

## Viewpoint Paper

**Architected materials: Expanding materials space**Y. Brechet<sup>a,\*</sup> and J.D. Embury<sup>b</sup><sup>a</sup>*SIMAP, Grenoble Institute of Technology, Grenoble, France*<sup>b</sup>*McMaster University, Hamilton, Canada*

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**Abstract**—The objective of this introduction to the viewpoint set on architected materials is to illustrate the paradigm shift which occurs by introducing additional length scales into a material in addition to those provided by the microstructure. This provides new opportunities both to relate the processing of materials directly to design needs and to develop a variety of multifunctional materials in which both the microstructure and the overall architecture of the material are optimized.

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The historical evolution in the use and development of materials reflects a progression from “materials by chance” to “materials by design”. In early civilizations, the strategy with respect to materials was “using the materials available on site” (such as flint obsidian, wood, or even native metals). This is evident in a variety of tools and weapons in archaeological collections. Later, the strategy progressively evolved from optimization of specific classes of materials, first by empiricism, then by science-based approaches. This evolution was the essential contribution of metallurgy and later polymer science. Then came the stage of “hyperchoice of materials”, which triggered the development of tools for comparing and selecting materials from different classes which were already optimized in terms of their engineering potential. Finally, and more recently, environmental as well as economical concerns have generated a tendency toward multifunctionality of materials, a decrease of over-dimensioning using parameters such as safety factors, and in general a search for materials capable of fulfilling conflicting needs. This is the most recent step in the evolution: the development of “materials by design strategies”. This general evolution from “materials by chance” to “materials by design” is a long term-and durable trend, and comes with an increased importance of modelling, and an increased demand for multifunctionality. The present viewpoint set aims at illustrating one possible innovative route to meet this challenge, the development of “architected materials”

[1,2]. This approach blends, in addition to microstructural design, combinations of materials and the optimization of geometry, to obtain “materials” with unusual combinations of properties [Figure 1](#).

The classical strategies to meet requirements for a given component can be usefully pictured in terms of scales. Metallurgists and polymer scientists have thoroughly explored the possibility of “microstructure by design” (grain size, precipitation, polymer chain design and interchain bonding, state of crystallization). These strategies operate at scales between 1 nm and 10  $\mu$ m. The ultimate illustration of this strategy is to be found in the rapid recent development of a variety of nanomaterials. The general aim is to obtain, when possible, microstructures which are much smaller than the overall component size, and are homogeneous in their spatial distribution. At the opposite end of the scale, engineers in structural mechanics have developed a number of strategies, using the geometry of components, to meet the requirements without greatly changing the materials. Stiffeners in the aeronautical industry are a well-known example, but the same strategies exist for the design of heat exchangers, or even microelectronics circuits. This strategy aims at distributing matter in a purposely heterogeneous and controlled manner at the level of the component. The strategy that this viewpoint set illustrates, “architected materials”, sits at the intermediate scale: developing either geometries or the association of materials, or microstructure gradients, at scales which are comparable to the scale of the component [Figure 2](#). The result of this evolution is that the classical distinc-

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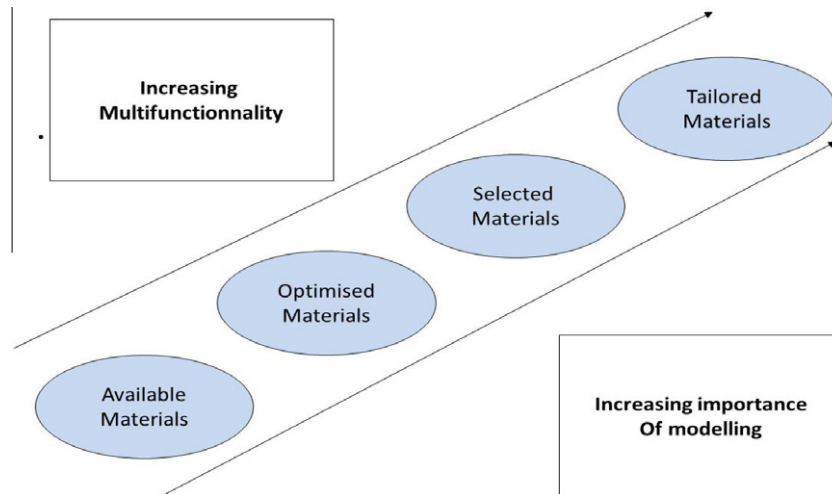


Figure 1. Evolution of strategies for materials development.

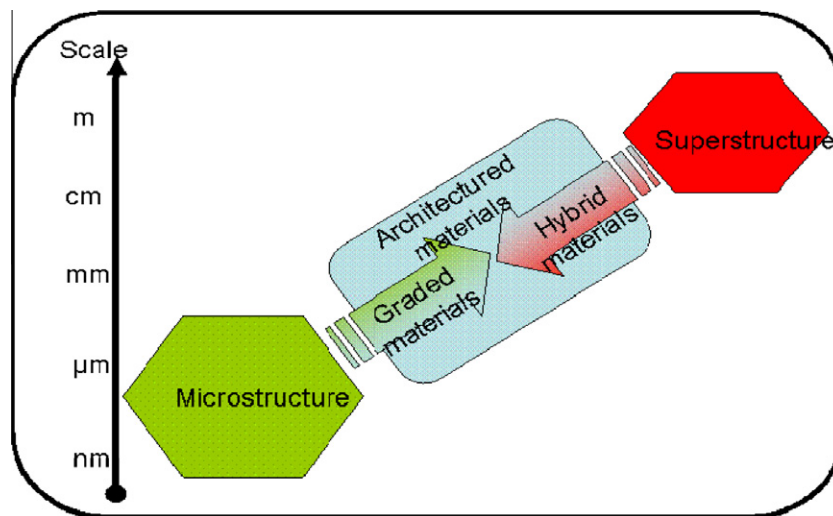


Figure 2. Architected materials and length scales.

