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Brains of Steel: Mind Melding with Materials*

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A systems approach to the computational design of materials as dynamic multilevel structures integrates process/structure/property/performance relationships based on mechanistic understanding. In analogy to the structure of materials, new insights into the structure of the human brain provide a mechanistic basis for the design of engineering education. The development of the highest-level emotional synthetic functions controlled by the limbic system is best achieved by an integrated techmanities curriculum fostering the full skillset for value creation.

MATERIALS DESIGN

SINCE 1985, the multi-institutional Steel Research Group (SRG) program [1] has explored the integration of research and education in materials design, following a systems approach based on the philosophy of the late Cyril Stanley Smith [2]. Smith wrote extensively about interactive structural hierarchy in materials (and space-filling aggregates in all branches of science including geology and biology). He envisioned a multilevel structure with strong interactions amongst levels, with an inevitable interplay of perfection and imperfection, and a *duality* of description in which structure can be equivalently regarded in terms of space-filling units or the array of interfaces which bound them. This is a view of materials that admits a *necessary complexity*.

Smith also described a tension which has existed throughout the history of materials science between the *real complexity* of nature and the *artificial simplicity* which science attempts to impose on it. He described a golden age of materials science which existed in the 17th century under the leadership of René Descartes and the Cartesian school of corpuscular philosophy, who developed a sophisticated view of the multilevel structure of materials. This complex view was, however, completely supplanted by two divergent simplistic notions. One was Dalton's *atom*, which held there was only one important level of structure and all higher levels could be ignored. The other was Newton's *continuum*, by which structure could be ignored entirely. These simplifying concepts were so intellectually compelling that they put materials science on the shelf for two centuries. We have reconstructed it over the past century, but the atom and the continuum remain the dominant philosophies of science today.

In recent years, however, the adaptation of atomistic and continuum approaches to the multilevel heterogeneous structure of materials has contributed greatly to our scientific understanding. While the powerful simplifying methods of scientific analysis provide quantitative relationships as raw ingredients for design, these methods tell us nothing of how to integrate our understanding for the creation of new complexity. For this purpose, engineering has developed its own set of fundamental principles embodied in the *systems approach*. A concise summary of the approach, which we employ in our materials design course at Northwestern [3], is given in a review paper by Jenkins [4] of the Open University. Jenkins' summary of the general characteristics of engineering systems as dynamic hierarchical structures with strong interactions amongst levels is strikingly similar to Smith's view of materials; Smith in fact recognized this and advocated the systems approach for materials science.

The Steel Research Group (SRG) has adapted such a systems methodology to the science-based design of new classes of high performance alloy steels. Research has integrated physical and process metallurgy, ceramics, applied mechanics, quantum physics and chemistry, mechanical engineering and management science. A key step in devising system structures to support the conceptual design of materials meeting performance requirements has proved to be the essential paradigm of Fig. 1. The concept of four primary elements of materials science and engineering is well accepted. In the spirit of Smith's structural duality, Fig. 1 emphasizes the key interfaces between these elements in the form of a three-link chain by which processing and performance can only be connected through structure and properties. This structure offers a resonant bond between the science and engineering of materials in which the deductive *cause-and-effect* logic of science flows to the right, while the inductive

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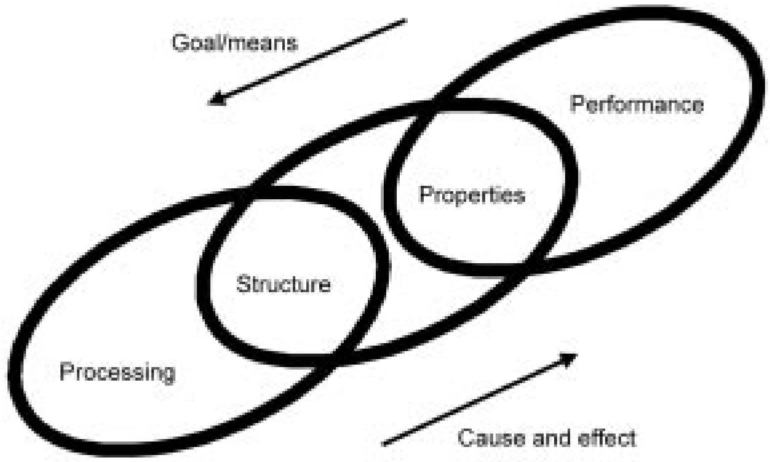

Fig. 1. Three-link chain model for central paradigm of materials science and engineering.

goal-means relations of engineering flow to the left [5, 6]. Consistent with Smith's universal view of all structure, further support for the utility of this paradigm is offered by its direct correspondence to general design decision methods developed to apply across all engineering disciplines [7–9].

