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Multifunctional Material Systems: A state-of-the-art review

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ABSTRACT

An increase in system-level efficiency and multifunctionality of products and components is one of the main advantages of the use of some novel polyvalent materials and structures. This polyvalence or multifunctionality is currently a hot topic in science and engineering circles and is gathering more and more attention. Presently, this multifunctionality can be achieved by stimuli responsive materials such as temperature, stress and light, by using shape memory materials, by using surface structures with anti-biofouling and drag reduction capabilities, among many others. In this article, an overview of the topic is presented, including state-of-the-art review and future directions to increase innovation in developing both these materials and structures.

1. Introduction

Multifunctional Material Systems (MFMS) approach the concept of ideality by being more autonomous and polyvalent than their counterpart monofunctionals. This concept of material system is being introduced in order to simplify nomenclature, and will be further explained in the following chapter, Nomenclature I, but now the reader only needs to know it refers to either materials, composites, structures or a mix of either.

An electrically conductive material eliminates the need for wires, a shape morphing material may eliminate the need for actuators, a flame retardant material eliminates the need for severe fire protection mechanisms, a renewable material minimizes the need for continuing of extraction of raw materials, and of course a combination of these eliminates the need for all of those and maybe some more, because many times the combination of materials can result in new functions not present in either of the single materials by themselves.

The use of MFMS will, and in some cases already do, allow savings in number of parts, reducing the need for joining operations. An effective integration should be able to eliminate traditional boards, connectors, bulky cables yielding major weight and volume savings (Fig. 1) increasing system-level efficiency. They should also be vastly more tailorable to the application than current unifunctional materials, because of the wide range of combinations of materials and resulting properties and functions.

An example of the potential advantages of the use of MFMS can be seen, for example, in electric-propelled unmanned air vehicles (UAVs).

The equation below [1] shows that a decrease in the weight of the aircraft increases by 1.5 times the flight time whereas an increase in battery capacity only increases the same variable by a factor of 1. This supports the notion of combining battery with structural parts in order to increase flight time.

$$\frac{\Delta t_E}{t_E} = 1\frac{\Delta(E_B\eta_B)}{E_B\eta_B} - 1.5\frac{(\Delta W_S + \Delta W_B)}{W_S + W_B}$$

t_E = flight endurance time
E_B = nominal stored battery energy
η_B = efficiency factor of the battery that accounts for the influence of the current draw rate, temperature, etc., on the amount of energy that can be extracted from the battery
W_S = weight of the aircraft structure
W_B = weight of the battery

Besides system performance, the reduction in costs, at least in the post-production phase, these composites could bring also something that should be taken into consideration (Fig. 2).

Below is a detailed explanation for each component of the above figure.

- Raw material:
  - o It is to be expected that in most cases different materials will be used in a MFMS, because that's easier than to find a MFM that performs all the desired functions. On the other hand, there are several hierarchical MS being developed, as

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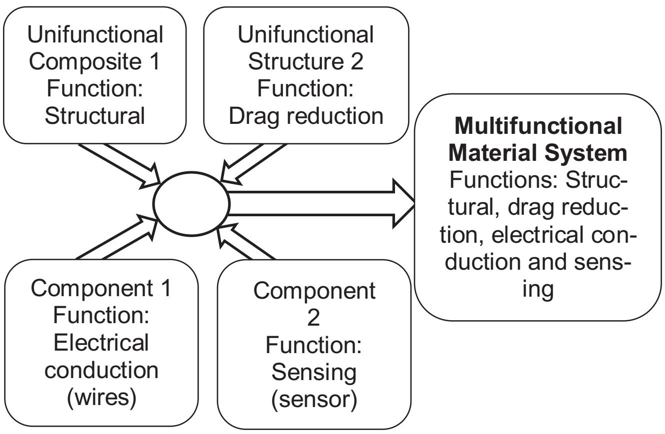

Fig. 1. A multifunctional material system should integrate in itself the functions of two or more different components and/or composites/materials/structures increasing the total system's efficiency.

