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Bioactive glass nanofibers produced by Laser Spinning for biomedical applications

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Abstract

The Laser Spinning technique was employed to produce long, dense and flexible glass nanofibers with different bioactive compositions. Laser Spinning is a novel technique that allows the rapid and scalable production of high quantity of glass nanofibers under ambient conditions. The bioactive glass nanofibers have potential utility as reinforcement in composites, fillers in bone defects or scaffolds for tissue engineering. The morphology and structure of these nanofibers was analyzed using SEM, XRF, NMR, TEM and ATR-FTIR. The bioactivity of the glass nanofibers is demonstrated with in-vitro tests. They also present antimicrobial properties against different bacteria. The flexibility of this material, easy of manipulation and sterilization as well as antibacterial properties, made the laser-spinning glass nanofibers an excellent alternative to present granulated material for bone defect restoration and for tissue engineering.

Keywords: Laser Spininng; Nanofibers; Glass.

1. Introduction

Extensive research is been carried out on bioactive materials capable of promoting cell differentiation, proliferation, three-dimensional growth and integration to surrounding bone (Ratner et al., 2004). Selection of the proper geometrical architecture of scaffolds for tissue engineering is essential to achieve mechanical requirements, improve nutrients transport and biofactor delivery. Many investigations demonstrated the importance of nano-scale architectures, surface patterns and stimuli to enhance their performance (Stevens et al., 2005).

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The extracellular matrix in living tissue provides a natural web of intricate nanofibers to support cells and strongly influences changes in cell shape that affect the differentiation process. Therefore nanofibrous structures with controlled architecture have excellent potential to mimic natural extracellular matrix and to be used as scaffolds for tissue growth. A wide variety of works employed the technique of electrospinning to produce polymeric fibrous meshes for tissue scaffolding. At the same time, the potential of bioactive glass fibers as scaffolds for tissue engineering was demonstrated. Two main different techniques were initially employed to produce the glass fibers: spraying (Hatcher et al., 2003) or dry-spinning (Peltola et al., 2001) of a sol-gel precursor or by directly melting the glass and forming it through a platinum bushing (Clupper et al., 2003; Brown et al., 2008; Ahmed et al. 2004). Typical diameters of these fibers range from one micron up to several tens of microns. All of these works concluded that these kinds of scaffolds have the potential to direct and mediate cell growth as tissue engineering constructs in bone regeneration with different degrees of bioactivity depending on the composition, microstructure and surface features.

With these perspectives, the Laser Spinning technique was employed to produce nanofibers of 45S5 Bioglass® for the first time (Quintero et al., 2009a). Laser Spinning is a novel technique which yields a great quantity of free-standing fibers in the form of a mesh of disordered intertwined nanofibers. In this work, we present the advances in the production of bioactive glass nanofibers with different compositions using this novel technique.

2. The Laser Spinning Technique

The process of Laser Spinning involves the quick heating and melting up to high temperatures of a small volume of the precursor material using a high power laser under ambient conditions. The plate of the precursor material being irradiated is in relative motion with regard to the laser beam. The rapid melting combined with the continuous motion generates a stable molten volume advancing through the solid plate, which produces a complete or incomplete cut. At the same time, a supersonic gas jet drags the molten material down to the bottom of the cut. The viscous material reaching the bottom edge of the cut forms a pending viscous droplet which is further propelled by the gas jet. Thus, the molten material forms glass fibers as a result of its viscous elongation by the drag force and rapid cooling by the convective heat transfer promoted by the gas jet. Figure 1 shows a schematic representation of the process.

The laser is operated in continuous wave mode emitting the radiant power necessary to melt the plate of precursor material, therefore a high power laser is employed. The type of laser depends on the absorbance of the material to be processed. The CO_2 laser radiation is highly absorbed in all materials mentioned in the present case, this is the kind of laser most suitable. The laser beam is focused some millimeters over the sample, so that the cut produced is typically 3 or 4 mm width, thus a suitable volume of molten material is achieved and the gas jet can penetrate completely the whole thickness. Detailed discussion on the influence of different process operation conditions was presented in a previous work (Quintero et al., 2009b).

