POLY(LACTIC ACID)/HYDROXYAPATITE COMPOSITE FIBRES FOR 3D OSTEOCONDUCTIVE WOVEN SCAFFOLDS

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Abstract
This study presents a method to melt-spun biocompatible composite fibres from poly(lactic acid) (PLA) and nano-sized hydroxyapatite (HAp) particles. Different loading concentrations of HAp particles in the PLA fibres and solid-state draw-ratios (SSDR) were evaluated in order to study their influence on the mechanical, thermal and morphological properties. The results showed that the incorporation of the HAp particles was homogeneously distributed in the PLA fibres towards their surface and that the SSDR played an important role in order to improve the mechanical properties. The melt-spun PLA/HAp composite fibres, produced in this study, had also the potential to be processed into a fibrous scaffold, which was demonstrated by a 3D woven structure.

1 Introduction
In bone tissue engineering, bioresorbable materials in form of fibres and yarns have attracted increasing attention since they provide a large surface area and can be processed into various shapes and sizes, thus desirable as a scaffold matrix material. There are several biodegradable polymers available for medical applications, but they can hardly be used in orthopedics since it required some degree of load bearing. In order to improve the formation or regeneration of bone tissue, it is necessary to develop materials with good mechanical properties and improve the cell interactions with the scaffold. Hydroxyapatite, which mimics the natural bone mineral and stimulates bone in growth, is well investigated for bone tissue engineering, but has been hindered due to lack of mechanical strength. To overcome this it is better to combine the HAp as fillers in the polymer. In fact, natural bone matrix is an organic/inorganic composite material [1]. From that point of view, the aim if this study was to produce a PLA/HAp composite fibre that could be used in a 3D woven scaffold for bone regeneration. To our knowledge, we are the first to melt-spun a PLA/HAp composite fibre that can resist the tension that is generated during weaving. The tension during weaving is of primary importance, since a too high tension or too low tension will make the weaving impossible [2].

2 Materials and testing

2.1 Materials

Polylactide (PLA; NatureWorks® 6201D, melt spinning-grade) was obtained from NatureWorks® LLC, MN, USA. Hydroxyapatite nanoparticles (< 200 nm) were purchased from SigmaAldrich Co. Ltd. 1,4-dioxane (laboratory reagent grade) was purchased from Fisher Scientific, UK. All reagents were used as received.

2.2 Preparation of melt-spun PLA/HAp composite fibres

The PLA/HAp composite fibres were prepared in three steps. First, the PLA granules were dissolved in 1,4-dioxane followed by addition of a certain amount of HAp particles. The nano-composite solution was then stirred with a magnetic bar stirrer until the solution become homogeneous; then, PLA/HAp microspheres were obtained by freezing droplets of the solvent in liquid nitrogen. To remove the residual solvent, the microspheres were freeze dried for at least 24 h. Subsequently, the dried microspheres were extruded at 200˚C using a laboratory-scale twin-screw extruder (DSM Research, Netherlands). Granules were thereafter made from the extruded material. Finally, the granules were melt-spun into fibres by a two-stage process, i.e. melt extrusion and solid state drawing, using a piston spinning machine from FOURNÉ Polymertechnik GmbH, Germany. Solid state draw-ratios (SSDR) of 3-5 were employed at draw temperature of 70˚C.

2.3 Tensile testing

Mechanical properties of the fibres were evaluated using a tensile test machine (Tinius Olsen H10KT, Salfords, UK) with single bollard grips (reference HT 33) and controlled by software QMat. The tensile measurements were performed with a load cell of 250 N at a crosshead speed of 12 mm/min and an initial grip separation of 50 mm. Before testing, the fibres were conditioned in a climate chamber at 23˚C and 50% relative humidity for 40 h. The mean linear density was calculated from the weight of five meters from the fibres. The average value of 10 replicates per each sample was presented with standard deviation.

2.4 Differential scanning calorimetry (DSC)

The thermal properties of the fibres were measured with a Q1000 DSC (TA® Instruments) at a heating rate of 20˚C/min under nitrogen atmosphere. The heat of fusion of an infinitely large crystal was taken as 93.7 J/g [3] and the degree of crystallinity was calculated according to the following equation.

$$X_c^{DSC}(\%) = 100(\Delta H_m - \Delta H_c) / 93.7 \quad (1)$$

where the X_c, ΔH_m, ΔH_c are, respectively, the degree of crystallinity (%), the melting enthalpy and the enthalpy of crystallization.