tion between “materials” and “structures” becomes blurred; the classical strategy of aiming at a homogeneous material is no longer operative, and the classical modelling tools always aiming at “homogenization” need to be adapted. The architected materials are not totally new (all the surface-hardening techniques may be seen as examples of graded materials, and foams are clearly architected materials) but the systematic use of a defined strategy to fulfil the conflicting requirements for niche applications is an emerging trend in materials science which needs to be brought to the attention of the general materials community. It is worth noticing (and this point is well illustrated in Ref. [3]) that the combination of microstructure gradients and well-controlled architecture is ubiquitous in natural materials and that the development of this strategy has a lot to learn from biomimetics approaches [3].

Architected materials often require the provision of either multiple length scales in the structure at both the microscopic and mesoscopic level or a controlled spatial distribution of the constituent phases. Thus the develop-

ment of architected materials produces an important paradigm shift in materials engineering because it targets the development of tailored heterogeneous materials and changes as summarized in Figure 3 (a diagram comparing the usual structure–properties–processing triangle with one linking defined engineering objective to tailored structures to new processing routes).

Thus the production of tailored heterogeneous materials requires the development of new processing routes or important changes to conventional routes.

A number of the papers in this viewpoint set illustrate the important changes which can be made by modifying existing processing routes. The work of Lloyd [4] uses the development of the fusion process to illustrate how co-casting of two different alloys can produce valuable changes in the forming by bending operations. Similarly the paper by Ciccioria [5] shows the potential for expanding the conventional gas decarburization reactions to non-isothermal situations combined with masking techniques to develop spatially controlled mixtures of hard and soft phases in a variety of steels.

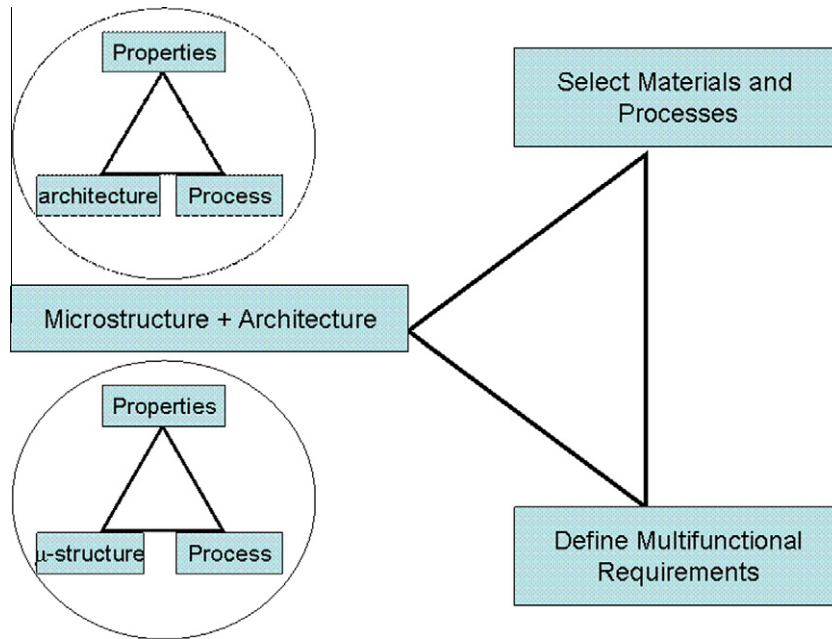


Figure 3. Designing architected materials.

The production of controlled architectures can often be accomplished by the combination of deformation and phase transitions in a given processing route. Some existing processing routes, such as the concept of austempering in steels [6], can be modified to produce materials with gradients of structure and properties.

However, new processes such as the surface deformation process discussed by Wang et al. [7] use non-uniform plastic deformation of materials of low stacking fault energy to produce a range of new structures in which exciting combinations of strength and ductility can be achieved.

These types of localized deformation process can be combined with a variety of electrodeposition processes or pre-assembled structures to provide new processing routes.

The paper by Bouaziz [8] outlines a new approach to the development of architected materials by utilizing not only the intrinsic structure of the material itself but also its geometric form to provide work-hardening capacity and toughness.

Thus in summary we can see that varying the architecture of materials provides an exciting new pathway to linking the overall structure of materials to design needs and that an essential part of this development will be the use of innovative new processing routes linked directly to the control of the spatial variations of structure and properties. A number of examples using combinations of matter and voids, and a variety of porous struc-

tures (trusses [9], felts [10], hollow sphere stackings [11], foams [12]) provide structures for a variety of possible multifunctional applications such as electromagnetic damping [13]. It is not the aim of this viewpoint set to be exhaustive (see other examples in Ref. [14]), but we hope to bring to the attention of the community an expanding field in which many new and innovative approaches are developing.

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