The gas jet employed is usually compressed air, since no chemical reactions are involved in the process and this is the most easily available gas that doesn't react with any of the materials processed. The jet of compressed air is injected on the molten volume at high pressure using a supersonic nozzle in order to supply a high speed gas jet which produces a quick elongation and cooling of the fluid filament.

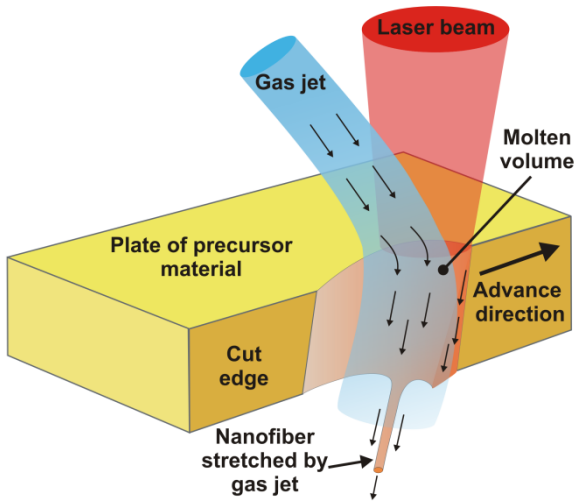


Figure 1. Schematic representation of the Laser Spinning process.

The precursor material employed is a solid plate with a thickness between 4 and 10 mm. Several compositions of bioactive glasses have been successfully processed to produce glass nanofibers. In any case, the composition of the fibers closely reproduces that of the precursor material.

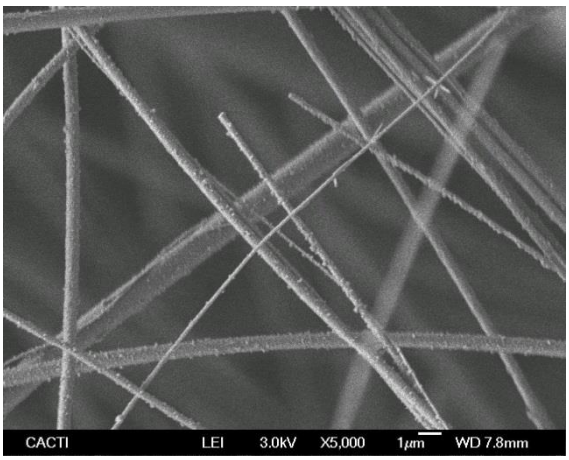
3. Production of bioactive glass nanofibers

Several compositions of different bioactive glasses were successfully processed. Table 1 shows the denomination and composition of the most significant examples.

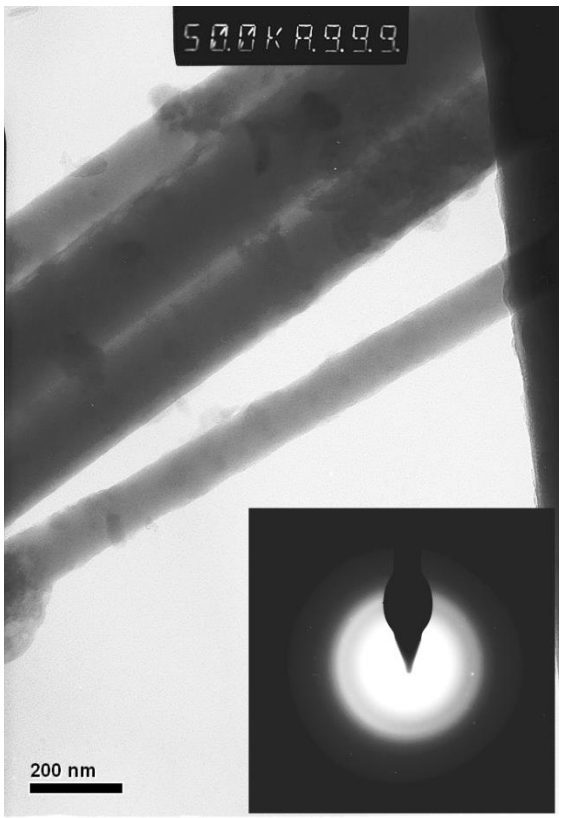
Table 1. Compositions of the bioactive glass nanofibers produced (mol%).

