NOVEL SYNTHETIC FIBERS BY MULTICOMPONENT MELT-SPINNING

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ABSTRACT
Empa's laboratory for Advanced Fibers develops synthetic fibers with distinct functionalities in new combinations. Our custom-made pilot melt-spinning plant enables the prototype production of mono-, bi- and tri-component fibers with various cross-sections and material combinations with a throughput of up to several kg/h. The plant is, on one hand, a very flexible setup with features corresponding to an industrial plant; on the other hand it requires only a small throughput, enabling us to work with very precious materials. Ongoing projects include photocatalytic, reinforcing, artificial turf, biodegradable and rheological core fibers.

Key Words: Synthetic fiber, melt-spinning, bicomponent, reinforcement, biomaterial

1. INTRODUCTION

Melt spinning is the most commonly used method for manufacturing commercial synthetic fibers. The current trends in polymer melt spinning are manifold. Recent research activities include enhancement of mechanical properties [1, 2], implementation of electric or magnetic functions [3, 4], introduction of biologically active species like drugs or silver composites [5, 6], as well as variation of fiber morphology by bicomponent spinning [7, 8]. Bicomponent fibers are among the most interesting developments in the field of synthetic fibers [9-11].

Bicomponent or multicomponent fibers are synthetic fibers made from two or more polymers of different chemical and/or physical structure, extruded from a common spinneret to form a single filament [12]. The polymer flows are kept separate up to the spin pack and brought together in or before the spinneret capillary. When the filament leaves the spinneret, it consists of non-mixed components that are fused at the interface. Depending on the characteristics of the different polymers, the multicomponent fiber can provide functional properties such as thermal bonding, self-crimping, unique cross sections, and achieve functionality of special polymers or additives at reduced cost [13]. The three main geometries of multicomponent fibers are side-by-side, core-sheath, and multiple core configuration (Figure 1).

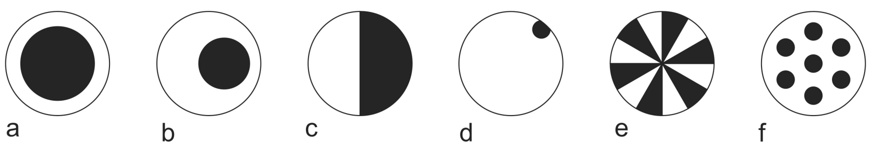

Figure 1. Typical cross-sections of multicomponet fibers: a) concentric core-sheath, b) eccentric core-sheath, c) 50/50 side-by-side, d) unequal side-by-side, e) segmented pie, f) islands-in-the-sea

Side-by-side and eccentric core-sheath bicomponent fibers are most commonly used to produce self-crimping yarns applied in voluminous products. By combining two polymers that undergo differential shrinkage, the yarn curls up after thermal or other relaxing treatment and develops spiral crimp. Core-sheath types are predominately used as binding fibers for nonwovens, with a standard polymer as core and a low softening-point as sheath. When such fibers are laid in a nonwoven structure and heated to a temperature above the softening point of the sheath polymer, the fibers adhere wherever they cross and touch [14].

Multiple core configurations, like islands-in-the-sea and segmented pie, are mainly applied to produce microfibers with diameters smaller than those obtained via conventional melt spinning [15]. Islands-in-the-sea fibers comprise fibrils dispersed in a dissolvable matrix polymer that will be removed in a follow-up process [14]. In the segmented pie technique, a bicomponent fiber is spun from two incompatible polymers that adhere poorly and split into microfibers when subjected to mechanical stress [13]. Fabrics made from microfibers are very flexible, and the high density of fibers make them inherently wind- and water-proof, while water vapor from perspiration can evaporate easily.

2. MELT-SPINNING EQUIPMENT

Empa's custom-made pilot melt-spinning plant, built by Fourné Polymertechnik (Alfter-Impekoven, Germany) [12], enables the prototype production of mono-, bi- and tri-component fibers with various cross-sections and material combinations with a throughput of up to several kg/h. It comprises two screw extruders and one piston extruder, a spin pack with thermally discrete polymer conduits, and a set of spinnerets allowing for elaborate fiber cross-sections. A schematic drawing of the melt spinning plant is shown in Figure 2.

