BRIDGING MECHANICAL ENGINEERING AND MATERIALS SCIENCE

To learn about the important connection between mechanical engineering and materials science, we turned to five experts with backgrounds in both fields for insight. Following are their perspectives on how the two disciplines informed their careers, which types of design challenges can be solved with materials information, and how ASM can improve that connection by leading with a "unity of disciplines" approach.

ASM PANEL OF EXPERTS

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Image courtesy of Ehsan Ahi, Velan Inc., Montreal.

Describe your education or career in relationship to the two disciplines of materials and mechanical engineering.

Scott Carpenter: I graduated from the University of California, Berkeley with a double major in mechanical engineering and materials science and engineering; so these worlds were brought together for me through my education. In my professional career, I began working with shape memory alloys at Raychem in the late 1980s and continue to work with these materials today. I have worked with numerous other metals and alloys, as well as polymers, ceramics, and coatings throughout my career. My main focus has been on Nitinol processes and products. Nitinol is a highly non-linear, anisotropic, and path dependent material, and as such requires computer simulation for all but basic analyses. This material is sensitive to thermomechanical processing history; so, you cannot separate the processing and its impact on properties from the mechanical design. Understanding the mechanical aspects of these materials requires an understanding of how the crystallography works.

Bertrand Jodoin: I have a bachelor's degree in mechanical engineering with a specialization in aerospace and a Ph.D. in chemical engineering. As part of my undergraduate studies, I took two courses related to materials and numerous courses about mechanical engineering. While pursuing my Ph.D., I again took a few courses on materials. My dissertation was on the development of a DC plasma torch for coating development and that was when I was introduced to the thermal spray world and community. After my Ph.D., I started an academic career at the University of Ottawa and decided to push the link between materials and mechanical engineering further by working on the cold spray process, which was at the time more of an engineering/science curiosity than a real spray/coating process. I have been working on the development and use of this process ever since, combining both mechanical engineering and materials for interesting applications.

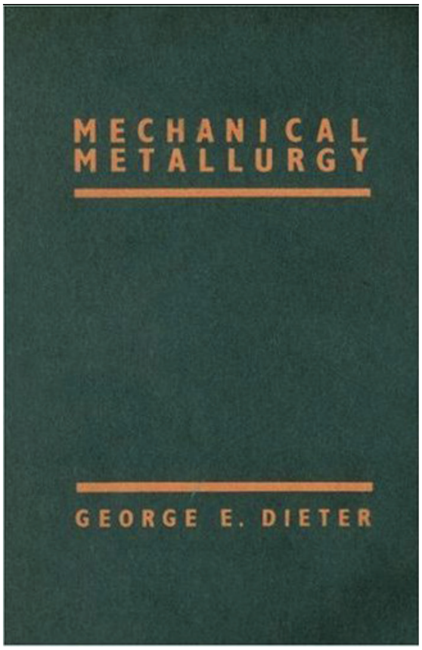
Vistasp Karbhari: My career in academia has been at the interstices of structures, mechanics, and materials, building on the disciplines of mechanical and aerospace engineering, civil engineering, and materials. This has enabled me to conduct cutting-edge research in the areas of composite materials from the nano level to the structure, on the durability of materials and structures, and in terms of structural design, rehabilitation, and multi-threat mitigation. The ability to combine knowledge from the different disciplines allowed me to study effects during the processing of polymers and composites and to develop methods for handling large structural components using ambient and moderate temperature non-autoclave cure processes. This background also enables me to teach courses at the undergraduate and graduate levels linking materials details at the nano and constituent level (i.e., fiber, matrix, filler) with structural response and design. The ability to integrate the disciplines enables innovation across levels with a true understanding of how materials selection and processing affects design and structural responses.

Marina Ruggles-Wrenn: My education (B.S. in mechanical engineering, M.S. in mechanics, and Ph.D. in mechanical engineering) focused primarily on mechanical engineering with little emphasis on materials science. During the early years of my professional career, I concentrated on experimental investigation and constitutive modeling of the inelastic deformation behavior of engineering alloys and on high-temperature structural design methods. My first significant (and exciting!) excursion into materials science occurred when I investigated effects of prior aging on rate sensitivity and cyclic hardening of a nuclear-grade stainless steel as part of my Ph.D. research. Thorough understanding of the microstructural nature of aging through the formation of precipitates was critical to selecting proper pre-test heat treatments. Microstructural investigation of the samples with an SEM and a TEM was critical to determining that the precipitation heat treatments indeed produced the desired degrees of aging. Then some 20 years ago, my growing interest in the mechanical behavior and environmental durability of advanced ceramic matrix composites necessitated an aggressive study of the material microstructure and physical methods of materials characterization.

