduate experience, I wanted to create similar opportunities for my students. Drawing on contacts made during two years living in Germany, I put together a three-week, faculty-led study abroad program to be offered during May term. This type of shorter program offered between semesters is often seen as a more accessible choice by engineering students [2]. In addition, the demographics of UAB mean that most students have very little travel experience; many have never been on an airplane or traveled outside the Southeast region of the country. These students are more willing to venture abroad when led by a familiar faculty member and traveling with well-known classmates.

In order to maximize availability to the students, I wanted to offer a three-credit elective course, dual-listed as MSE 490/590 (Special Topics in Materials), so that it could be taken for credit by both graduate and undergraduate materials engineering students, as well as any other students allowed by their programs to take unrestricted engineering electives. I selected the history of materials because it was a topic that has always been of interest to me, and because it tied well with the long history of the places where we would be traveling. The course has now been offered three times (May 2012, 2015, 2016) with the course content being continuously revised.

There is a particular focus throughout on metals and metals processing, which reflects both my personal background and an area of emphasis at my university. Although there is some emphasis on German (and European) history, the content is generally global in scope.

Course Description

The primary text for the course is *The Substance of Civilization: Materials and Human History from the Stone Age to the Age of Silicon* by Stephen Sass (2011, Arcade Publishing), now an emeritus professor in the MSE department at Cornell University. This book is well written and easy to read. It covers the development of all major classes of manmade materials, more or less chronologically. Intended for a lay audience, in addition to the history it provides a good introduction to the basic tenants of materials science (crystal structure, diffusion, etc.) for non-majors and a solid review for students who have already taken an introduction to materials course.

The second text that I use extensively is *Out of the Fiery Furnace: The Impact of Metals on the History of Mankind*, by Robert Raymond (1986, Penn State University Press). Based on a seven-part television documentary by the same name, the large book includes full color photographs on nearly every page. Although some of the material presented in this book is now outdated, it provides an opportunity to discuss with students how new findings continue to revise our understanding of the past and the importance of understanding our own bias when interpreting data. I also assign several chapters from Mark Miodownik's excellent new book "Stuff Matters: Exploring the Marvelous Materials that Shape Our Man-Made World (Houghton Mifflin Harcourt, 2014).

The course content is divided into six major topics as outlined below. There is an additional short section that considers the historical evolution of different society's views on metal and metal workers, both pro and con. Remembering that the students are receiving engineering credit for this class, I am conscientious about including as much scientific and technical content as possible. Through the course of the class, each student is responsible for completing a list of technical vocabulary and geographical terms. Some of these terms, along with examples of assigned and optional readings, are listed below by section. The readings include both primary source material from the eras being covered and modern research on archeological materials. These readings allow students to explore areas of particular interest to them, and include other geographical areas besides those I focus on in class.

Stone and Bronze Age: Begins with humans using materials as found in nature (wood, bone, stone, bark, etc.), perhaps changing only the shape. Use of fire to change materials (first ceramics). Development of agriculture and pottery, improvement in tools and establishment of trade routes. Interactions with native metals and smelting of tin and lead, redox reactions. Smelting of copper, development of significant mining operations. Intentional alloying of copper to make bronze, spread of technology from Near East, necessity of long distance trade routes to supply tin. Development of sophisticated casting technology, particularly in Far East.

- *The Use of Tin and Bronze in prehistoric Southern Indian Metallurgy*, S. Srinivasan, JOM, July 1998, p. 44-49
- *Early Pottery at 20,000 Years Ago in Xianrendong Cave, China*, X. Wu et al. Science 336 2012, p. 1696
- *Ancient Chinese Bronze Casting*, L. Reiner, Advanced Materials & Processes, August 2007, p. 38-41
- Vocabulary words: bronze, flux, foundry, malachite, native metal, obsidian, reduction, roasting, slag, smelting

Iron Age: Development of iron smelting technology, widespread upheaval that lead to the decline in bronze and spread of iron as dominant technology. Additional cultural milestones during Iron Age such as written language. Power shift from Near East to eastern Mediterranean, silver mines of Laurion financing ancient Greek. Rise and fall of Roman Empire, financed by mines at Rio Tinto. Role of iron in military conquests. Development of wootz steel in India and Chinese cast iron.