2.5 Thermal gravimetric analysis (TGA)

To confirm the presence of HAp particles in the polymer matrix the fibres were evaluated using a Q500 thermogravimetric analyser (TA® Instruments). Approximately 20 mg of each sample, including HAp particles, were heated at 10˚C/min from room temperature to 600˚C, under nitrogen gas flow.

2.6 Morphology

The surfaces of the fibres were observed by a scanning electron microscope (Hitachi tabletop microscope TM-1000) to evaluate morphological differences as a result of the different HAp loading fractions. Imaging was performed in the low-vacuum mode, and no sputtering of the specimens was required. Moreover, 3D morphological analysis of the microstructure of a woven scaffold was assessed with Micro-CT.

2.7 Fabrication of scaffold

The melt-spun composite fibres were woven into a 3D orthogonal woven structure using a handloom. The woven structure had three fibre filaments directions; five layers of warp, six layers of weft and 1/1 Z was used for the binding yarns.

3 Results and Discussion

3.1 Mechanical properties

The mechanical properties of the fibres were examined and the obtained results are presented in Figure 1.

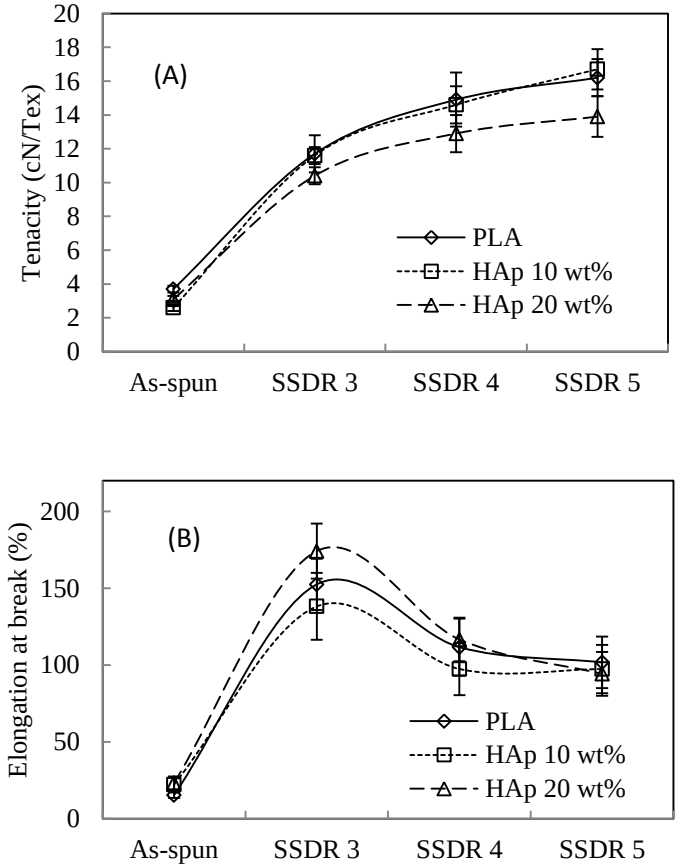

Figure 1. Tensile properties of PLA/HAp composite fibres at various solid-state draw-ratios; (A) tenacity, and (B) elongation at break.

It was observed that the tenacity was significantly improved with increasing SSDR and the maximum tenacity was detected for PLA fibres containing 10 wt% of HAp particles, i.e. 16.7 cN/Tex. In contrast to previous studies [4], there were in general no differences in the tenacity between neat PLA fibres and PLA fibres containing 10 wt% of HAp particles. At higher loading concentration (> 10 wt%) of HAp particles a decrease in the tenacity was observed at all SSDRs. Furthermore, it was apparent that all as-spun fibres had a brittle tensile behavior with an elongation at break of 20%. In comparison to the fibres with SSDR 3 a much more ductile behavior was observed. As the SSDR increases, the elongation at break was observed to decrease.