Denomination	SiO_2	CaO	Na_2O	P_2O_5	MgO	K_2O	ZnO	SrO	TiO_2
45S5	46.1	26.9	24.4	2.6	–	–	–	–	–
52S4.6	52.1	23.8	21.5	2.6	–	–	–	–	–
ICIE16	49.5	36.3	6.6	1.1	–	6.6	–	–	–
ICIE16M	49.5	27.3	6.6	1.1	3.0	6.6	3.0	3.0	–

The 45S5 Bioglass® and their derived products are the most intensely studied and extensively distributed for clinical use. However, 45S5 glass cannot be easily drawn into fibers due to devitrification that occurs during the fiber drawing process. Notwithstanding, using the Laser Spinning Technique we produced micro- and nanofibers with this composition (Quintero et al., 2009a).



a)



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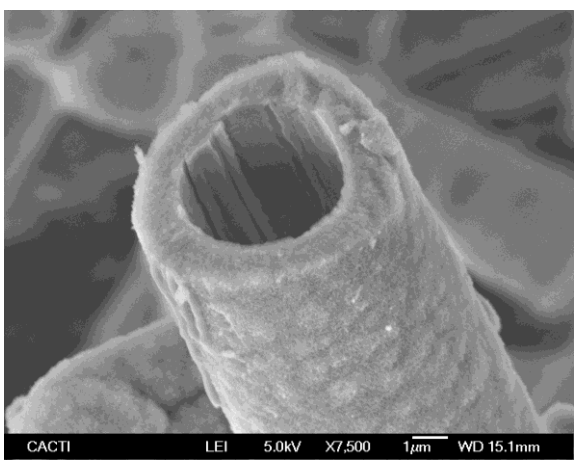

c)

Figure 2.(a) SEM micrograph of the as-produced Bioglass® 45S5 micro- and nanofibers. (b) TEM image of a bundle with several nanofibers with the composition of the Bioglass® 45S5, the inset shows the electron diffraction pattern of one of them revealing its amorphous structure. (c) SEM image of one of the Bioglass® 45S5 fibers after 2 days of immersion in SBF, the glass core of the fiber was completely dissolved and the cladding of hydroxyapatite appears clearly forming a hollow tube.

Analysis of the morphology reveals that the fibers have a high length to diameter ratio with a distinct cylindrical shape and they appear completely separated (Fig. 2.a). The electron diffraction pattern obtained by TEM reveals their amorphous structure (Fig. 2.b). XRF analyses demonstrate that the composition of the fibers maintain the same chemical composition as the precursor glass. MAS-NMR studies probe that there is no other effect on the glass structure of the laser spinning process other than that promoted by the subtle change in composition. These results allow us to predict a minimal influence on the bioactivity of the glass with a substantial effect of the high surface area of the nanofibers. It was investigated by the assessment of their dissolution rate and precipitation of hydroxyapatite (HA) after immersion in Simulated Body Fluid (SBF). Indeed, after incubation times in the order of 5 days their silica network was almost completely dissolved,

most of the fibers appear hollow with an amorphous and porous layer of HA nanocrystals covering the former solid nanofibers (Fig 2.c).

The ICIE16 is also a composition of a soda-lime silicate glass with high calcium content (Elgayar et al., 2005). This composition was also successfully processed by Laser Spinning to produce amorphous nanofibers which demonstrated good biocompatibility and high antibacterial activity (Echezarreta-López et al., 2014). The ICIE16M is a variation of the former composition where calcium was substituted by magnesium, strontium and zinc. The addition of strontium was suggested to increase osteoblast proliferation and inhibits osteoclast-mediated resorption of CaP films (Gentleman et al., 2010). While the addition of small amounts of zinc may increase the antibacterial effect of the bioactive glass. In a recent work, we report the production of glass nanofibers with this precise composition containing strontium and zinc using the Laser Spinning technique (Echezarreta-López et al., to be published).

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