

Integration of Materials Instruction in the Field of Manufacturing

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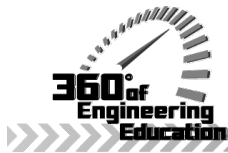
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INTEGRATION OF MATERIALS INSTRUCTION IN THE FIELD OF MANUFACTURING

Abstract

This paper focuses on the integration of materials technology into the overall field of manufacturing. These two fields are inextricably interwoven since manufacturing processes can change the properties of a material, hence changing the behavior of the ultimate product. Materials technology emphasizes the properties of materials, their influence on the design of products and systems, and the processing of the materials during manufacturing. Educators from the materials education area and the manufacturing education area collaborated in the preparation of the paper to communicate the interdependence of these fields. A tool for facilitating this dialog is included, called the Four Pillars of Manufacturing Knowledge, developed by the Society of Manufacturing Engineers. This paper is a collaborative effort between the National Resource Center for Materials Technology Education (MatEd), and the Society of Manufacturing Engineers (SME), through its Center for Education and the Manufacturing Education & Research Community.

1. Introduction and Background

This paper focuses on the integration of materials technology into the overall field of manufacturing. Manufacturing relates to the transformation of materials from one form to another. In this process, the properties of the materials involved can also be transformed—that is, the manufacturing process can change the properties of materials. Thus in the materials selection and manufacturing planning phases of the design process for a product, it is essential that engineers and technologists understand what properties are affected by which processes.¹ The field of manufacturing engineering covers the broad spectrum of topics that impact manufacturing, derived from the definition, “Manufacturing requires that a modification of the shape, form, or properties of a material that takes place in a way that adds value.”² Engineers must ensure that they understand the potential changes in properties to ensure the development of a useful product.^{3,4}

Parts of this paper were extracted from a more comprehensive treatment of this topic completed by representatives of MatEd, SME, and the National Center for Manufacturing Education (NCME).¹

The following topics are included in this discussion:

1. Introduction and background
2. An overview of materials technology, education and resources
3. An overview of the manufacturing engineering field
4. The Four Pillars of Manufacturing Knowledge
5. Role of MatEd in materials education
6. Examples of where materials impact manufacturing
7. Manufacturing competitiveness issues related to materials and manufacturing

8. Other resources in manufacturing education
9. National issues related to materials and manufacturing education
10. Future directions and conclusions

2. Overview of Materials Technology, Education and Resources

The basis of materials engineering, science and technology involves the relationship between the desired properties of a material and the atomic structure and microstructure of that material. The result of this interrelationship of materials structure, properties and processing is that the materials professional must understand the intimate details of the material in order to design processing and manufacturing techniques that will result in a product with the desired properties.⁵ Variables in processing and manufacturing that must be understood and controlled include (but are not limited to) temperature, pressure, process speed and environmental factors such as atmosphere and vacuum. The recent introduction of nano-structured materials and the broadening applications in aerospace, energy, bio-materials and microelectronics emphasize the need for control of source material, materials components and processing techniques to achieve desired products.^{6,7} The general relationship between properties and processing is valid, but not identical, for all classes of materials, including both crystalline and amorphous metals, ceramics, glasses, polymers and composites.

Education in materials is focused on University-level programs such as Materials Science and Engineering, Materials Engineering, Metallurgical and Ceramic Engineering, Polymer and Composite Engineering, either as a separate department or departments and sometimes part of another university department. Also available are Community and Four-year College technology-related programs, often focused in areas such as corrosion and environmental degradation, welding and joining, and metals, ceramics and composites technology. Manufacturing engineers and technologists can also earn credits and certification in a wide variety of materials technology-related areas. Educational and certificate programs are available from ASM International in areas from corrosion to welding and heat treatment.⁸ Other societies offer courses on line and in short course format in many areas from ceramics to steel technology.

Materials education is also useful and when applied in K-12 education. Materials concepts and experiments can deliver hands-on activities shown to excite students to learn more about science and engineering.⁹ Materials as well as hands-on manufacturing at the K-12 level fits well with the recently developed Next Generation Science Standards¹⁰ and can be used to re-build science curricula with a greater focus on the influence of science on everyday life.

