The Future of Engineering Materials: Multifunction for Performance-Tailored Structures

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THE DESIRE FOR PERFORMANCE-TAILORED STRUCTURES

In the future, the new, functional, and reduced-scale materials that are currently on the forefront of technology will be hybridized into designer materials that will realize dramatic, performance-tailorable functions from large engineered systems. These performance-tailored structures will have the ability to change or adapt the performance or style of a structure on demand. An engineer can now begin to imagine designing adaptive flight profiles from morphing aircraft wing structures, comfort-tailored performance such as active structural vibration and noise suppression or temperature compensation from louvered or pore-based "smart skins," energy-efficient structures such as plant-inspired tropic solar structures, and adaptive structures that undergo distortion compensation, self-heal, or reconfigure for your style preference. Imagine the ability to commute to work in a stately, professional car but reconfigure it into a sportier look for the weekend.

The ability to adapt a structure's performance at will is increasingly more attractive as system-operating scenarios become more space and logistics constrained. Currently multi-mission objectives are answered with multiple structures: a car to drive to work and a car for the weekend. These solutions work if there is excess capacity in the system, e.g. a two-car garage, but further increases in mission objectives make the procurement, storage, and maintenance of a large number of structures prohibitive. As a consequence, engineered subsystems that provide structural adaptability are under development in programs such as DARPA's Morphing Aircraft

Structures program (Wax et al., 2003), General Motors' Autonomy Concept (Burns et al., 2002), and many structural health monitoring programs. These programs are designed to produce performance tailoring but from large, multicomponent system structures.

Researchers are now imagining the ability to obtain these same functionalities from the materials used to construct the system themselves: a thin but smart materials skin that undergoes a radical but controlled change in mechanical strain, a coating that changes color on demand, a shell that reconfigures shape to meet styling or mechanical performance criteria. These materials would enable the same system-level goals that are currently designed as subsystems; however they are more readily integrated into the larger engineering structures because they are lighter, smaller, less difficult to interface, and easier to maintain. Fueled by recent advances in biomaterials and nanotechnology, multifunctional materials are now emerging as a new interdisciplinary field that promises to provide a new level of functionality, adaptability, and tailoring to future engineered systems.

MULTIFUNCTIONAL MATERIAL SYSTEMS

Multifunctional materials are typically a composite or hybrid of several distinct material phases in which each phase performs a different but necessary function such a structure, transport, logic, and energy storage. Because each phase of the material is used to perform an essential function so there is little or no parasitic weight or volume, multifunctional materials promise to achieve performance flexibility but with higher weight and volume efficiency and potentially less maintenance than the traditional multicomponent, brassboard system solutions. In addition, as the integration scale in the material becomes finer and more distributed, reaction times may become faster and more autonomous.

Multifunctionality within a material can be integrated on several dimensional scales with increasing interconnectivity between phases and engineering difficulty as the scale decreases. Matic (2003) has categorized these different materials scales as types: a Type I material is comprised of phases in which one function is simply mounted, coated, or laminated on the other phase, usually a structural component. Type II materials are comprised of distinct phases in which one function is embedded in another phase, usually a structural component. Type III materials are truly integrated materials in which the phases of each material are intermeshed so that the physical distinction between phases becomes less clear. The true promise of multifunctional materials to performance-tailored structures is found in Type III materials and is the ultimate goal.

The drive for improved overall system performance determines the design of a multifunctional material, therefore its performance metrics are inherently different from its single component phases. In the component phases, the improvement of a single function, such as electrical conductivity, mechanical strain or force, energy density, etc. is maximized or minimized. In a multifunctional material however, a new materials design methodology is required in which the system-level performance is emphasized over the optimization of the individual functions. This involves the use of optimization methodologies that are not commonly used in materials science.