3.2 Thermal properties

The thermal stability for the as-spun fibres and the presence of HAp particles in the PLA matrix, were analyzed using TGA. The TGA scans showed that the HAp particles did not undergo any thermal decomposition within the range of temperature tested, as illustrated in Figure 2. Comparison between the neat PLA and the PLA/HAp composite fibres showed that the onset of thermal decomposition was higher for the neat PLA fibres. The decrease in the thermal stability for the composite fibres could be attributed to a non-homogenous dispersion of the HAp particles in the polymer matrix. It has also been suggested from previous studies that high amounts of nano-sized fillers can result in agglomeration of the particles and the structure may shift from nanocomposite to microscomposite. Thus, the shielding effect of the nano-sized particles is lessened [5]. It was also observed (see Figure 2), that when the temperature exceeded 380˚C the undecomposed components, corresponding to HAp particles, were approximately 20 wt% and 10 wt% for the composite fibres.

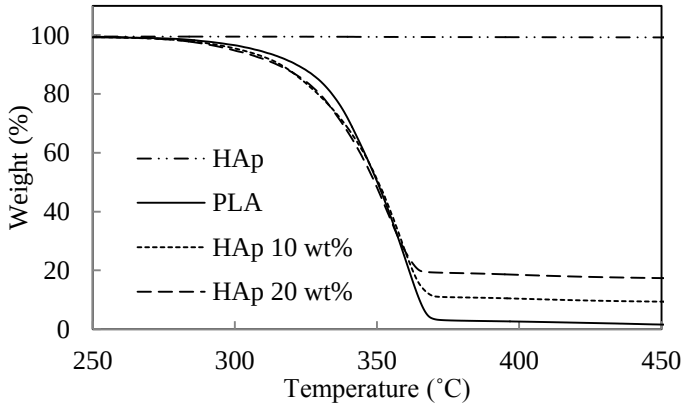

Figure 2. Thermogravimetric analyses of as-spun PLA/HAp composite fibres

The thermal properties of the fibres were further investigated using DSC in order to see the degree of crystallinity, which was analyzed from the first heating scan. All of the scans showed a range of glass transitions temperature (T_g) at about 58.2-63.8˚C for the as-spun fibres and T_g was observed to increase to 68.2-73.0˚C for the solid state drawn fibres. A cold crystallization peak was detected around 124˚C for the as-spun neat PLA fibres, and it was observed to decrease 10˚C for the as-spun composite fibres. For all solid-state drawn fibres the cold crystallization peak decreased to around 80˚C. The melting temperature peak took place around 166.2-168.4˚C, irrespective of HAp contents. The degree of crystallinity of the fibres is illustrated in Figure 3. As shown, the higher loading concentration of HAp particles promotes the degree of crystallinity for the as-spun fibres. However, this was not observed for the solid-state drawn fibres. The degree of crystallinity decreased with higher loading

concentration of HAp particles. These results, therefore, suggest that the HAp particles block the macromolecules to be fully oriented along the drawing direction during the solid state drawing process. The maximum degree of crystallinity was observed for the neat PLA fibres with SSDR of 5, i.e. 44.6%.

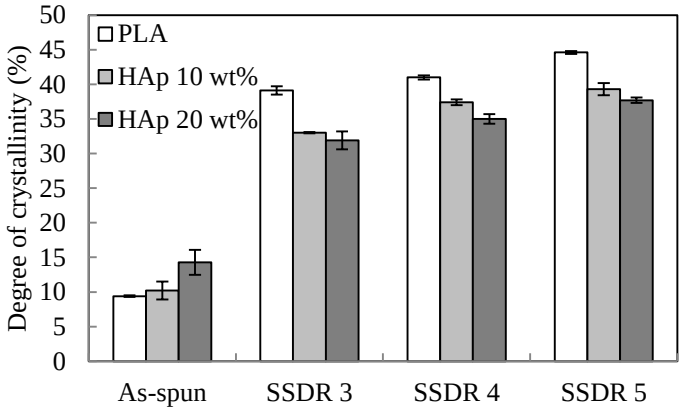

Figure 3. Degree of crystallinity of PLA/HAp composite fibres with respect to the solid-state draw-ratio obtained from the differential scanning calorimetry thermograms.

3.3 Morphology

The surface morphology of the fibres was characterized using SEM, as illustrated in Figure 4. The images revealed that the HAp particles have been homogeneously distributed in the polymer matrix towards the surface and there is no clear evidence of agglomerated particles.