- Pliny the Elder's *Historia Naturalis*, 77 AD, Chapter 33 and 34
- Iron Age Architecture and Everyday Materials in Britain, http://www.dot-domesday.me.uk/defence.htm
- *The Decorative Bell Capital of the Delhi Iron Pillar*, R. Balasubramaniam, JOM, March 1998 p. 40-48
- *An Archaeometallugical Study of Iron Artifacts from Mabotse* [South Africa], A. Koursaris et al., JOM, May 2007, p. 22-25
- Vocabulary words: bloom, carburizing, cast iron, cupellation, forge, puddling, quench, steel, temper, tuyére, wrought iron

Middle Ages: Decrease in mining, materials and technology during "Dark Ages;" decrease in precious metals for coinage meant knights had to be paid in land and development of feudal system. Agricultural revolution in Europe resulting from increased iron production for heavy ploughs and horse shoes. Role of Charlemagne in reestablishing commerce and centralized government. Role of Catholic church; lead for stained glass, bronze for bells which could also be melted down into cannon.

- *Of Iron and Steel*, by Künigung Hergotin,1532 (foundry practice pamphlet), available in *Sources for the History of the Science of Steel 1532-1786*, Ed. C.S. Smith (1968)
- *Medieval Technology and Social Change*, Lynn White Jr., Oxford Univ. Press, 1962. (Chapter 2: The Agricultural Revolution of the Early Middle Ages)
- Vocabulary terms: blast furnace, Catalan forge, Stückofen, Flüssofen, Istanbul/ Constantinople/Byzantium, Aachen

Age of Exploration: Major globalization, improved communication and transportation, driven in part by quest for gold, silver, spices. Blossoming of science during Renaissance (Copernicus, van Leeuwenhoek) but gulf between science and practical applications. Invention of printing press, importance of alloying to produce good type metal. Largescale demand for weapons drove iron industry; largescale mining operations required financing; first shareholder arrangements. Shortage of fuel for smelters and foundries; transition from charcoal to coal to coke. Role of

Abraham Darby in mass producing cast iron. Thomas Newcomen's development of the steam (atmospheric) engine; first source of power that wasn't wind, water or muscle.

- *De la pirotechnia*, Vannoccio Biringuiccio, 1540 (proper foundry practice)
- *De re metallica*, Georgius Agricola, 1556 (first systematic treatise on mining and extractive metallurgy)
- *Della Scienza Mechanica*, Galileo 1593 (scientific consideration of strength of materials)
- *The Sacred in Mesoamerican Materials*, G. Salas et al. JOM May 2006, p. 44-47
- *Glassmaking in Renaissance Italy: The innovation of Venetian Cristallo*, W.P. McCray, JOM May 1998 p. 14-19
- *About the Pre-Hispanic Au-Pt "Sintering" Technique for Making Alloys*, M. Noguez et al, JOM May 2006, p. 38-43
- Vocabulary terms: coke, coking, colliery, pig iron, Coalbrookdale

Industrial Revolution: Reasons it began in England. James Watt and the first true steam engine; use of new engines to mine more coal, produce cheaper iron. Rediscovery of cement/concrete; setting underwater allowed development of canal system. Development of railroads. Cast iron as the first new structural material in thousands of years. Development of glass technology to allow larger pieces, more windows. Concurrent developments in America; copper boom in Michigan corresponding with invention of telegraph.

- *On the Metamorphoses of Iron of Iron and Steel*, by P.C. Grignon in 1775, available in *Sources for the History of the Science of Steel 1532-1786*, Ed. C.S. Smith (1968)
- Excerpts from *At Home: A Short History of Private Life* by Bill Bryson (2010) (e.g. Crystal Palace, transition from iron to steel, cement)
- Vocabulary terms: potting and stamping, crucible steel, cementation process, trip hammer, blister steel, Keeweenaw Penninsula, Mesabi Iron Range

Modern Era: Transition from iron to steel. Development of aluminum; reactivity series and reasons that aluminum wasn't isolated earlier, concurrent development of reliable sources of electricity, Hall-Heroult method. Development of synthetic polymers, from South American rubber to celluloid to Bakelite; role of global conflict in development of synthetic rubber. Role of new materials in automobiles and airplanes. Semiconductors, transistors and integrated circuits.

- *The Evolution of Wrought Age-Hardenable Superalloys*, R.F. Decker, JOM Sept 2006, p. 32-36
- *Louis Comfort Tiffany: Artistry, Chemistry, Secrecy*, M. Byko, JOM Sept 2007, p. 16-20
- Vocabulary words: cryolyte, electrolysis, bauxite, semiconductor, transistor, polyethylene, crosslink

I would like to add a "Today and Tomorrow" section that covers issues of the 21st century, but I have yet to find time in the curriculum to get that far. Potential topics include green manufacturing and recycling, sourcing rare earth materials, projected markets and how price fluctuations could affect design, and materials for space travel.

