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Porous Ti_6Al_4V scaffold directly fabricating by rapid prototyping: Preparation and in vitro experiment

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Abstract

Three-dimensional (3D) fiber deposition (3DF), a rapid prototyping technology, was successfully directly applied to produce novel 3D porous Ti_6Al_4V scaffolds with fully interconnected porous networks and highly controllable porosity and pore size. A key feature of this technology is the 3D computer-controlled fiber depositing of Ti_6Al_4V slurry at room temperature to produce a scaffold, consisting of layers of directionally aligned Ti_6Al_4V fibers. In this study, the Ti_6Al_4V slurry was developed for the 3D fiber depositing process, and the parameters of 3D fiber depositing were optimized. The experimental results show how the parameters influence the structure of porous scaffold. The potential of this rapid prototyping 3DF system for fabricating 3D Ti_6Al_4V scaffolds with regular and reproducible architecture meeting the requirements of tissue engineering and orthopedic implants is demonstrated.

Keywords: Titanium alloy; Porosity; Scaffold; Rapid prototyping-three-dimensional fiber deposition

1. Introduction

Scaffolds are of great importance for tissue engineering and orthopedic implants because they enable to provide biological anchorage for the surrounding bony tissue via the ingrowth of mineralized tissue into the pore space [1]. These scaffolds require a specific external shape and a well-defined internal structure with interconnectivity [1–3]. Recently, porous ceramics and polymers have been extensively studied to promote bone or tissue ingrowth into pores [4–9]. However, ceramics and polymers are not very strong and can easily transform [10,11], they are less appropriate in load-bearing applications, such as in spinal interbody fusion. Therefore, metals like titanium and its alloys are widely used for orthopedic and dental implants [12]. They possess low density, good mechanical properties (elastic modulus, toughness, and fatigue strength) and biological and chemical inertness. Recently, there has been an increasing interest in fabricating porous titanium scaffold for bone tissue engineering [13–15]. Porous titanium and its alloys have been used in dental and orthopedic applications since the end of 1960s [16–18]. Many available methods for producing porous titanium and titanium alloy scaffolds include sintering together of the particles [19] or plasma spraying of the powder on a dense substrate followed by the cutting of the porous layer [20], compressing and sintering of titanium fibers [21,22], solid-state foaming by expansion of argon-filled pores [23] and polymeric sponge replication [24]. However, none of these conventional techniques has allowed for building scaffolds with a completely controlled design of the external shape as well as of the interconnected pore network. The imperfection of the conventional techniques has encouraged the use of a rapid prototyping (RP) technology [25]. Since 1980s RP technologies have emerged

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as a revolutionary manufacturing process with inherent capability to rapidly make objects in virtually any shape. RP, combining computer-aided design (CAD) with computer-aided manufacturing (CAM), has the distinct advantage of being able to build objects with predefined microstructure and macrostructure [26,27]. This distinct advantage gives RP the potential for making scaffolds or orthopedic implants with controlled hierarchical structures [28–33]. Until now RP developments mainly focused on polymer and ceramic materials [34–39]. The transfer of RP technologies to metal materials for tissue engineering and orthopedic implants possesses a significant challenge. There are few investigators on making metal scaffold for orthopedic and tissue engineering application by rapid prototyping techniques [3,40,41]. Two methods were applied to make metal scaffold. One is indirect to make porous scaffolds by invest casting melt metal or metal powder slurry into a mold where the mold was made using RP [40–42], in addition to indirect processing, other researchers have been developing porous titanium scaffolds for tissue engineering using direct metal deposition [3,43,44].

Here, we report the first example of RP Ti_6Al_4V scaffold with self-supporting features fabricated directly by 3D fiber deposition. In this paper, we investigated the design and fabrication of 3D Ti_6Al_4V scaffolds and performed in vitro studies to assess cell attachment, cell proliferation and differentiation of the scaffolds.

2. Materials and methods

2.1. Materials

- Ti_6Al_4V powders with a mean particle diameter of 45 μm (Bongen Titanium (China) Co, ltd) were used in this study. The particles are spherical in shape.
- Methylcellulose (MC, Fisher Scientific B.V) and stearic acid (Acros organics, USA) were used as binder and dispersant.

2.2. Methods

2.2.1. Preparation of the Ti_6Al_4V slurry

The Ti_6Al_4V slurry was prepared as follows: The Ti_6Al_4V powder (66 vol%) was mixed with an aqueous solution of methylcellulose and stearic acid (34 vol%). The slurry was stirred for 1 h at room temperature (RT) to obtain homogenous slurry.