Judith A. Todd: I completed my B.S. and Ph.D. degrees in materials science at Cambridge University with a strong emphasis on metallurgy and mechanical behavior. I then accepted a postdoctoral position at Imperial College of Science and Technology, London, to conduct research on the mechanical behavior of materials, advanced fracture mechanics, and fatigue. In this collaborative program between the materials science and engineering and mechanical engineering departments, I worked on the early development of the parameter C* (creep equivalent of the J contour integral) to predict creep crack growth in Cr-Mo steels (power plant steam pipe), and in aluminum alloy RR-58, (skin of Concorde). This began my life-long engagement with mechanical engineers. Except for my position as Department Head of Engineering Science and Mechanics at Penn State, I have held courtesy faculty positions in mechanical engineering departments throughout my academic career.

What have you learned from a knowledge of mechanical engineering that helps in your materials career?

Ruggles-Wrenn: My background in mechanical engineering has taught me to see the difference between the design *of* the material (typically a purview of materials scientists) and the design *with* the material (typically a purview of mechanical engineers). Both are extremely important. The best results are achieved through collaboration, when the design *of* the material goes hand-in-hand with the design *with* the



Many engineers point to *Mechanical Metallurgy* by George Dieter, a seminal text from their undergraduate education. Its third printing is still used today.

material. We should aim to link the material behavior we observe on the macroscale (say in mechanical testing of laboratory sized specimens) to the phenomena we observe on the microscale. Improvements in material processing can be recommended and executed based on such observations.

Todd: Mechanical engineers place a very strong emphasis on design of components and their integration into large systems—power plants, automobiles, electronics, medical devices, among many others. It is essential to know how all the parts fit together and how designs can be tuned to optimize the performance of the system. Mechanical engineers rely heavily on materials property data, codes, and standards to select appropriate materials compositions, component dimensions, and manufacturing processes that they expect suppliers to meet. It is essential for materials scientists and engineers to supply the highest quality materials information to ensure the integrity of our safety-critical and humanitarian infrastructures.

Jodoin: Being primarily involved with surface and coatings technologies, the goal is always to produce the perfect coating that can withstand the specific environment it is exposed to as well as the various stresses. However, the production of these coatings usually involves complex equipment as well as complex interactions of the various process parameters. My training in mechanical engineering has been extremely beneficial to understanding the intricate interactions and various complexities of the processes to allow going beyond "turning knobs and seeing what happens." Most coating technologies, especially thermal spray processes, involve heat transfer, fluid mechanics, gas dynamics, solid mechanics, and many other topics that are covered in mechanical engineering. As such, it has helped me understand the process fundamentals and be able to foresee the effect of various spray parameters ahead of time.

Karbhari: The fundamentals of solid mechanics, thermodynamics, fluid mechanics, and analysis have helped me develop a better understanding of materials, configuration, and process interactions, and tailor materials for specific response modes using anisotropy to optimize design and failure modes at levels not possible with isotropic materials. Mechanical engineering helps in the appropriate selection and use of materials, obviating the "over the shoulder" transfer between design and manufacturing, and enables a better understanding of service life, durability, and damage tolerance. In the case of composite materials—my specialty—that background enabled a much better ability to understand and tailor failure modes, develop optimized load paths through configuration tailoring, and develop better processes, taking into account aspects of flow and cure at the micro and macro levels. This has allowed for design to be considered simultaneously at the materials and structural levels, especially in the development of ceramics through preceramic polymer methods.

What are the challenges mechanical engineers encounter that can be overcome by an increased knowledge of materials?

Karbhari: Mechanical engineers are required to analyze structural response and design components that will withstand a range of thermomechanical loads and vibrations. A thorough understanding of materials leads to not just better, more effective, and cost-efficient materials selection, but also tailoring of the materials and configuration to best handle loads over

Tensile testing is an essential tool in determining material properties related to strength.

a product's lifetime. It further allows for better analysis of failures leading to improved designs and lowering of costs. In addition, an increased knowledge of materials ensures that designs are developed that can be manufactured and will respond over their intended service lives as anticipated. It also enables the development of cutting-edge innovation where new structures and components must be based on designer and tailored materials enabling the implementation of multifunctionality.