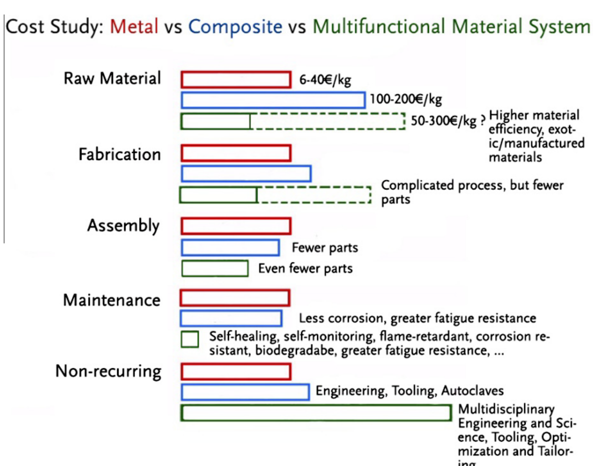

Fig. 2. Cost study: Metal vs Composite vs Multifunctional Composite.

we will see, that increase material efficiency, thus using less material to achieve a greater performance. It is then unclear where would MFMSs stand in terms of raw material costs. Some may be cheaper others may be more expensive than current materials, but either way, for the same price it is expected that the performance for each function will increase, so the value will tend to get better.

- Fabrication:
  - o Currently manufacturing is one the greatest challenges in the production of MFMS, and many methods used are expensive and haven't been transferred to industry because of difficulty in achieving scalability. It is to be expected that these issues eventually subside, but still, since MFMS are of higher complexity than monofunctional ones, it might be the case that their production will also be more expensive and require more expensive tooling. On the other hand, with the increasingly improving 3D-printing technology some of those difficulties may significantly reduce.
- Assembly:
  - o Assembly should be a clear winner for MFMS. Shape morphing technologies and multifunctionality reduce the number of articulated and external components, which in turn reduce the number of parts and joining complexity. For example, if one part made of a MFMS can do functions that used to need 5 different materials/parts, then it's a 5-fold decrease in joining operations.
- Maintenance:
  - o Maintenance is the area where MFMS should shine the most. Because of their increasingly autonomous status, sel f-healing/sensing/regulating (homeostasis)/etc., the need for human control should gradually decrease, and therefore so should maintenance costs.
- Non-recurring:
  - o The fact that MFMS require an extensive knowledge often from a wide range of fields, has to have some impact in the final cost of the material. The design phase needs to integrate engineers from several fields as the material itself will satisfy the requirements of several functions of different schools: electrical, mechanical, biological, environmental, chemical, etc. Simulation software and material databases should get more complex because of this reason.

1.1. Nomenclature I

Recently, there has been a surge in a new class of materials and structures that have as their defining factor the fact that they are able to perform several functions. Traditionally this doesn't happen. Some are used for their structural properties, others are used for their electrically conducting properties, others for their semiconducting ability and so on. But rarely were there materials and structures used for the combination of those. The promise that these hold have gradually and increasingly come to the attention of the scientific community (Fig. 3).

As the number of people working in a field increases so does the need for clarification. By reading several articles and reviews it quickly becomes clear that many terms are used interchangeably with slightly different meanings. For example, the term "smart material" is a very lose term whose meaning varies significantly from author to author. As time goes on, and as these materials, composites and structures gain mainstream acceptance, there will be need for a defined nomenclature to develop. Hereby a few suggestions that might be useful are presented.

Multifunctional materials (MFM), Multifunctional composites (*MFC*) and multifunctional structures (MFS), will here be group into a broader group named Multifunctional Material Systems (MFMS).

The definition of material systems (MS) in this context encompasses materials, composites and structures (Fig. 4). The necessity for this definition arose because one could have, for example, a monofunctional ceramic with a textured surface and an internal structure of a nanolattice. It wouldn't be correct to call it a MFM because the multifunctionality arises both from the material and the structure. An example of a MFM would be Carbon Nanotubes (CNTs) which inherently have high mechanical strength and electrical conductivity or PZT which can provide both sensing and actuation. An example of a *MFC* would be epoxy/CF-(Fe powder) (mechanical strength and electrical conductivity), and an example of a MFS would be shark denticles which provide anti-bioufouling and reduce drag. The definition of MFMS, then, encompasses all of these.

Another clarification to make is defining exactly what constitutes multifunctionality. Some authors consider materials with multiple structural functions (e.g. damping and toughness) to be multifunctional, and dividing the functions in two groups: structural and non-structural [2,3] while others treat structural functions like any other [4]. We see no reason why structural functions should be treated differently. Otherwise one might also divide functions as electrical and non-electrical, or biological and non-biological since there are also a lot of electrical and biological