Polymer 55 (2014) 2153–2162

Contents lists available at ScienceDirect

Polymer

journal homepage: www.elsevier.com/locate/polymer

Nanogel-modified polycaprolactone microfibres with controlled water uptake and degradability

Dominic Kehren, Astrid Catalina Molano Lopez, Andrij Pich*

Functional and Interactive Polymers, DWI RWTH Aachen University, Forckenbeckstr. 50, D-52056 Aachen, Germany

ARTICLE INFO

Article history:
Received 16 December 2013
Received in revised form
11 March 2014
Accepted 16 March 2014
Available online 21 March 2014

Keywords:
Nanogels
Electrospinning
Composite material

ABSTRACT

In this work we prepared composite poly(caprolactone) (PCL) microfibres decorated with temperature-sensitive poly(*N*-vinylcaprolactam) nanogels by an one-step electropsinning process. Microfibres with variable internal structure were prepared by using two different solvent systems: methanol/toluene (Me/Tol) and chloroform/dimethylformamide (Ch/DMF). Our experimental data shows that the nature of the solvent mixtures allows obtaining microfibres with different morphologies: Microfibres with nanogels on the fibre surface (Me/Tol) and microfibres with nanogels in the fibre interior (Ch/DMF). The morphology of composite fibres was visualized by scanning electron microscopy (SEM) and their properties investigated by differential scanning calorimetry (DSC), thermo-gravimetric analysis (TGA) and contact angle measurements. The results show that combining hydrophobic poly(caprolactone) with hydrophilic nanogels leads to microfibres exhibiting controlled swelling in water. Additionally, the thermo-sensitive properties of the nanogels are maintained whether they are on the surface or inside of the fibres. The presence of nanogels in the fibre structure also allows regulating their degradability.

1. Introduction

Polymer microfibres are in the focus of modern materials research not only because of their one-dimensional structure and various morphologies, but also because of their wide range of possible compositions, which provide a wide range of properties just depending on the polymer they are based on. The fibres can be conductive [1], fluorescent [2] and they can be combined with carbon nanotubes [3,4], metallic nanoparticles [5], hydrogels [6,7] or even proteins or cells [8–10]. Therefore their field of application ranges from textiles, over electronics or constructions, to medicine [11].

In this work we attempt to combine microfibres with polymer nanogels to extend their application potential further. Microgels or nanogels are cross-linked polymer particles of a size between 50 nm and 5 μm [12] with a network structure that swells in solvents [13]. They can be synthesized out of a multitude of monomers and polymers, providing a variety of possible properties like a high biocompatibility [14] or degradability [15]. Also composites with proteins or metal nanoparticles are possible [16,17]. The unique property of microgels is their stimuli sensitivity; the swelling and de-swelling behaviour can be controlled by changes in temperature [18,19], pH value or via activation by light [20]. Thermo-sensitive microgels are swollen in water below the Volume Phase Transition Temperature (VPTT), but above this temperature they shrink rapidly to form a collapsed polymer globule. This reversible swelling is at the basis for one of the most famous application of microgels, namely as uptake and release system for controlled drug delivery [21,22].

The integration of nanogels into microfibers is a promising way to design materials with extraordinary properties. The fibres are fabricated via electrospinning, which is the simplest approach that provides access to uniform and long fibres with different morphologies (solid, hollow, core–shell etc.) and chemical compositions [23]. Previously we demonstrated that nanogels could be used as building blocks to design microfibers [24]. Also we synthesized crosslinked composite poly(vinylalcohol) (PVA) fibres decorated with nanogels and additionally we proved that the nanogels retain their thermo sensitivity after incorporation in the hydrophilic PVA matrix [25].

In the present study we focus on poly(caprolactone) (PCL) as fibre polymer, which is known to be biocompatible [26]. Due to the hydrolytic and enzymatic degradability [27,28] PCL has often been used in medical applications: scaffolds [29], biomedical coatings [30] or drug carriers [31]. PCL is a hydrophobic polymer and numerous approaches have been developed to improve the

* Corresponding author.
E-mail address: pich@dwi.rwth-aachen.de (A. Pich).

http://dx.doi.org/10.1016/j.polymer.2014.03.025
0032-3861/

hydrophilicity of PCL. The hydrophilicity of PCL chains can for example be improved by copolymerisation [32] or the material can be modified by post-modifications with in situ surface modification via physical adsorption of poly(ethylene oxide)-poly(propylene oxide)-poly(ethylene oxide) (PEO-PPO-PEO) triblock polymeric stabiliser [33] or with the immobilisation of collagen [34]. These techniques aim to change or tune the hydrophilicity of PCL and others are especially important for medical purposes and to tune cell growth and adhesion [35,36].

The aim of this work is the development of a one-step method for the preparation of PCL microfibers with a hydrophilic surface/interior and controlled swelling and degradation in aqueous solutions. This has been achieved by controlled integration of colloidal nanogels into PCL microfibers during the electrospinning process. The combination of poly(*N*-vinylcaprolactam) (PVCL) nanogels with a PCL polymer matrix leads to degradable, biocompatible microfibres with thermo-sensitive properties. We demonstrate that the distribution of the nanogels in the fibre structure is key to the adjustment of the surface roughness, swelling degree and degradability. Therefore we pay particular attention to the fabrication of fibres with different morphologies: one exhibiting nanogels only on the surface of the microfibre and another with nanogels distributed only in the interior of the fibre. This has been achieved by using different solvent mixtures and optimisation of the spinning parameters leading to homogenous fibres with controlled properties.