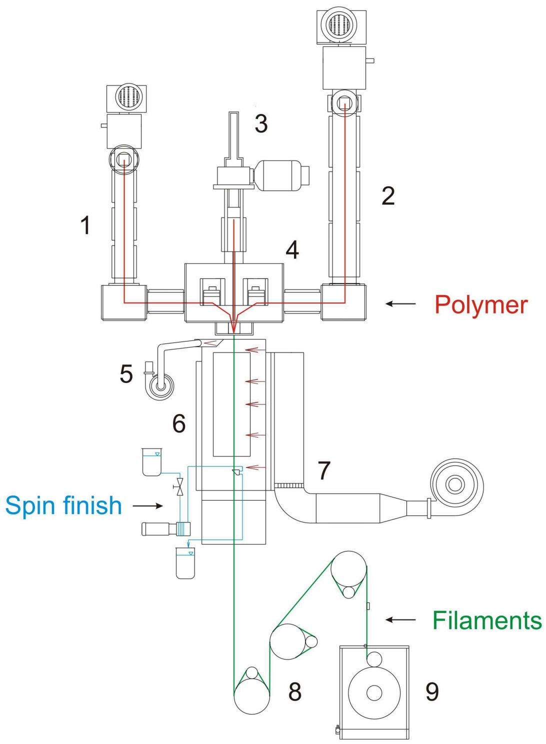

Figure 2. Schematic assembly of the pilot melt spinning plant (see text for an explanation of the numbered parts)

The polymers are melted using two single screw extruders (1, 2), for instance one to be used for the core component and one for the sheath component of a bicomponent fiber. In that case the coaxially-combined polymer melt is extruded through a spinneret featuring up to seven positions with core/sheath-geometry. By way of example a bicomponent monofilament die consists of a tube with 0.4 mm inner diameter and 0.7 mm outer diameter within a 1.2 mm capillary. The diameters of the extruder screws are 13 mm (1) and 18 mm (2), respectively, with a length-to-diameter (L/D) ratio of 25. The maximum extrusion temperature is 400°C. Spin pumps enable a constant mass flow of 0.5-40 cm^3/min.

In order to produce tri-component fibers, an additional piston extruder (3) has been installed, with a throughput of 1.5-15 cm^3/min. Due to the possibility to fit sealing rings, also low-viscosity liquids can be processed. A special spin pack (4) was designed and built in collaboration with Inspire (St. Gallen, Switzerland), comprising an oil cooling and heating system (oil temperature 10-360°C) to keep the three polymer melt flows at different temperatures down to the spinneret plate.

Evaporating monomers and oligomers are sucked in by an exhaust (5). The extrudate is spun into the 2.8 m free-fall section which is equipped with a removable or extendable chimney with a maximum temperature of 350°C. The quenching chamber (6) has a maximum air flow of 520 m^3/min and a length of 1.4 m; its height within the free-fall section is steplessly variable. The temperature of the quench air (7) can be adjusted between 8°C and 160°C, using either a two-step cooling system or a heater. After cooling and, where applicable, wetting with a spin finish, the filaments are drawn by three heated godets (8). The maximum temperature of the godets is 210°C, their speed can be varied between 100 rpm and 1800 rpm. The draw ratio, i.e. the ratio of speeds of draw and feed godets, can be chosen accordingly. Finally a winder (9) with a maximum speed of 2000 rpm is used to spool the filaments on a bobbin.

3. RESULTS AND DISCUSSION

3.1 Photocatalytic fibers for odor control textiles

Many textiles have a distinct ability to adsorb unpleasant odors that can leave the textile through desorption. A smart way to face this problem are odor control textiles that degrade the malodor itself at the surface through e.g. photocatalytic processes on TiO_2 based photocatalysts [16].

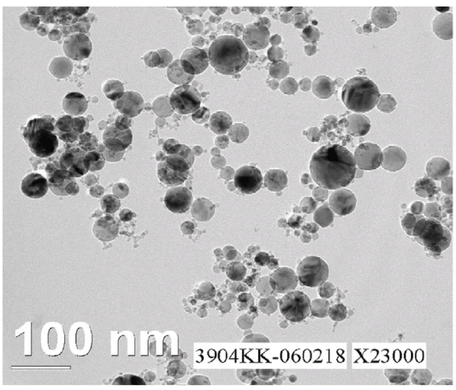

Figure 3.TEM micrograph of TiO_2 nanoparticles synthesized in an aerosol flame reactor [17]

We developed PET-based fibers for the degradation of malodor in air, with photocatalytic particles incorporated directly into the fiber [18]. Photocatalytic TiO_2 nanoparticles with high degree of crystallinity and surface area were obtained by flame synthesis (Figure 3). The as-spun fibers were subjected to formaldehyde decomposition tests to evaluate photocatalytic activity. The results indicate that malodor degradation can be expected.

3.2 Bicomponent fibers for the mechanical reinforcement of concrete

The reinforcement of concrete with fibers can be an economical alternative to conventional steel bar reinforcement. We successfully applied polyolefin based bicomponent fibers with high tensile strength and elastic modulus to enhance the mechanical properties of concrete [19]. The effects of an introduction of nanoparticles and other additives, and of a structuring of the fiber surface, were assessed. The performance of such fiber reinforced concrete was studied with respect to fiber pull-out characteristics and the bending behavior of concrete. Ductile post-peak behavior of fiber reinforced concrete was achieved, making these fibers interesting for the applications in pre-cast elements, industrial floors and earth quake protecting systems.