The National Resource Center for Materials Technology Education (MatEd) provides a collection of instructional resources in materials technology for teachers, faculty and other interested personnel who can then provide students with the understanding of materials that they need to function properly in manufacturing and engineering technology.¹¹ With the materials utilized in manufacturing becoming more complex and sophisticated, it is essential for engineers and technicians to understand these complexities and their implications on the manufacturing process. Having appropriate curricula focused on needed core competencies in materials technology enables the enhancement of the educational level of technicians and ensures that the US remains globally competitive in advanced materials and manufacturing technologies.

3. Overview of the Manufacturing Engineering Field

The manufacturing field covers the broad spectrum of engineering and technology concepts, knowledge areas, skills, and abilities that affect the planning, implementation, operation, continuous improvement, and management of the industrial functions required to develop, produce, and improve products of all kinds. The operative term, *manufacturing*, is derived from the definition, “Manufacturing requires that a modification of the shape, form, or properties of a material that takes place in a way that adds value”.² Note that the definition includes the integration of materials science, engineering and technology with the broader aspects of manufacturing, supporting the premise of this paper.

In outlining the body of knowledge for certification of manufacturing engineers and manufacturing technologists, the Society of Manufacturing Engineers has identified ten major knowledge areas that are important to the field.¹² They are:

<i>Engineering Sciences</i>	<i>Materials</i>	<i>Manufacturing Processes</i>
<i>Product Design</i>	<i>Process Design</i>	<i>Equipment/Tool Design</i>
<i>Production System Design</i>	<i>Automated Systems and Control</i>	
<i>Quality and Continuous Improvement</i>	<i>Manufacturing Management</i>	

Of course, it is expected that these knowledge areas are supported on the foundations of mathematics, science, and the fundamentals of personal effectiveness – interpersonal skills, negotiating, conflict management, innovation, creativity, written and oral communication, presentation skills, and lifelong learning to continue to gain knowledge to keep pace with and contribute to new knowledge.

Recent work by the Society of Manufacturing Engineers through its Center for Education and the Manufacturing Education & Research community have consolidated this work and created a concise, graphical representation of the manufacturing field – The Four Pillars of Manufacturing Knowledge. The basic structure and content of the Four Pillars model are described in the next section.

4. The Four Pillars of Manufacturing Knowledge

The *Four Pillars of Manufacturing Knowledge* essentially differentiates the unique character of manufacturing, manufacturing engineering and manufacturing engineering technology. It defines the standard for advanced manufacturing topics, and identifies the body of knowledge with which all those engaged in advanced manufacturing education can align. Developed by the Society of Manufacturing Engineers (SME) through its Center for Education, the four pillars are derived from the ABET accreditation criteria for manufacturing engineering programs and build on the topics in the SME-defined “Body of Knowledge for the Certification of Manufacturing Engineers and Manufacturing Technologists.”¹² These criteria were developed with significant industry input on the skills and knowledge required by manufacturing professionals.

The four pillars term encompasses:

- **Materials and manufacturing processes:** understanding the behavior and properties of materials as they are altered and influenced by processing in manufacturing

- **Product, tooling, and assembly engineering:** understanding the design of products and the equipment, tooling, and environment necessary for their manufacture
- **Manufacturing systems and operations:** understanding the creation of competitive advantage through manufacturing planning, strategy, and control
- **Manufacturing competitiveness:** understanding the analysis, synthesis, and control of manufacturing operations using statistical methods, simulation and information technology

The *Four Pillars of Manufacturing Knowledge* model is a tool for promoting greater understanding of the breadth and depth of the field of manufacturing engineering. Initiatives are underway, led by the SME Center for Education, to build on this foundation, to promulgate the model broadly within SME, and to engage in dialog with other professional societies that represent engineering, engineering technology, industrial technology, and related educational programs from which graduates enter manufacturing-related career paths. This article outlines how this tool applies to materials science, engineering, and technology programs.