Student Assessment

Assessment was designed to balance making sure students were prepared for class discussions with allowing them as much time as possible to explore their surroundings. Assessment included periodic reading-comprehension quizzes, completion of the list of terms and relevant geographical areas, an oral presentation, and a final paper. Before the trip, students were asked to choose a relevant topic and prepare a 10-15 minute oral presentation with a 2-3 page handout. Students were guided to topics which, due to time constraints, would not otherwise be covered, such as the development of glass, Damascus steel, and metallurgical development in India or Africa. One student reported on the history of chocolate, complete with phase diagrams and taste testing. The final paper was due about a month after the trip ended. Students were asked to pick a topic related to some aspect of the course and write a research paper of approximately ten pages on that topic, with a special emphasis on the role of engineering materials. Some topics selected include the role of iron alloys in the rise of the Industrial Revolution, and the importance of copper to the rise and fall of the Roman Empire. Throughout the assignments, an emphasis was placed on allowing students to choose their own areas of investigation, based on personal interests. During class discussions, students would often ask questions to which I had no answers. I assigned extra credit liberally to students who would investigate the issues raised and report back during the next class period.

Future Direction

At most American universities, engineering students are required to take a large number of courses in such "core" topics as English, history, social sciences and the fine arts. At UAB, these state-mandated core curriculum classes take up more than a quarter (36/128) of the credits that are required for an engineering degree, but most are entirely unrelated to the students' chosen area of study. Meanwhile, engineering departments across the country wrestle with how to address necessary issues like communication, ethics and sustainability in their curriculum without sacrificing existing technical content. One possible solution is to partner with the humanities faculty who are teaching required core classes to create new courses that better engage students and help them understand the relevance of the other disciplines to their work and identity as engineers.

The history of engineering materials course described above served as the starting point for development of a new two-course world history sequence that will be co-taught by a history professor and an engineering professor. After several years of effort, the courses have been approved and will be taught for the first time during the 2017-2018 academic year. The courses will satisfy the undergraduate core curriculum requirements for students to take either one or two history classes. The classes are World History and Technology I & II (HY 106 and 107). The primary resource will be a new textbook called *Big History: Between Nothing to Everything* by Christian, Brown and Benjamin (McGraw-Hill, 2013). The relatively new field of Big History approaches world history from a broad, science-based context. For example, the textbook begins with the Big Bang, then spends three full chapters on the formation and evolution of the universe, the formation of our solar system and planet Earth, and the origin and evolution of early forms of life. The textbook will be extensively supplemented with additional material and guest lectures from various engineering faculty. In addition to engineering materials, broad topics like power, water, and navigation will be considered. Student assessment will include debates, group research projects, and oral presentations, as well as exams.

Designed with engineering students in mind, the classes seek to establish patterns of thinking around complex issues and to provide meaningful case studies that will inform students' work in the engineering classes they take. These history classes will also provide a vehicle for students to wrestle with issues of professional responsibility, ethical dilemmas and the role of engineers in the modern workplace. The classes will be designed particularly to support ABET outcome (h): the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context. Additional ABET outcomes addressed by the course sequence include (c) an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability; (d) an ability to function on multidisciplinary teams; (f) an understanding of professional and ethical responsibility; (g) an ability to communicate effectively; and (i) recognition of the need for, and ability to engage in life-long learning.

A long-term goal is to incorporate a study abroad component into this history sequence; however, it has the potential to benefit students' "global competency" without them ever having to leave campus. What precisely constitutes global competency is a matter of much discussion, but one of the leading experts, Dr. Bill Hunter, states that "in order to become globally competent, one must establish a firm understanding of the concept of globalization *and of world history*. It is here that the recognition of the interconnectedness of society, politics, history, economics, the environment, and related topics becomes important [3]." Most discussions of global competency, including those specific to engineers, include knowledge of history as a means of better understand present status [4-7]. Although students are currently required to take history classes, it is a missed opportunity since most students at the undergraduate level are not capable of connecting the contents of a traditional U.S. or world history class with their studies or future work as an engineer. By making these connections more explicit, emphasizing the role of science, engineering and technology in shaping both the past and the present, students will develop a better appreciation of both the societies and the professions that they are inheriting.

With some creativity and innovation, those of us developing these courses believe that required history classes can become a vital and engaging component of engineering education that assist in developing both engineering competency and global competency in students, rather than just another hoop to be jumped through on the path to graduation.

Conclusion

Human interaction with and manipulation of materials is one of the longest stories in the history of our species. It is a richly compelling narrative that can serve as an entry point to introduce engineering students to history and non-engineers to materials science. The course described here is intended to help students appreciate the influences of new materials and materials processing technologies on society, and how societal influences have in turn shaped the development of materials. Through investigation of historical materials, students learn a variety of fundamental materials concepts still relevant today, in addition to developing global competency, whether studying at home or abroad.

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