Appropriate design performance goals and property objectives relative to existing materials can be devised through the quantitative property cross-plot methods developed by Ashby [10] for materials selection. Once a set of property objectives has been deduced from such property/performance relations, the chain of Fig. 1 can serve as a backbone to which the addition of Smith's hierarchy can provide a first-order representation of a full system structure. The product of such an exercise as first applied to the system structure of a UHS martensitic alloy steel in SRG research [1] is represented in Fig. 2. The chart denotes the selected microstructural subsystems controlling the properties of interest, and the substages of processing (represented by a vertical process flow chart) governing the evolution of each. This representation of the full system was employed to identify and prioritize the key structure/property and process/structure links to be quantified by the mechanistic computational models of the SRG program. The range of computational models developed and their design applications are described in a recent overview [11].

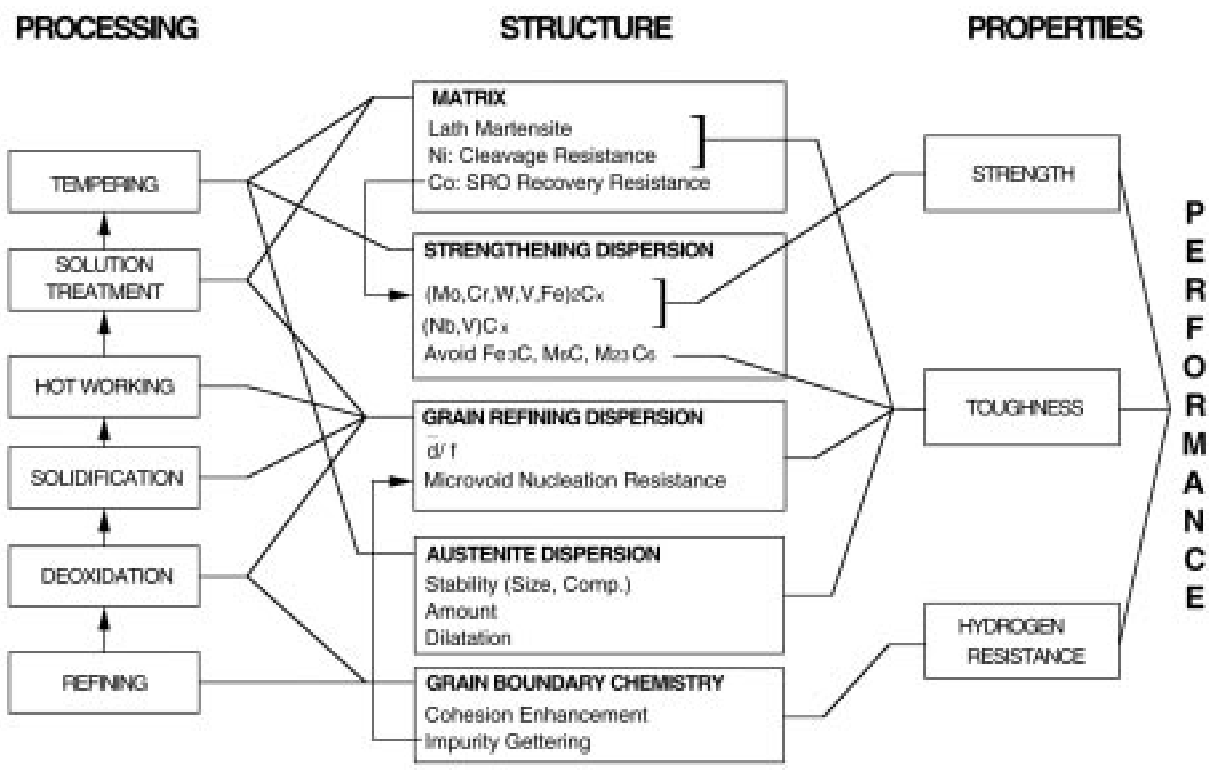

Fig. 2. Materials system chart for secondary hardening martensitic alloy steel.

Table 1. C90 Proposed Projects Spring 99.

I.	Andretti Steel (Newman-Haas, QuesTek)	VII.	Noburnium: Stainless Nb Superalloy (P&W, GE, Howmet)
II.	Pd Quantum Steel (NAWC, ARL)	VIII.	HSHC Copper (Electronics; MEF)
III.	CGL Bumper Bainite (Inland)	IX.	Hydrate Ceramics: Super Plaster (USG, QuesTek)
IV.	NUCu Bridge Steel (FHA; MEF)	X.	Ultrahard PVD Coatings (ACTG) A. PH TiN B. PH NiCr
V.	Ferritic Superalloy (EPRI, QuesTek)	XI.	Thin Film Shape Memory Alloy (ACTG)
VI.	Dragonslayer: Mystical Steel (QuesTek, Angel Sword, EDC)	XII.	Terminator 3: Self Healing Biomimetic Smart Alloy Composite (ARO, QuesTek; EDC)