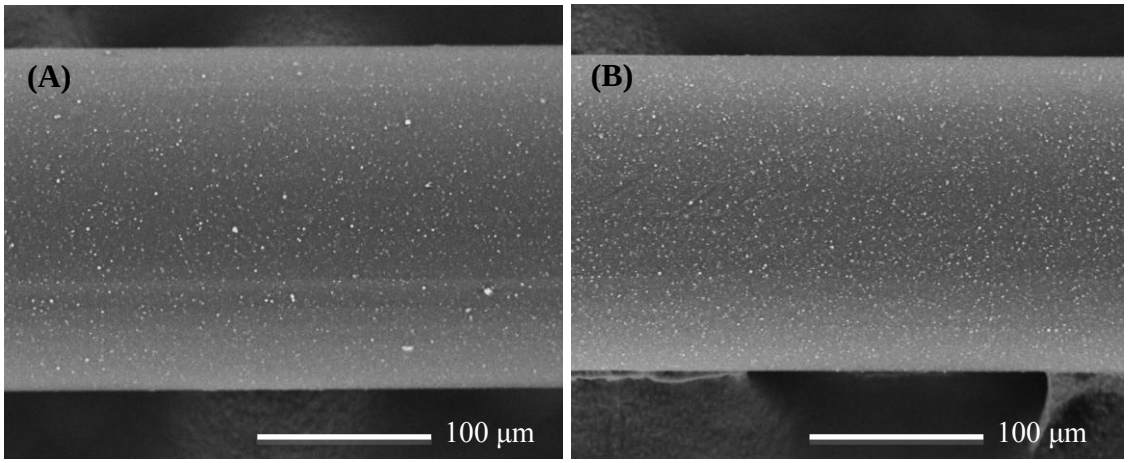

Figure 4. SEM images of as-spun PLA/HAp composite fibres, (A) HAp 10 wt%, and (B) HAp 20 wt%

3.4 Scaffold construction

The aim of this study was to evaluate and validate the mechanical properties of melt-spun PLA/HAp composite fibres, with the goal to use them in a 3D woven scaffolds for bone tissue engineering. Although, the mechanical properties were better for PLA fibres containing 10 wt% of HAp particles it was decided to make the woven structure from PLA fibres containing 20 wt% of HAp particles with SSDR of 5. It is hypothesized that the higher loading concentration of HAp particles can promote cell adhesion and proliferation. However, more

research on this topic needs to be undertaken. The architecture of the 3D woven structure is illustrated in Figure 5.

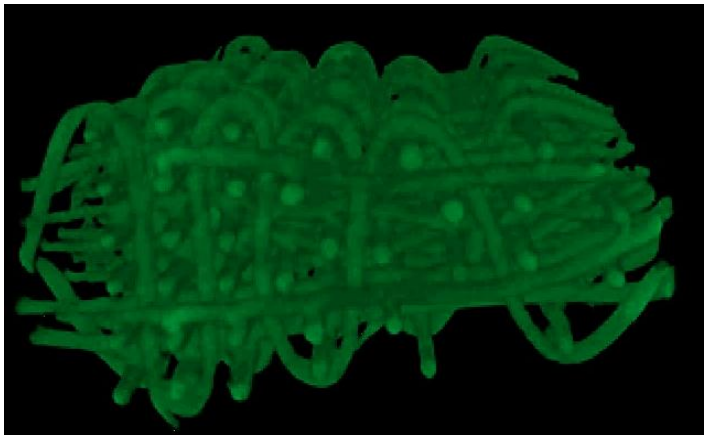

Figure 5. Micro-CT image of the 3D woven scaffold from PLA/HAp composite fibres, width ~ 4mm

4 Conclusions

It can be concluded from these experiments that the incorporation of the HAp particles were homogeneously distributed in the PLA fibres towards their surface. The results indicate the mechanical properties were basically independent at low loading concentration (> 10 wt%) of HAp particles and that the SSDR played an important role in order to improve the properties. A 3D orthogonal woven structure was successfully made from the PLA/HAp fibres obtained in this study. The overall conclusion is that 3D woven structure has a promising outlook for the future in developing biodegradable scaffolds for bone regeneration.

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