Graphic Representation of the Four Pillars of Manufacturing Knowledge: To help communicate the Four Pillars model and the attendant details to a wide range of people and organizations, a graphic representation was developed using the metaphor of a building whose roof structure representing a product-producing industry is supported by four pillars that rest on a foundation (Figure 1).¹³

The foundation shows the educational fundamentals on which the manufacturing engineering field is based, including mathematics and science, communications, and the many aspects of personal effectiveness.

The four pillars are capped with the titles shown above for the four major proficiencies expected of graduates of manufacturing programs. Within the four pillars, the ten major subject areas mentioned earlier are arrayed to give more detail to the content included in academic degree programs. The lintel spanning the pillars emphasizes that laboratory experiences, quality, continuous improvement, and problem analysis pervade the manufacturing engineering field and integrate its various facets.

Below the titles of the major subject areas are lists for the detailed topics that make up the content of the programs. This list forms the basis for SME certification exams for Certified Manufacturing Engineer and Certified Manufacturing Technologist.

It is understood that the Four Pillars model must be adapted by each type of educational program and other entities depending on their own purposes, objectives, and goals. Variations naturally exist among associate degree programs, baccalaureate degree programs and graduate programs in terms of breadth and depth to which the concepts incorporated in the Four Pillars model are included in curricula based on the expected career paths of graduates. Furthermore, it is recognized that there are differences in the goals of engineering, engineering technology, industrial technology and technology management programs having manufacturing-named curricula, guided by their respective accreditation criteria. Other programs that do not have “manufacturing” in their names but whose graduates often enter the manufacturing functions of product-producing industries should have some knowledge of the fundamentals of manufacturing as outlined in the Four Pillars model. It is recommended that the Four Pillars model be used by all who design and deliver curricula that are relevant to manufacturing. Some may be satisfied

with an awareness level of coverage while other may choose to include more depth in selected topics.

Section 5 of this paper discusses more details for how the Four Pillars model can be used in materials education and manufacturing education and how they are inter-related.

5. Elements of the Four Pillars Model that are Directly Impacted by Materials Technology

Topics included in the Four Pillars model that are pertinent to this paper are discussed next. Key terms are underscored. See also Section 7 that discusses the impact of these observations on the competitiveness of a product-producing industry.

The prominent subheading for Materials in the Four Pillars model is an obvious area of mutual interest and detailed study by any program promoting materials education or manufacturing education. Listed within this subheading are ten types of materials: metals, plastics/polymers, ceramics, composites, fluids, glasses, nanotechnology, foams, hybrids, and natural materials. It is incumbent on any program teaching either materials or manufacturing to promote mastery of the physical nature of these types of materials, the manner in which they are produced, and how they are processed into useful forms for components of completed products.

The properties of materials depend on their atomic and molecular arrangement as well as their microstructure. The microstructure, in particular, is dependent on manufacturing techniques. All of these factors differ for different classes of materials, and assumptions that may be relevant for metals, for example, will probably be completely at odds with the appropriate assumptions for a composite material. Properties are chosen for specific applications, such that mechanical strength, for example, is important for metal, whereas optical luminescence may be important for a ceramic sensor and anti-corrosive properties play a role in the development of biological implants.

Figure 2 shows the graphical representation of the Four Pillars model with only the major headings and the ten categories of content included without the details shown in Figure 1. The following discussion outlines where materials science is particularly connected with the field of manufacturing. The letter designations of each paragraph are shown in Figure 2.