The concentration of the Ti_6Al_4V powder in the slurries has influence on the viscosity of the slurry. The effect of powder concentration was studied by utilizing the slurries with Ti_6Al_4V powder concentrations ranging from 64 to 68 vol%. A powder concentration of 66 vol% was used for most studies unless otherwise specified.

2.2.2. 3D fiber deposition

As a 3D fiber depositing device, the "Bioplotter" was used, which has been reported by Landers and Mülhaupt [45,46]. Fig. 1A shows the system, consisting of: (1) a Ti_6Al_4V slurry dispensing unit consisting of a syringe and nozzle; (2) air pressure plunger to regulate flow of slurry; (3) positional control unit linked to a personal computer containing software (PrimCAM) for generating fiber deposition paths.

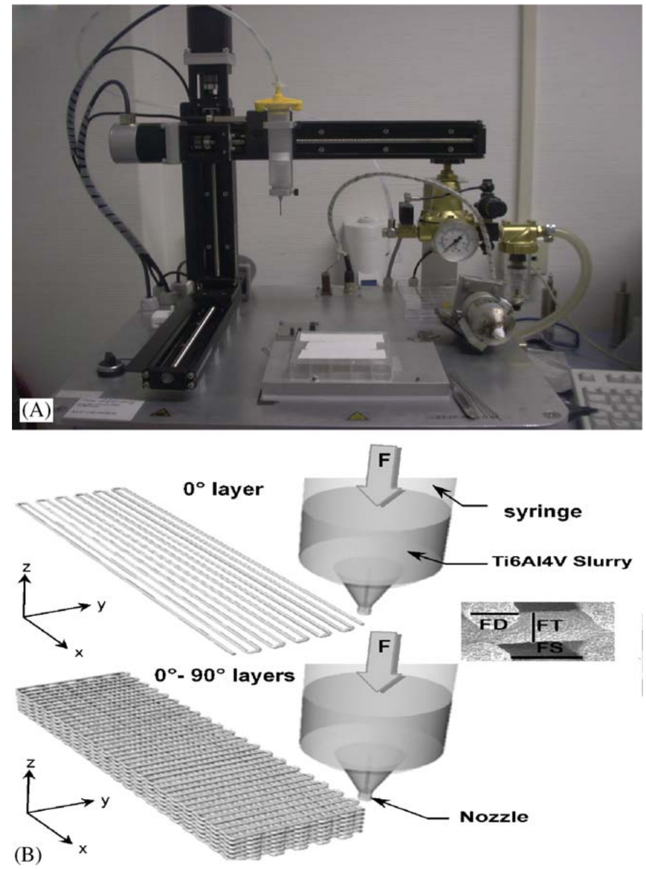

Fig. 1. 3D fiber depositing system. (A) 3D fiber depositing system, (B) 3D fiber depositing scaffold process.

2.2.3. Scaffold development

The Ti_6Al_4V slurry was placed in a plastic syringe, through a fixation unit mounted on the "Y"-axis of the apparatus and kept at RT. Air pressure (P) was applied to the syringe through a pressurized cap. Rectangular block models were loaded on the Bioplotter CAM software. The process involved depositing continuous fibers of material to produce two-dimensional (2D) layers with alternating 0°/90° lay-down patterns of finite thickness and then building the 3D scaffold up layer-by-layer. Fig. 1B shows the processing of 3D fiber depositing porous Ti_6Al_4V scaffold.

The nozzle used to extrude Ti_6Al_4V slurry fibers is a stainless steel hypodermic needle. The nozzle size is expressed as inner diameter of the nozzle, and a length of 16.1 mm. A nozzle diameter of 400 μm was used for most studies unless otherwise specified. For all the experiments addressed, fiber spacing was set to 0.5 mm to create pore size around 400 μm since pore size around this range assure a rich blood supply, nutrient and waste exchange and promote in growth of bone [47–49], and the thickness between fiber layers was kept at 0.35 mm which is about 0.85* nozzle size as discussed previously [46].

After fiber depositing the samples were first dried for 24 h at RT, then dried for 24 h at 50 °C, and finally sintered in a high vacuum furnace (10^{-5} mbar) applying a heating profile as follows:

$$\text{RT } 600\text{ min} \rightarrow 500\,^{\circ}\text{C } 450\text{ min} \rightarrow 1250\,^{\circ}\text{C } 120\text{ min} \rightarrow 1250\,^{\circ}\text{C furnace cooling} \rightarrow 25\,^{\circ}\text{C}.$$

2.2.4. Optimization of 3D fiber depositing parameters for fabrication scaffold

The principle of 3D fiber deposition is similar to that of fused deposition modeling (FDM). Many groups have applied FDM to fabricate scaffold for tissue engineering [10,50–52]. The optimized FDM