FRONTIERS IN MULTIFUNCTIONAL MATERIALS TECHNOLOGY

Materials Technology

Multidisciplinary research efforts in multifunctional materials have been initiated, many of them under the auspices of DARPA’s Synthetic Multifunctional Materials program

(Christodolou and Venables, 2003) with the goal of demonstrating weight and volumetric efficiencies, and performance enhancements from these materials systems. A majority of these efforts only integrate two functions, a transport and a structure function and typically of low interconnectivity (e.g., Type I or Type II). Much of the research also relies heavily on inherently two-phase structural materials such as fiber composites, laminates, foams, and other porous structures as the matrix for the multifunction. Even at this early stage however, system level benefits have been noted.

Structural batteries, which reduce weight and form complexity by directly integrating energy storage into the load-bearing structure, have been developed by several teams using fibers, laminate, or nanotube construction. The energy density of the storage medium, such as a battery or supercapacitor, is reduced due to the incorporation of less conductive structural materials; however, the loss in parasitic structure results in an overall weight savings and therefore improved energy density for the greater system.

The integration of actuation or sensing mechanisms into tailorable structural materials, essential for mechanical reconfigurability and structural morphing, is also under active investigation. Research using metallic foams or highly engineered mesostructured materials (dos Santos e Lucato et al., 2004), elastomeric polymers (Pei et al., 2002), and hybrid laminate materials (McKnight, 2004) as the controllable flexible structural matrix for integrated actuation and sensing shows tremendous promise for producing large structural motions. Self-healing composite structures are also underdevelopment (Chen et al., 2002) in which a second phase such adhesives and toughening agents are added into the structure to reseal on impact.

The development of materials integrating other functions such as electromagnetics, thermal management, and optics into structures are also underway.

Optimization and Computational Design

Advances have also been made in developing optimization tools for the design of integrated multifunctional materials. Sigmund and Torquato (1999) have done extensive work using topological optimization methods to determine the best morphological materials architectures to optimize performance from highly integrated Type III materials embedding very dissimilar physical mechanisms. They have simulated many functional combinations with as many as three phases. While purely theoretical, the result of their simulation work has been validated by the similarity of their optimized topological solutions to micro and mesostructures found in biological systems. More macroscopic optimization tools for the design of less integrated Type I or II multifunctional materials level have also been developed (Qidwai et. al, 2002).

CHALLENGES AND PROSPECTS FOR THE FUTURE

The achievement of two phase multifunctional systems show the promise of true materials integration; however, the combination of three or more functions including logic, sensing, energy storage, structure, and actuation will be required to achieve truly smart material systems, ultimately analogous to biological systems. Biological systems have perfected multifunction on a small scale but the ability to *a priori* design multiple functions into a material system will allow extensions of these concepts into large-scale structures. The complexities of these higher order systems will require a more sophisticated understanding of basic physical mechanisms to create new, potentially less singly optimal means of achieving function and multivariable optimization tools. For example, the ionic conduction mechanism that is the foundation of energy storage systems will also have to be examined for new logic capabilities, or electrical conductivity mechanisms will have to be examined to see how they can influence mechanical strength.

In addition, the increased knowledge of understanding of materials on the nanoscale level will increase the control and range of physical properties of materials while further decreasing the integration scale. While we are on the cusp of understanding and harnessing physics on the nanoscale, there is a tremendous amount of work required to be able to fabricate large-scale materials from nanoscale elements. While self-assembly and biological processing techniques hold promise, the maturity of these techniques is not yet sufficient to address the fabrication of multicomponent systems.

The new system-level design methodology for materials not only changes the tools that the materials scientist needs to know and understand, but it also requires a fundamental change in the role of the materials scientist in the system design process. Typically the system designers choose from a toolbox of materials that have been already developed; the materials scientist commonly pre-designs these materials to improve a single function. Often the materials scientist acts independently of the design team and is only present to provide characterization data or to troubleshoot a problem after design. In this new paradigm however, the materials scientist must be actively involved at the inception of the system design, providing a finely engineered material on the meso-, micro-, or nanoscale to meet the overall system goals. This will require that the materials scientist be more familiar with system design tools and a suite of computational tools that ranges from the system scale to the micro- or nanoscale. In the future, the design of a new car, airplane, or satellite will truly start on the atomic scale.

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