- A. In the Mathematics and Science part of the Foundation section of the Four Pillars model, all of the listed topics are relevant to the study of both materials and manufacturing. The physics of materials must be understood in terms of their electronic, optical and magnetic properties. Physical properties and materials behavior can change, sometimes drastically, when undergoing processing. The chemistry of the materials must be well understood to enable adequate description of their basic nature and manner of formation. Materials aspects of bio-science are critical to their production, application, processing, use, and safety. Use of all of the six named aspects of mathematics is necessary to describe quantitatively the behavior of materials processes.
- B. In Engineering Sciences, knowledge of materials science and engineering is important to understanding the nature of solid bodies as studied in Statics and Dynamics. The strength and stiffness properties of materials must be well understood for proper study of Mechanics of Materials. Properties of fluids such as density, specific weight, compressibility, and viscosity are critical to the study of Fluid Mechanics. Thermal properties of solids, liquids, and gases are essential to the understanding and application

of thermodynamics and heat transfer. The electrical properties of materials applied to electrical circuits, or to electronic, semiconducting or nanostructured components and systems are important parts of the detailed understanding of such devices and systems. It must also be understood that properties for bulk materials change, sometimes drastically, for nanostructured materials.

- C. The entire section of the Four Pillars model on Manufacturing Processes has essential interfaces with materials science for many of the same reasons just mentioned in regard to the engineering sciences. Manufacturing processes inherently involve the change of the form or internal structure of materials to achieve some value-added result. Materials choices will limit the manufacturing methods available and will establish the processes and post-processing that is required. The understanding of the ultimate relationship between a manufacturing process and the properties of the final product is critical to the proper functioning of that product.
- D. Product Design is also heavily dependent on both materials and manufacturing engineering principles and practices, which should be considered together as a materials/manufacturing system. Materials selection relates directly to product cost, since materials choice determine manufacturing, processing and finishing costs. Product volume also relates to ultimate cost of a part or system. In addition, if a sub-optimal material is chosen initially, this may lead to costly change orders and delays in the future. The very nature of the design process involves the specification of how materials are to be worked, shaped, formed, heat-treated, coated, plated, joined, cast, molded, and fabricated to achieve specific functional and appearance parameters of use to customers who will use the product. Proper materials selection, involving detailed understanding of materials specifications and materials behavior, must be deeply imbedded in product design to ensure that the product exhibits the behavior desired.
- E. Process Design involves the specification of the equipment and the definition of how it is used to create real products that can be manufactured economically and with high quality. Such specifications typically involve defining materials processing practices and testing methods used to ensure accuracy and properties of the final product. Careful process design can eliminate errors that require rework or subsequent product repair.
- F. Equipment and Tool Design methods require understanding of the capabilities of materials in regard to strength, stiffness, ductility, hardness, wear resistance, friction characteristics, corrosion potential, and many other materials-related factors.
- G. Production System Design topics having significant materials aspects include process planning, manufacturing system design, process documentation, equipment selection, ergonomics, environmental protection, and waste management.
- H. Automation Systems and Control Power and control systems inherently involve materials knowledge in terms of the mechanical, electrical, and fluid properties of the elements of those systems. Packaging design and automated systems design and operation are critically dependent on the behavior of the materials from which the product is made in regard to strength, stiffness, formability, chemical compatibility, handling, appearance, ability to be painted or otherwise decorated, and environmentally responsible disposal.

- I. Quality and Continuous Improvement processes and systems must take into account the properties of materials from which products are made. Quality control starts with control of materials structure and microstructure, and continues through all of the steps noted above. Continuous feedback of product characteristics and process behavior provides the basis for continuing process improvement.

6. Role of MatEd in Materials Education

MatEd, the National Resource Center for Materials Technology Education, is a resource center housed at Edmonds Community College, Lynnwood WA. MatEd collects information on materials education, provides instructional resources for instructors and maintains a website for dissemination of these resources. MatEd works with a network of professional and technical societies, educational institutions and groups focused on materials education and research to extract and provide access to available resources.¹¹

The MatEd resource center was created by and is funded by the National Science Foundation's Advanced Technological Education Program. The primary focus is to enhance technology and manufacturing education by providing basic materials-related curricula for inclusion into manufacturing and engineering technology curricula. MatEd's studies show that many technologists have little basic knowledge of materials behavior and how it can be influenced by processing techniques during manufacturing. Using a national study of professionals, MatEd first developed a set of core competencies needed for manufacturing technologists.^{1, 11} It then set out to identify available curricula in the needed areas, focused primarily on technician education programs in community and technical colleges.