Todd: Understanding how materials processing and manufacturing determine the development of materials internal structures or microstructures and their resultant physical, chemical, and electrical properties (from atomistic to bulk levels) is essential for understanding the performance of the materials themselves and their integration into components and systems. Easy access to customized materials knowledge for technical staff (from technicians to Ph.D.s and workforce retraining) that integrates state-of-the-art educational, digital, simulation, and analytical tools with materials data repositories, handbooks, codes, and standards, is an important part of the solution. Finding immediate custom solutions to solve specific materials challenges, particularly related to failure analyses, is a domain where materials expertise is essential.

Jodoin: I always joke in the classroom that all our problems stem from the materials side. We have known for decades how to build more efficient engines and devices and the challenges always remain to have materials that can withstand the ever-increasing demand of harsher environments to reach higher efficiency. Everything outside the virtual world must be manufactured using materials; as such, materials dictate what we can build and the resulting performance.

Ruggles-Wrenn: Computational models and life-prediction methods for specific structural components are incomplete unless they address the evolution of the material's microstructure during component fabrication and operation. Understanding the mutual influence and interaction between the mechanical loading and operating environment of the engineering component and the microstructure of the material from which the component is made is vital. Increased knowledge of materials can provide valuable information on how a material changes during the fabrication and operation of an engineering component. Mechanical engineers can and should incorporate such information into design and analysis considerations.

Carpenter: Materials selection is always key to design, particularly where high performance and minimum material use is critical, as in aerospace applications or medical-device implants. Each material has capabilities and limitations that need to be considered and evaluated. Handbook properties may not be representative for very large- or small-scale applications. For example, at smaller scales, grain sizes and inclusions begin to play a much more critical role and the processing that leads to that material has a great influence on those features. Interactions between materials can also be important. One example of this is galvanic corrosion between dissimilar metals. Another example can be emission from a polymer causing corrosion of a metallic element.

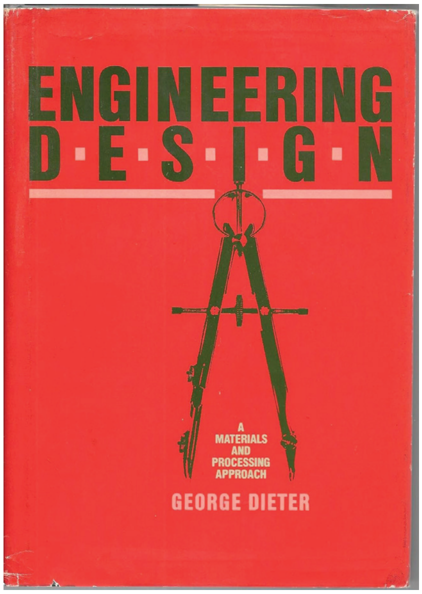
George E. Dieter, FASM, created a bridge between materials science and mechanical engineering through his teaching, textbooks, and handbook. What has happened between the two disciplines since then?

Todd: George Dieter's books are as foundational today as they were when written. Emphasizing mechanical metallurgy and design, including conceptual design, he showed how design contributed to society, industry, and technological advancement. Always the innovator, George would be proud to see how far his vision has come. Today, materials and mechanical engineers are applying the latest computational methods and digital tools to understand how the behavior of "soft matter"—polymers, biological tissues, brain—influences their performance and can interpret disease states. Modification of such behaviors is the next step toward disease diagnostics and mitigation—the medical and health care professions are waiting!

Today, the importance of curated, validated materials data and their incorporation into national and international codes and standards is one of ASM's highest priorities and is of the highest relevance to materials and mechanical engineers. Through development of the ASM Data Ecosystem and the ASM Materials Solutions Network, our Society has the potential to create even greater bridges between materials and mechanical engineers.

Dr. George E. Dieter, Jr., FASM, 1928-2020.

Carpenter: This is a great union between two very closely connected disciplines, which has become increasingly important as designs have become more aggressive and new materials and fabrication methods have emerged. A lot has changed in the decades following the start of this important connection. In my experience, I see a lot more cross-pollination between the two disciplines. Some embellishment of these principles, considering the changes in materials and processes would be highly welcomed. A more thorough discussion of applicable techniques for analyzing non-linear, anisotropic, composite, or other material and geometry complexities in university teachings is needed. This was glossed over when I attended



Engineering Design: A Materials and Processing Approach was one of George Dieter's foundational texts, now in its sixth edition.