2. Experimental part

2.1. Materials

2,2′-Azobis[2-methylpropionamidine] dihydrochloride (AMPA, 97%, Aldrich), chloroform (99.5%, VWR), dimethylformamide (DMF, 99.8%, VWR), methanol (99.8%, VWR), *N*,*N*′-methylen-bis-(acrylamide) (BIS, 99%, Sigma–Aldrich), phosphate bufferd saline (PBS, Aldrich), poly(caprolactone) (PCL, M_W = 70.000–90.000 g/mol, Aldrich), toluene (99.5%, VWR), sulfamethoxazole (SMX, Aldrich), and distilled water were used as received without having undergone any other cleaning procedures. 2-(methacryloyloxy)ethyl acetoacetate (AAEM, 95%, Aldrich) has been purified before use. *N*-Vinylcaprolactam (VCL, 98%, Aldrich) was purified by vacuum distillation under nitrogen before use.

2.2. Nanogel synthesis

The synthesis of the PVCL/AAEM nanogels was performed according to the previously published procedure [37–39]. The reaction was set in a double-wall glass reactor equipped with a stirrer, reflux condenser and was purged with nitrogen. The monomer solution (VCL – 1.877 g (13.40 mmol); AAEM – 0.338 g (1.579 mmol); BIS (crosslinker) – 0.06 g (0.389 mmol) and water 150 g) was placed in the reactor and stirred for 8 h at 70 °C, the initiator (0.05 g (0.268 mmol) was added after 30 min when all monomers where dissolved. The nanogel dispersions were purified for 72 h by dialysis (Millipore Labscale TFF System).

2.3. Fibre formation by electrospinning

For the electrospinning aperture a simple horizontal set-up was used. 1 mL syringes with metal tip cannulas in an automatic syringe pump (Al 6000-20Z World Precision Instruments) were used. The electrical field was created using an Eltex KNH34 generator. Simple aluminium foil was used as target.

For the preparation of the spinning solutions, the nanogel dispersions were freeze-dried to later be able to calculate the exact amount of nanogel that is used. Afterwards the solutions were prepared by mixing the nanogel powder with PCL-solutions by using the Omni TH homogeniser (OMNI International) for 5 min at 10,000 rpm. Viscous solutions with variable nanogel/polymer ratios in methanol/toluene (different ratios) and chloroform/DMF (different ratios) were prepared (see Supporting Information Table S1 for additional details). The most important physical constants for the solvents used are summarised in Table 1.

2.4. Degradation of the fibres

For the investigation of the degradation behaviour 2 cm^2 of the fibre samples were put into 10 mL phosphate buffered saline (PBS) (0.01 M). PBS was used to simulate the conditions in the human body fluids. These samples have been analysed with electron microscopy after different time intervals to study the degree of degradation and erosion effects on the fibre surface. Dynamic light scattering was used to detect the released nanogel particles from the degraded fibres in buffer solution. The mass loss was studied gravimetrically by weighting the dried samples after the different time intervals. Afterwards, the mass lost was calculated according to equation: % mass loss $= [(m - m_f)/m] \times 100$, where m is the initial mass and m_f is the mass of degraded fibre.

2.5. Characterisation methods

2.5.1. Dynamic light scattering (DLS)

The size of the nanogel particles was measured with an ALV/LSE-5004 Light Scattering Multiple Tau Digital Correlator and Electronics with the scattering angle set at 90°. Prior to the measurement nanogel samples were diluted with doubly distilled water.

2.5.2. Contact angle measurements

The contact angle on different fibre matt samples of 1 cm^2 was measured with the Krüss G2/DSA II with distilled water.

2.5.3. Sedimentation analysis

The sedimentation analysis was applied to study the behaviour of nanogels in methanol/toluene and chloroform/DMF spinning solutions. We used the separation analyser LUMiFuge (LUM GmbH, Germany) to measure the sedimentation velocity of nanogels in the corresponding solvent mixtures. The samples have been measured in quartz glass cuvettes at an acceleration velocity of 2000 rpm.

2.5.4. Field emission scanning electron microscopy (FESEM)

The samples were analysed with a Hitachi FE-SEM S4800. Fibres were analysed on the aluminium support like they are fabricated by the electrospinning. Films have been glued directly on carbon-tape. Film-cross-sections have been done by cutting with a razor knife after freezing in liquid nitrogen.

Table 1
Properties of the solvents used for the electrospinning process.

Solvent	*M*, (g/mol)	Boiling point, (°C)	Density, (g/cm^3)	Dipole moment, (Debye)	Solubility parameter ($MPa^{1/2}$)
Chloroform	119.4	61.2	1.470	1.15	19.0
DMF	73.1	153.0	0.940	3.86	24.0
Methanol	32	64.7	0.790	1.7	29.7
Toluene	92	111	0.857	0.375	18.5