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Fracture characterization of continuous fibre-reinforced polymer matrix composite laminates by Nuclear Magnetic Resonance

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Abstract

In vitro results obtained from Nuclear Magnetic Resonance Imaging (NMRI) of Continuous Fibre-Reinforced Polymer (CFRP) matrix composite laminates, which had been previously damaged and subsequently immersed in simulated body fluid are provided in this work. Irrefutable evidences are given in regard to the NMRI technique's ability to detect and fully characterize two different fracture types, namely translaminar and delamination, in two distinct classes of solid composites, namely with thermosetting and thermoplastic matrices reinforced with carbon fibers. The study lays and establishes solid foundation for *in vivo* application of this nondestructive, noninvasive, painless, reliable, non-lethal radiation and fast technique in determining the degree of structural integrity of technologically advanced orthopaedic implants. Furthermore, the residual life estimation and the lifetime extension of human orthopaedic implants are also envisioned by means of this technique.

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Keywords: Damage and defect; human orthopaedic implant; nondestructive inspection; nuclear magnetic resonance imaging; polymer matrix fibrous composite.

1. Introduction

1.1. Initial considerations

The existence of nondestructive and noninvasive techniques for *in vivo* determination of the structural integrity of human orthopaedic implants made with lightweight composite biomaterials exhibiting outstanding structural efficiency is almost inexistent. In fact, only an acoustic wave-based technique has been proposed by Yang *et al.*

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(2012) for this purpose. The availability of new nondestructive, noninvasive, painless, reliable, non-lethal radiation and faster techniques based on high-definition imaging for periodic monitoring of the integrity state of technologically advanced human implants would therefore be highly desirable. The possibilities to estimate the residual life of the implant, as well as to extend its service lifetime in the most favourable cases would bring extraordinary benefits to the patients in terms of their quality of life and the cost reductions associated to postponing, or even avoiding surgeries to replace the implanted element. Even in situations where additional surgery to repair or replace the implant is inevitable, the existence and utilization of a real-time, imaging-based nondestructive examination technique would afford the surgeon with fundamental information in order to establish the best surgical strategy well before the medical procedure begins.

1.2 Biocompatibility

Biocompatibility is the ability displayed by a material implanted in a living body to perform its function without inducing immune response in the host tissue. In this sense, the biomaterials are in principle able to stay in direct and constant contact with human tissues without causing local or systemic damage, and fully execute its therapeutic purpose. As stated by Purohit *et al*. (2012) and Williams (2008), an important aspect of biocompatibility of implanted materials is their capability to provide support to the appropriate cellular activity, including the facilitation of molecular and mechanical systems to effectively assist the process of regeneration of soft and hard tissues.

1.3 Structural osseointegrated implants in humans

Increased life expectancy of the human population and the number of victims of traumatic incidents has boosted the need for advanced materials for use in devices (implants) capable of directing, complementing or replacing the functionality of human living tissues, especially for orthopaedic deals. As noted by Purohit *et al*. (2012) and Ramakrishna *et al*. (2001), some implants are made from natural, skin, bone or other body tissue; others are artificial and made of metals and alloys, polymers, ceramics or composites. The successful modelling and mechanical testing of fourth-generation composite femur and tibia models by Gardner *et al*. (2010) indicate that full artificial bones with performance equivalent, or even superior to the natural ones might be on the corner. However, even considering the tremendous advances in biomedical engineering related to the conception and design of medical devices, as well as in regard to the implantation techniques in the human body, implants can move, damage, fracture and therefore stop working properly. Strictly speaking, so far no structural implant displays infinite durability if one considers the very aggressive environment in which it operates and the severe mechanical functions that it invariably performs.

1.4 Fibrous polymer matrix composite implants

According to Lee (1995) engineered composites are rationalized multiphase materials formed from a combination of two or more materials which are not soluble in each other, differ in composition and/or form, remain bonded together, retain their identities and properties, and preserve well defined interfaces among the components, which act in concert to provide improved specific or synergic characteristics and properties not obtainable by any of the original materials performing alone. Composite biomaterials are quite compelling options in the replacement of human tissues, particularly those exhibiting excellent biocompatibility and a wide range of physicochemical and mechanical properties to suit each specific case. Particularly, high performance Continuous Fibre-Reinforced-Polymer (CFRP) matrix composites exhibit the following advantages compared to its competitors in biomedical applications: very low density, very high specific stiffness and mechanical strength (i.e., property by unit mass), low probability of failure by catastrophic fracture and remarkable design flexibility to perfectly suit the mechanical loads experienced in service. Moreover, Shellock (2002) emphasizes that high-performance CFRP biocomposites are intrinsically non-magnetic, thereby in principle (since electrical conductivity might be a serious issue) enabling patients to be examined and imaged without any risk in Nuclear Magnetic Resonance (NMR) equipments typically employing magnetic fields of 3 Tesla. Rodríguez-González (2009) points out that synthetic composite materials, notably those produced from fibre-reinforced thermosetting polymer matrix composites have given rise to unparalleled orthopaedic implants devised to osteosynthesis, which aims to bring the fractured bone ends together