MatEd's website collection consists of a set of modules that are appropriate for insertion into courses in manufacturing at several levels to enrich those courses in materials concepts. It provides labs, demonstrations and classroom-ready resources appropriate for introductory, intermediate and advanced levels of instruction developed by instructors and professionals in the materials area. The collection includes traditional materials areas such as metals and ceramics, along with polymeric and plastic materials, with applications in structural, electronic and biological areas. The collection also includes newly developing materials areas, including biomaterials and nanotechnology. Additive manufacturing¹⁴ is a rapidly developing and very materials-focused area and is included, along with composite materials fabrication, aspects of electronic and optical materials, and sustainable design with materials.

MatEd's collection includes other references as well, including a variety of types of materials educational and instructional resources and other projects related to materials education. These include educational materials available at other locations on the Internet, along with a series of focus papers on relevant topics, including this one. These resources are available for free access to the MatEd website (<http://www.materialseducation.org/>) to allow for wide dissemination of materials science and technology information.

MatEd also provides the overall leadership for the annual National Educators Workshop [NEW]. NEW promotes interactions between middle and high school teachers, 2 and 4-year instructors and professional societies. NEW supplies a platform that promotes manufacturing and materials and provides a venue for the publishing of presentations and development of journal articles. This annual conference has been held at a variety of locations across the U.S. to ensure access by

as broad a spectrum of teachers and instructors as possible. Proceedings are published on the MatEd website and relevant presentations are published in the MatEd collection of educational modules.

7. Manufacturing Competitiveness Issues Related to Materials and Manufacturing

In addition to the relationship of materials to manufacturing mentioned above, there is a particularly important role for materials selection in manufacturing competitiveness. There is an obvious relationship between the properties required in the final product and the properties of the materials that make up the product. However, there often are many materials that will result in the required properties. As engineers and materials scientists, we frequently choose materials with which we are most familiar, and tend to neglect those with which we are less familiar, but which may offer a strong competitive advantage in a variety of ways, from initial material cost, to manufacturability, to the ultimate reuse or recycling of the material and the total life cycle cost and impact.

Einstein is credited with a statement to the effect that ‘90% of solution to a problem lies in correctly framing it in the first place’. The issues of quality of the product/process relates to this. If we don’t have time to do it right, selecting the correct material, in the first place, how can we find time to fix it later? This gets to the notions of strategic planning, reliability and waste management. Without adequate attention to systems planning, the result is a series of engineering change orders (ECOs) that do not add value, but merely raise cost and delay introduction of the product.

Choice of materials early in the design cycle, while not incurring immediate significant expense, lock in the future costs associated with procurement of materials, supply chain costs, manufacturing processes, decisions about making vs. buying, and more. Specifying unnecessary properties or constraints on composition merely drive up cost and delay supply without adding value. Specifying particular materials affects the make/buy decision, and may dictate the need to outsource vs. make in one’s own factory. Materials selection also establishes the processes, and post-processes, required to develop the final desired properties. Paying particular attention to options of materials/processes early in the design phase can greatly reduce cost and delay product introduction.

The prediction of product volume, a strategic decision, can also have a significant effect on ultimate material/manufacturing costs. Some processes have high initial tooling cost with low unit production cost; others have low tooling cost, but higher unit production cost. Knowledge of both materials and manufacturing methods, combined with accurate estimates of product volumes, determine the profitability of the end product.

There is also the issue of ethics. Selection decisions for materials and processes have a dramatic impact on environmental protection, waste management, engineering ethics and social responsibility. The ‘Obligation of the Engineer’, promulgated by the National Society of Professional Engineers (NSPE), requires that engineers ‘conserve nature’s resources’. This is an obligation that engineers of all disciplines, and particularly design engineers, materials engineers, and manufacturing engineers, should consider in any professional decision. See the following website for discussion of the Obligation of the Engineer.