3.3 Artificial turf fibers for future sports flooring

Artificial turf is a lower maintenance all-weather alternative to natural turf [20]. On one hand, polyamide (PA) carpets have excellent resilience but provoke abrasion injuries (friction burn). On the other hand, polyethylene (PE) monofilaments are skin-friendly but tend to permanent deformation. PA-PE bicomponent fibers render a robust, skin-friendly artificial turf. The goal of our respective work was to develop a bi-component monofilament with optimized cross-section and material combination to maximize resilience while minimizing risk of skin abrasion, in order to achieve artificial grass for sports flooring that resembles natural turf with respect to playability and appearance [21]. We succeeded in producing fibers for artificial turf that show a better resilience than up-to-date synthetic grass, without cut-back in skin-friendliness (Figure 4).

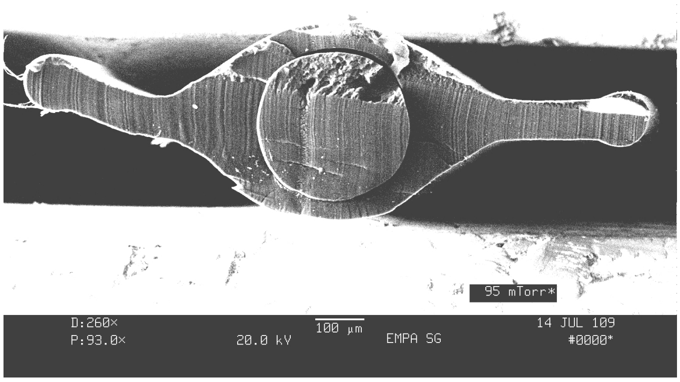

Figure 4.SEM cross-section of a PA-PE bi-component monofilament intended for skin-friendly artificial turf with good resilience

3.4 PET-PPS bicomponent fibers

The high-performance polymer polyphenylene sulfide (PPS) reveals good chemical resistance and high temperature stability. We melt-spun PPS in combination with the standard polymer polyethylene terephthalate (PET) in order to achieve economic bicomponent fibers for filter fabrics or geotextiles, where chemical resistance is required [22]. Parameters that guarantee stable processing of PPS and PET during coaxial extrusion with different core/sheath volume ratios were explored. By changing the core/sheath volume ratio from 2 to 0.5 in the PPS/PET fiber, the crystallinity of the PET-component was switched from 10 to 50%, whereas the crystallinity of the PPS dropped from 68 to 7%. It was determined that bicomponent fibers can exceed the strength of monocomponent fibers up to 28%. The flammability and chemical resistance of the new developed fibers were characterized. In contrary to what was expected, the encasing of PET with PPS reduced the flame retardancy, though PPS has a higher flame resistance than PET. The chemical resistance of the PET core against hydrolysis was imparted by coextruding a PPS sheath.

3.5 Biodegradable fibers from renewable sources

For temporary textile implants, fibers from biocompatible and biodegradable polymers are preferable [23]. Furthermore, polymers from renewable sources are future-oriented. The commercially available polyesters polylactide (PLA) and polyhydroxyalkanoate (PHA) combine these aspects. However, inflammatory response to degradation by-products limits the application of PLA as biomaterial, whereas the low crystallization rate of PHA renders melt-spinning difficult. We produced PHA-PLA core-sheath fibers with a maximum tensile stress of up to 0.34 GPa and a Young's modulus of up to 7.1 GPa [24]. X-ray diffraction measurements revealed that the PLA component alone is responsible for the tensile strength. In vitro biocompatibility studies with human dermal fibroblasts showed that cells adhere on the fibers, making them good candidates for medical therapeutic approaches.

3.6 Fiber with rheological core for flexure-rate responsive damping

Instead of using hard shell components to dissipate the energy of the impact, state-of-the-art-concepts of impact protective garments rely on flexible materials [25]. We start to develop fibers that exhibit rate-dependent viscoelastic properties owing to the presence of a fluid core with distinctive rheological characteristics [26]. The fluid shall be confined inside a suitably structured fiber core that induces fluid flow upon fiber bending, resulting in a rate-adaptive damping effect (Figure 5). Challenges involve the use of non-equilibrium multi-component polymer melt flow behavior during melt-spinning to generate the desired fiber core geometry, filled with a fluid of suitable rheological properties. Fibers with a rheological core are expected to open an entire field of adaptive product applications, notably as protectors against impact, or for rate-adaptive damping in fiber-reinforced high-performance composites.

