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Composite based on polyetheretherketone reinforced with carbon fibres, an alternative to conventional materials for femoral implant: Manufacturing process and resulting structural behaviour

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ABSTRACT

Composite stems obtained by injection moulding of polyetheretherketone reinforced with carbon fibres (CF/PEEK) can concurrence metallic ones in total hip replacement. By the combination of process simulations and structural analysis, different compositions of CF/PEEK and injection conditions are explored. The resulting implants are compared to the bone alone and the bone-implant system based on conventional metallic materials, under walking load. Comparisons are done through four objective criteria: stress shielding, stress deficiency, debonding and global deformation. CF/PEEK injected implant presents very good results.

1. Introduction

Total hip replacement (THR) is a surgical operation where a damaged hip joint is replaced with prosthesis. The number of THRs increases constantly: in the 1980s the annual number of total hip arthroplasty was estimated to 170,000 in the USA and 300,000 worldwide [1].

Conventional materials used for the femoral shaft and neck in THRs are Stainless Steel (316L), Co–Cr and Ti alloys. But these materials present an important difference of stiffness with the femur bone that can induce stress shielding effect in the bone. As a result the bone remodelling process can be affected leading to bone resorption and eventually aseptic loosening of the prosthesis [2–4].

Implant loosening can be reduced through improvements in the prosthesis design [5] but also through the use of new materials with mechanical properties close to the ones of bone. Biocompatible polymer matrix composites are then interesting candidates for THR [2,6–11].

Stress shielding is generally in competition with micro-motions between the bone and the stem. Too low stiffness for the implant can increase these micro-motions, not to mention pains cause to the patient. Composite implants based on PEEK polymer matrix reinforced with carbon fibres have been designed and realised by injection moulding. The first clinical tests on animals have shown a good mechanical stability of such prosthesis [2]. A clinical test on a 55-year-old man is reported in [13]; unfortunately, a car accident 21 months after the operation stopped the experiment.

In the present paper, numerical investigations on CF/PEEK artificial hip joint realised by injection moulding are proposed. Particularly the influence of the manufacturing process on the structural behaviour of the implant is studied. Furthermore comparisons with conventional metallic prosthesis are proposed.

Section 2 presents the environment of the work. The material and the CAD model for the implant are specified. Simulations of injection moulding and structural analysis of the prosthesis are described. A method for linking the two finite element programmes, in order to take into account the potential influence of the process on the functional behaviour, is proposed. The approach is checked on a standard test where numerical predictions and experimental measures are compared.

In Section 3, the procedure is applied to the final stance of horizontal walking loading conditions where the different (CF/PEEK, 316L, Ti and Cr–Co alloys-made) implants are evaluated.

2. Material and material models

2.1. Material and CAD model for implant

The selected material for the implant is a CF/PEEK composite. It has been chosen for its mechanical properties close to bone, its

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Table 1
The three CF/PEEK composites used in the study.

Name	Volume fraction in carbon fibres (%)
Composite 1	15
Composite 2	20
Composite 3	30

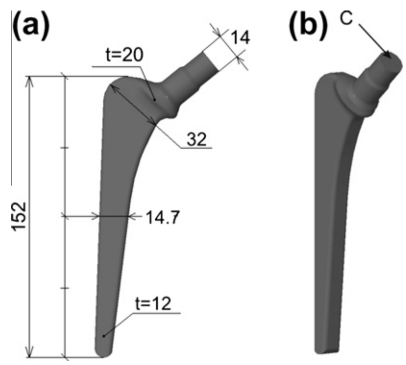

Fig. 1. The Echelon model proposed by Smith & Nephew for the hip implant (a) geometry and dimensions and (b) 3D CAD model.