(http://www.nspe.org/PEmagazine/pe_0709_Called.html?printerFriendly=true)

There are a number of ABET student outcome requirements for accreditation that relate to the issue of materials and manufacturing, particularly in the capstone design criteria. Among those outcomes is the ability to use the techniques, skills, and modern engineering tools necessary for engineering practice. (ABET, Criterion 3. Student Outcomes, (k)) There are a number of modern tools that can help engineers design and choose the materials and manufacturing processes that optimize the system, and reduce the total carbon footprint and environmental impact. One of those tools is provided by Dr. Michael Ashby's approach to materials selection.⁵ (See also: Granta Design, <http://www.grantadesign.com/>)

It is therefore important for everyone educated in materials science and materials engineering to have a working knowledge of manufacturing and all that it entails to be able to make good, professional decisions about materials choices and applications.

8. Other Resources on Manufacturing Education

The Society of Manufacturing Engineers has long been at the forefront of supporting manufacturing education and developing the ways and means of continuously improving curricula and methods of delivering quality programs in this field. SME publications and other resources may be useful to those in materials education by providing additional ideas on the inter-relationships between manufacturing and materials in industry and academia.

Recent publications include:

- *Workforce Imperative: A Manufacturing Education Strategy* - A white paper released nationally on September 10, 2012 that summarizes the importance of manufacturing in the United States and that presents six recommendations that educators, industry, professional organizations, and government can use to attract more students, support STEM education, and develop faculty that can deliver a world-class manufacturing education.¹⁵ This paper can be downloaded from: sme.org/workforceimperative .
- *The Advanced Manufacturing Competency Model* – A tool developed by the U.S. Department of Labor, through its Employment and Training Administration (DOL-ETA),¹⁶ in collaboration with SME along with the National Association of Manufacturers (NAM), and the National Council for Advanced Manufacturing (NACFAM). The main components of this tool and the thrusts for its use are directed toward enhancing the quality and supply of technicians and skilled workers for high technology industries.
- *Curricula 2015: A Four Year Strategic Plan for Manufacturing Education* – This extensive document was developed by the SME Manufacturing Education & Research community with input from a large number of academic, industry, government, and association professionals to recommend updating and upgrading of manufacturing education programs of all types; high school, associate degree, bachelor degree, and graduate degree.¹⁷
- A group, called the Advanced Manufacturing Partnership (AMP)¹⁸, represents the private sector perspective on manufacturing. [www.manufacturing.gov/amp.asp]

9. National Issues Related to Materials and Manufacturing Education

A variety of recent studies by national organizations have focused on materials as related to manufacturing. A detailed discussion of “Next-generation Materials Measurements, Modeling and Simulation” is included in a recent review of manufacturing-related programs at the National Institute of Standards and Technology.¹⁹ Two excellent reviews related to additive manufacturing are in the National Academy of Engineering’s *Bridge* journal, Spring 2012.^{14, 20} These references stress the close ties between materials and manufacturing.

The Department of Commerce, through its National Institute for Standards and Technology (NIST), is strongly promoting the research and development of the general field of additive manufacturing. The [National Additive Manufacturing Innovation Institute](#) (NAMII – Now called ‘America Makes’) states,

“Improving additive manufacturing is an important part of the administration’s efforts to help U.S. manufacturers by supporting new opportunities to innovate,” said Under Secretary of Commerce for Standards and Technology and NIST Director Patrick Gallagher.²¹ Additive manufacturing, also known as 3D printing, is a group of new technologies that build up objects, usually by laying down many thin layers on top of each other. In contrast, traditional machining creates objects by cutting material away. A diverse array of manufacturing industries—from aircraft to medical devices and from electronics to customized consumer goods—are already using or exploring applications of these new technologies.

Additive manufacturing processes face a variety of hurdles that limit their utility for high-value products and applications. Technical challenges include inadequate data on the properties of materials used, limited process control, lack of standardized tests for qualifying machine performance and limited modeling and design tools.