Using computational thermodynamics as the principal integrative tool, models created in graduate research are applied in undergraduate design projects. The range of design projects considered by the most recent materials design class is listed in Table 1. The left column lists alloy steel projects derived from SRG research, typically recommended by member companies. The right column lists 'nonferrous' projects which test the generality of the design methodology, and also explore the level of conceptual design that can be practiced without support of a major research project. This has included projects in ceramics and polymers. Two of the projects listed have involved collaboration of upperclass materials design teams with our first-year Engineering Design and Communication course. The Terminator 3 Biomimetic Composite has involved both collaborative theoretical calculations and successful implementation of a prototype as a second-year project, demonstrating the first self-healing alloy [12]. As an exercise in integral aesthetics and product marketing, the Dragonslayer Mystical Sword project seeks to create a sword of maximum value to a collector while showcasing new technology. After drawing dragon specs from medieval literature and reviewing the history and legend of ancient swordmaking, relative values of attributes were assessed via internet surveys of sword collectors. Conceptual designs have integrated meteoric iron for mysticism with frontier steel technology to achieve a cutting edge capable of slicing through a Samurai sword. After auctioning the sword to collectors for publicity, it is proposed to market the steel as a new line of Dragonslayer golf clubs.

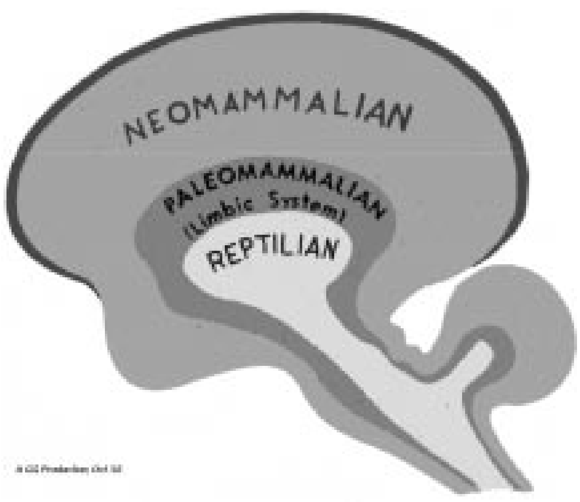

Fig. 3. Major regions of human brain denoting first appearance in brain evolution. After MacLean [14].

STRUCTURE OF EDUCATION

Returning to the three-link chain paradigm of Fig. 1, we can further explore its generality through parallels in the evolution of 'hard' sciences, and their implications for design education. In modern times, metallurgy began with an emphasis on the direct correlation of *processing* and *properties*. The advent of physical metallurgy opened the 'black box' of *structure* and brought a revolution in fundamental understanding of the mechanistic link between processing and properties. The power of this understanding created the conceptual foundation for the recent generalization to materials science, making possible the general materials design methodology described here.

Taking this analogy a step further, it is instructive to think of education as a form of manufacturing in which we *process* student brains to attain brain *structures* which improve students' *properties* or behaviors to enhance their *performance* in society. Educational psychology can offer some empirical *process/property* relations for guidance, but no matter how compelling the statistics, such empiricism will always be regarded with suspicion as 'soft science' for lack of a *structural* mechanistic basis. As in any manufacturing process, we would be able to do our job better if we actually knew what we were doing.

In the past decade, a physical metallurgy revolution has occurred in the field of cognitive neurophysiology, as new scanning technologies have established actual *structure/property* relationships in the living human brain [13]. These offer particular insights into the mechanistic basis of the higher level functions of *analysis* and *synthesis* of special relevance to the goals of engineering education. Their structural basis can be usefully discussed using the sketch of Fig. 3 based on an early developmental model by MacLean [14]. While earlier notions of highest level functions emphasized the outer 'cortex' region of the brain due to its relative developmental newness and accessibility to earlier experimental techniques, the new techniques have fostered an appreciation of the importance of the central 'limbic system' which has continued to evolve as a sophisticated processor since its paleomammalian origins. While the process of *analysis* through which we take problems apart occurs by essentially *serial* processing in the outer cortex, it now appears that the higher function of *synthesis* by which we bring ideas together to create new ideas, occurs under control of the limbic system sending signals to the cortex to operate it in a *massively parallel* mode. Recognition that the limbic system is also where our emotions are centered has brought the insight that *emotional reasoning*, contrary to our cultural bias, is the highest form of thought, through which our brains are wired to deal with the inherent nonuniqueness of complexity [15].

We have in place today an analysis-oriented technical education system which is almost entirely focused on the outer 1mm of the cortex. In the name of objectivity, we train students to shut down their higher level functions and operate their brains as primitive serial processors. There is no doubt that the future of engineering education must target the center of the brain, unleashing the subjective reasoning powers of the limbic system as the primary source of value creation. This is the essential role of *design integration* in future curriculum development. Going beyond engineering courses, a 'techmanities' curriculum can best meet this goal, using broader cross-disciplinary projects to reach into the normally isolated humanities component of the curriculum to develop the full set of skills that can bring the engineering profession to a new level.

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