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Research review paper

Functionally graded materials for orthopedic applications – an update on design and manufacturing

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A B S T R A C T

Functionally graded materials (FGMs) are innovative materials whose composition and/or microstructure gradually vary in space according to a designed law. As a result, also the properties gradually vary in space, so as to meet specific non-homogeneous service requirements without any abrupt interface at the macroscale. FGMs are emerging materials for orthopedic prostheses, since the functional gradient can be adapted to reproduce the local properties of the original bone, which helps to minimize the stress shielding effect and, at the same time, to reduce the shear stress between the implant and the surrounding bone tissue, two critical prerequisites for a longer lifespan of the graft. After a brief introduction to the origin of the FGM concept, the review surveys some representative examples of graded systems which are present in nature and, in particular, in the human body, with a focus on bone tissue. Then the rationale for using FGMs in orthopedic devices is discussed more in detail, taking into account both biological and biomechanical requirements. The core of the paper is dedicated to two fundamental topics, which are essential to benefit from the use of FGMs for orthopedic applications, namely (1) the computational tools for materials design and geometry optimization, and (2) the manufacturing techniques currently available to produce FGM-based grafts. This second part, in its turn, is structured to consider the production of functionally graded coatings (FGCs), of functionally graded 3D parts, and of special devices with a gradient in porosity (functionally graded scaffolds). The inspection of the literature on the argument clearly shows that the integration of design and manufacturing remains a critical step to overpass in order to achieve effective FGM-based implants.

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1. Introduction: a brief history of functionally graded materials

A functionally graded material (FGM) is a special material, usually a composite, whose composition and/or microstructure vary smoothly in space according to a designed law. Due to the gradual change in composition, also the FGM properties (physical, mechanical, biochemical, etc.) vary in space to meet the specific requirements for a given application (Birman and Byrd, 2007; Kawasaki and Watanabe, 1997). For example, it is possible to couple a strong material, such as alumina, on one side of a device and a bioactive material, such as bioglass, on the other side, as exemplified in Fig. 1. However, the absence of any abrupt interface greatly contributes to the system's reliability.

The constituent phases of an FGM are usually defined as “elements” or preferably as “material ingredients” (Miyamoto et al., 1999). In the simplest case, two material ingredients change from one to the other along one spatial direction, as already seen in Fig. 1; nevertheless, some applications may also require a functional gradient along two or even three different directions (Jackson et al., 1999).

Even if the most common idea of FGM implies that two different constituent phases change gradually from one to the other (for example, from ceramic to metal), FGMs include all those functional materials whose properties change locally according to a specific design, arbitrarily introduced to fit an intended application or to enhance a wide variety of properties, especially the mechanical ones (Miyamoto et al., 1999; Rabin and Shiota, 1995). As a matter of fact, if appropriately designed, the presence of a functional gradient at the microscale may result in improved properties at the macroscale (Wu et al., 2014). For instance, as proved by Suresh and co-workers in various contributions, the damage and failure resistance to normal and sliding contact or to impact can be changed substantially by means of a controlled gradient in elastic properties at the contact surface (Jitcharoen et al., 1998; Suresh, 2001; Suresh et al., 1999).

Some pioneering contributions revealed the potentialities of graded materials already in 1972, when Bever and Duwez (1972) considered various composites with graded compositions, and Shen and Bever (1972) analyzed graded polymers. However, the first explicit formulation of the FGM concept dates back to the end of the ’80s, when it was introduced in Japan to describe new thermal barrier coatings, thanks to the research project “Fundamental Studies on the Relaxation of Thermal Stress by Tailoring Graded Structures” (Koizumi and Niino, 1995). That was the first systematic description of FGMs as special materials with a compositional and functional gradient arbitrarily designed to meet non-homogeneous service requirements.

2. Graded materials in nature and the human body

Apart from the technological definition, it is interesting to note that graded materials are quite common in nature (a futuristic – as well as artistic – reading of natural multifunctional composites is provided by the new material method advocated by Neri Oxman at M.I.T., Boston (MA) (Oxman, 2010; Oxman, 2014)). Some examples of natural graded systems are bamboo structures (Amada, 1995; Low and Che, 2006; Nogata and Takahashi, 1995; Silva et al., 2006), mollusk shells, with their hierarchical architecture and related graded ligaments (Chateigner et al., 2000; Kaplan, 1998; Moshe-Drezner et al., 2010; Ritchie, 2014; Ono, 1995), the exoskeleton of arthropods, that is a

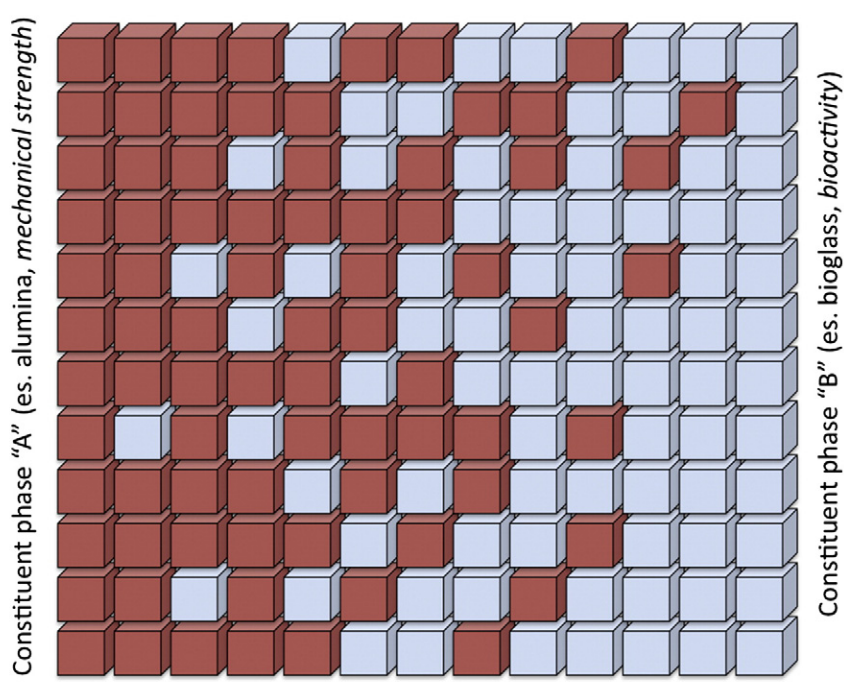

Fig. 1. Schematic representation of a FGM that combines a constituent phase “A” (for example, alumina, which provides mechanical strength) and a constituent phase “B” (for example, bioglass, which provides bioactivity) with a gradual change in composition and no abrupt interfaces.