These and other such national initiatives indicate that manufacturing and its close relationship to materials technology, is getting a significant amount of positive attention, creating expectations of resources and support for innovation that includes both product design and manufacturing that will have an impact on manufacturing education and research. All of these initiatives support advanced manufacturing and manufacturing education. And, because materials education and manufacturing education are inextricably interlinked, it is very desirable for educators in materials and manufacturing work in concert to promote improvement in their education programs.

10. Future Directions and Conclusion

This paper describes the interconnections between manufacturing education and materials education. Using the base of the Four Pillars of Manufacturing Knowledge model developed by the Society of Manufacturing Engineers, it focuses on the critical role of materials within the manufacturing system, beginning with materials selection and continuing through to product fulfillment. The paper emphasizes the need for education and careful communication between materials professionals, product designers, manufacturing process designers, and related systems operators to ensure successful outcomes, especially with the proliferation of new materials now available.

The paper demonstrates that the relationships between manufacturing and materials need to be promoted to a wide variety of constituencies, including the engineering, engineering technology, and industrial technology education communities. Potential uses of the Four Pillars model therefore extend beyond the manufacturing community to include materials and related communities. This could include creating a unified framework for manufacturing and materials curricula, guiding the accreditation and certification processes, building relationships with other disciplines, providing educational strategies for educational and professional groups in these related disciplines.

That the integral place of materials technologies in manufacturing has been realized in industry is demonstrated in a variety of our references works, including recent work at NIST relating to additive manufacturing¹⁴ and to materials research to advance manufacturing innovation.^{19, 20, 21} Extending this understanding to educational programs can ensure enhanced manufacturing productivity into the future.

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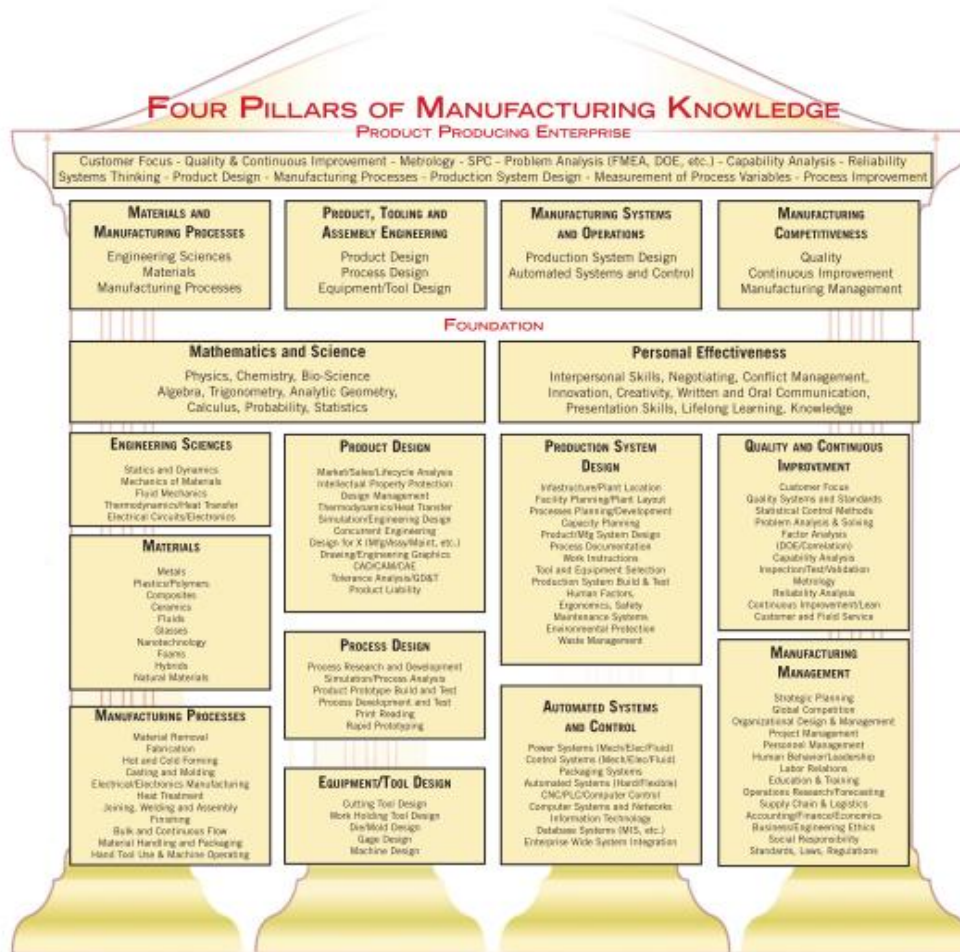