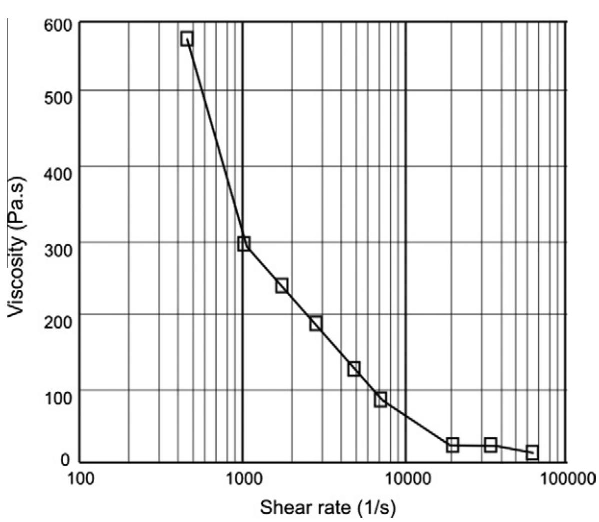

Fig. 2. Experimental viscosity-shear rate curve for a CF/PEEK 30 wt.% obtained for an injection temperature of 400 °C and a nozzle temperature of 180 °C.

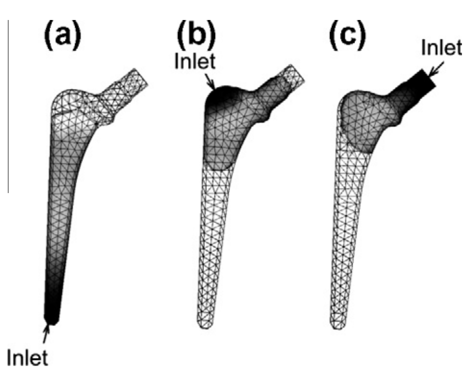

Fig. 3. The three inlet locations investigated for injection moulding simulations.

biocompatibility, its environmental stability, its excellent chemical resistance, its wear performances and its resistance to repeated sterilization by gamma radiations and steam [12,14].

This composite can be formed by injection moulding which is an interesting production process for mass production. Injection moulding is a repeatable process and a low cost process for a thousand batch production. Furthermore it is already largely used for producing numerous components for medical devices.

Composites prosthesis present the advantage to be tailored in such a manner that it is possible to optimise stress distribution in the bone when implanted. With CF/PEEK material, one can question about the possibility to find the right fibre volume fraction and the best fibres orientations and repartitions leading to an interesting compromise between stress shielding and micromotion for femoral implant application [12,15].

Then three types of CF/PEEK composites with different weight fractions of carbon fibres, named Composite 1, 2 and 3, are considered (Table 1). The variation in fibre orientation will be obtained with different conditions of injection moulding that is described later.

For the present investigation the chosen implant geometry is based on the Echelon model proposed by Smith & Nephew [16]. The simplified 3D CAD model for the implant used in the following is illustrated in Fig. 1.

2.2. Injection moulding simulation

Simulations of implant injection moulding are carried out using Moldflow Plastic Insight© (MPI©) software. The main results are the fibres orientation and distribution in the prosthesis that will be used for evaluating its anisotropic elastic properties for later use in structural analysis.

Table 2
Parameters used in injection moulding simulations.

Mesh characteristics	22,051 2D elements (tetrahedral 4-nodes element) 3832 nodes
Mould temperature	170 °C
Injection temperature	395 °C
Injection time	1 s
Mould material	TOOL STEEL P-20
Injected material	Poly-ether-ether-ketone (PEEK) with 30 wt.% high-modulus carbon fibres (from LNP Plastics)
Viscosity law	See Fig. 2

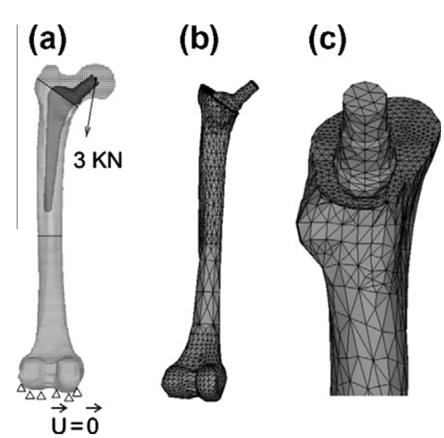

Fig. 4. The FE model for the structural analysis with ANSYS©: (a) boundary conditions in effort and displacement, (b) the 3D solid model, and (c) detail of the 3D solid model.