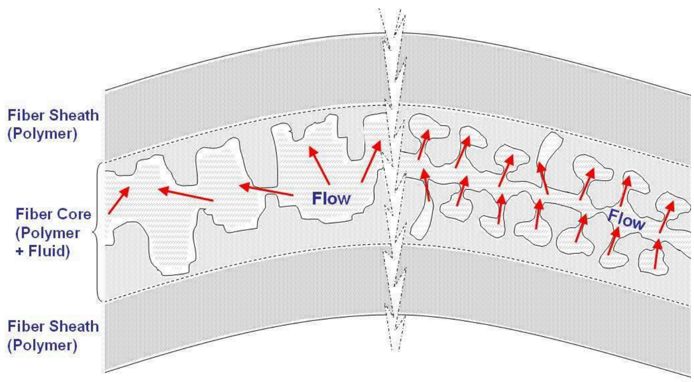

Figure 5. Illustration of a rheological core fiber with a polymer sheath around a polymer plus fluid mixed core

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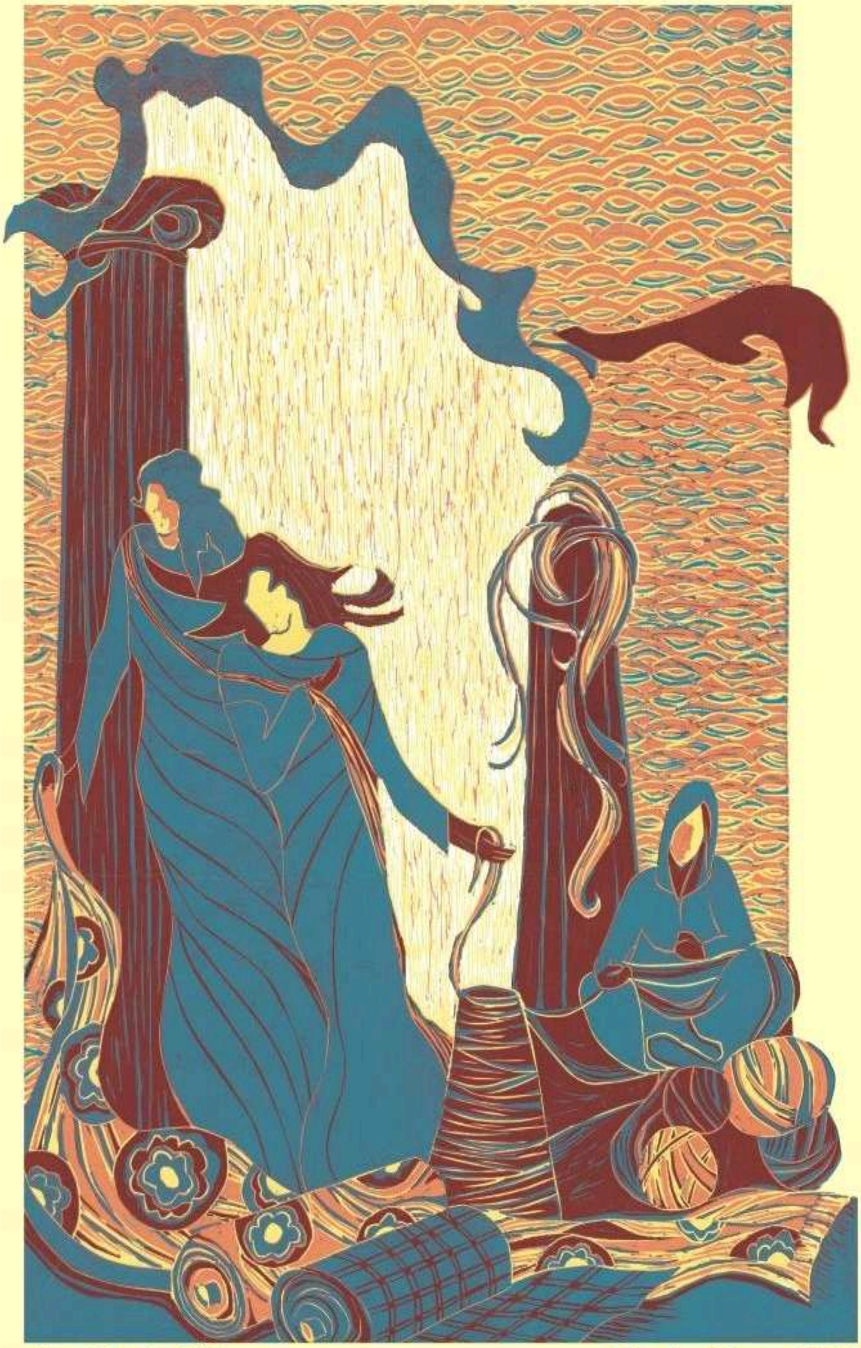

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