Figure 1 Graphic Representation of the Four Pillars of Manufacturing Knowledge
[Used with permission from the Society of Manufacturing Engineers]

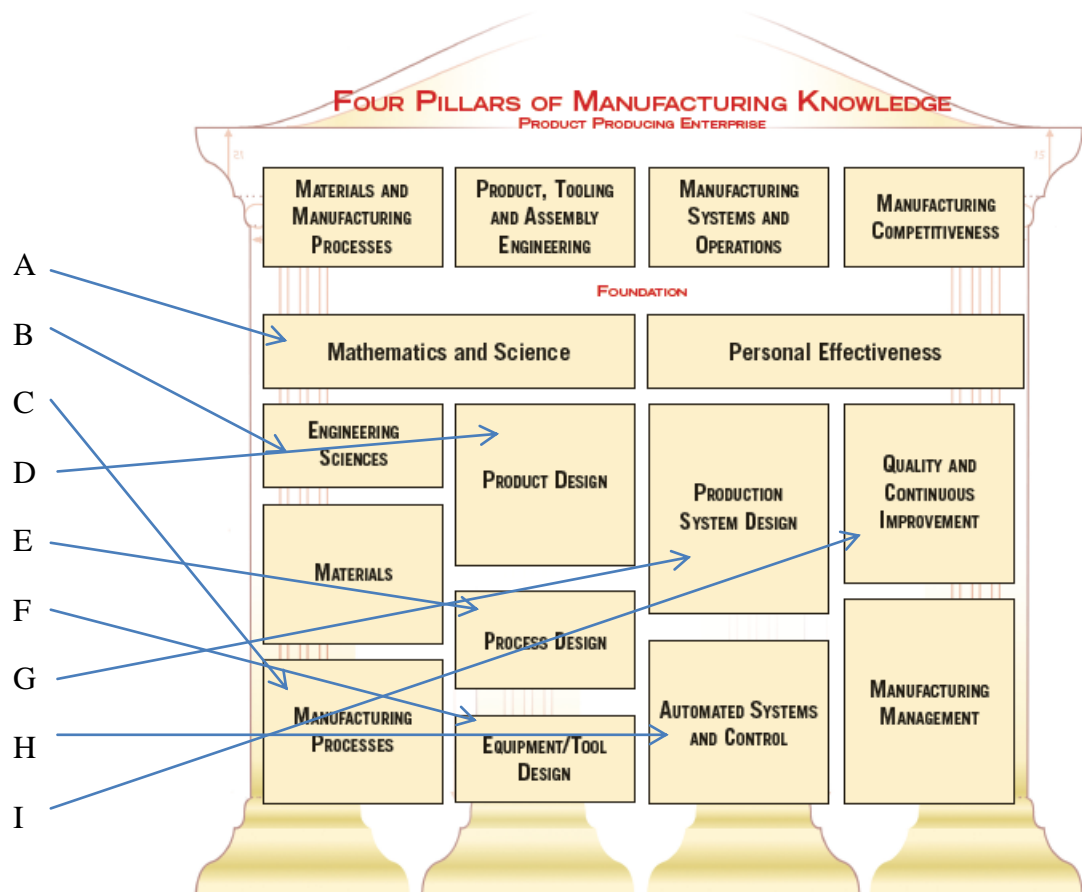


Figure 2 Aspects of the Four Pillars of Manufacturing Knowledge that are directly related to Materials Science. The letters refer to elaborations about materials/manufacturing relationships in the subheadings within Section 5 of this paper. See also the overall discussion in Section 5 on the Materials section of the Four Pillars model.