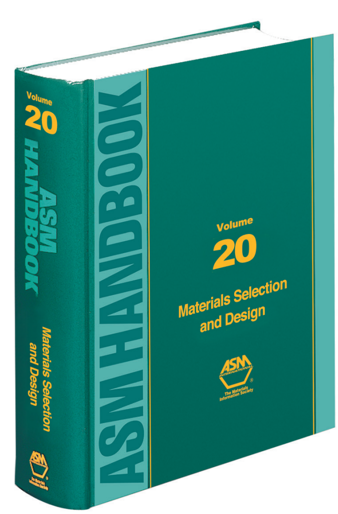
college. In talking with some current students, it still seems to be the case.

Ruggles-Wrenn: Dr. Dieter indeed created a bridge between materials science and mechanical engineering, as evidenced by his work on the *ASM Handbook*. However, it seems that often materials scientists and mechanical engineers still operate in two separate worlds. Materials scientists focus on material synthesis and microstructural characterization with limited attention to the mechanical behavior of the materials they develop. Mechanical engineers focus on developing computational predictive models of mechanical behavior for various components, sometimes neglecting the microstructural changes that occur in the material during component fabrication and other physical aspects of material response. A closer cooperation between these two worlds is needed.

Karbhari: Unfortunately, with a few exceptions the two disciplines have drifted apart with students either gaining a strong background in materials without the ability to design components and structures or to analyze performance at the macro-level. Or they develop a strong background in mechanical engineering without a good understanding of how to select and process materials for specific features and performance characteristics or to focus on desired failure modes. This has resulted in inefficient design, as in the use of composites as "black aluminum;" the mechanical engineer is more conversant with isotropic response and hence does not use the inherent anisotropy and ability to tailor composites; instead preferring to develop quasi-isotropic equivalents. This also leads to the use of excessive factors of safety and inappropriate use of materials such as not considering configurations that might be extremely effective in tension but not in compression or under hydrostatic pressure, or forgetting the intricacies of joining.

If an update was made to *ASM Handbook,* Volume 20: *Materials Selection and Design,* what information would you recommend adding, enhancing, or subtracting?

Ruggles-Wrenn: The *ASM Handbook*, Vol. 20, provides a wealth of information regarding materials properties and behavior, materials selection process, and design practices. It addresses several different families of materials such engineering alloys, brittle materials, and composites. However, the handbook does not address ceramic matrix composites (CMCs). Yet SiC/SiC and porous matrix oxide/oxide CMCs are now used in real-world applications, such as shrouds and combustor liners in gas turbine engines. I would consider adding information on microstructural characterization, mechanical properties and performance, and environmental durability of CMCs to the handbook.

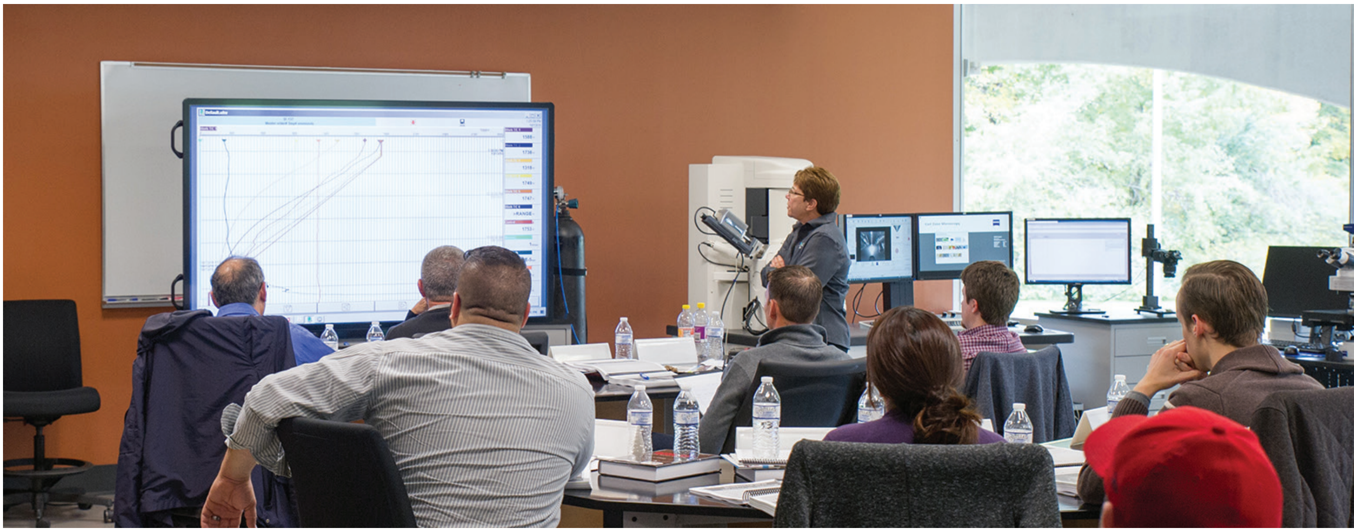


ASM Handbook, Vol. 20 was developed with Dieter serving as volume chair.

Carpenter: Include information on designing with newer or more complex materials, such as: high entropy alloys, Heusler alloys, composites, additive materials, and sustainable materials. Adding information regarding the analysis of 3D printed structures, which often consist of a sparse core, would be beneficial. Bolstering or updating the environmental design section, including energy storage materials, is suggested.

Todd: *ASM Handbook,* Volume 20 was an exceptionally comprehensive review of materials selection and design at the time it was published in 1997. It provided a foundational review of the field. In the intervening 26 years, advances in new materials, digital design, analytical tools, and cyber infrastructure now enable us to design materials and components with tailored compositions and properties from the quantum, atomistic, molecular, and cellular levels to bulk components and systems. We can collect data in amounts that were inconceivable in 1997. Perhaps a new volume entitled *Materials Selection – Data and Digital Design* could include: Computational materials design and integrated computational materials engineering; design across materials scales; selection and design of "soft matter" expanding beyond polymeric materials to biological tissues; materials selection and design in an interdisciplinary context; and materials selection and design for sustainability, cyber security, defense, and for addressing all the global grand challenges.

A new volume that emphasizes the importance of ASM's new Data Ecosystem, digital tools/interfaces, the Materials Solutions Network, and their value to the Society would be very timely. If a



ASM courses could help fill the materials knowledge gap for mechanical engineers.

new digital volume is to be developed, the Affiliate Societies should have a major role to play and a representative of each should be included in the volume team. George Dieter was expansive in this thinking of materials selection and design in 1997. We now have the opportunity to take this to the next level.

How can ASM and its members impact future generations to adopt a "unity of disciplines" mindset instead of a siloed approach?

Jodoin: The unity of disciplines is already out there in the mentality of most of ASM members. I think that some extra links could be made by holding multidisciplinary conferences. Sometimes colleagues from other disciplines have the answer we are looking for and can educate us and bring us up to date quickly. Creating those connections is crucial.

Karbhari: Some ideas include: 1) Conducting workshops and conferences focused on the interstices between the disciplines; 2) Developing curricula and course materials that enable students and practicing engineers from both disciplines to gain advanced knowledge; 3) Developing certificates/credentials taught and accredited through ASM after thorough design through a partnership between the end user (corporate company and employer), materials supplier, designer, and academia; 4) Developing modules taught by ASM practitioners that could be used as part of courses at the college and university level; 5) Enabling the publication of state-of-the-art and state-of-the-practice documents on key topics at the interstices of materials and mechanical engineering; and 6) Focusing on Manufacturing 4.0, which cannot be successful without a deep understanding of materials and processing.

Carpenter: One suggestion would be to start setting the stage for this in early STEM education. I know from presenting the engineering field to grade school students that they are open and receptive to these concepts and understand the basic principles and interactions.

Todd: The grand challenges facing our current society—global warming; securing our food, water, and energy supplies; cyber security and infrastructure; mitigating international and space defense; and global health and welfare; among others—resonate with ASM's future generations, who will be tasked with determining their solutions. Such solutions will require highly interdisciplinary approaches with breakthroughs occurring at many academic and professional interfaces—engineering, science, social science, agriculture, politics, business, law, medicine, and humanitarian causes, to name a few. All these challenges may involve materials solutions.

ASM can broaden its focus through targeted outreach to non-traditional materials communities. Examples may include "the material brain" exploring the properties of brain as "soft matter;" "sustainability" – addressing the life cycle, degradability, and reuse/repurposing of materials; and "humanitarian causes"—where inexpensive materials solutions can benefit the health and welfare of increasing populations that are being displaced by global climate changes and warfare. As the "Materials Information Society," ASM members and our future generations have an important role to play. **~AM&P**

ADDITIONAL RESOURCES

A Tribute to George Dieter, *Advanced Materials & Processes,* Vol. 179, No. 2, p 40-41, Feb/Mar 2021.

In Memoriam: George Dieter, *Advanced Materials & Processes,* Vol. 179, No. 2, p 46, Feb/Mar 2021.

ASM Handbook, Volume 20, *Materials Selection and Design,* Ed. George E. Dieter, 1997.