ADVANCED TEXTILES MANUFACTURING INDUSTRY
Learning unit 2
Lesson 1

Raw materials for functional (passive) textiles

HACKTEX
Innovative smart textiles & entrepreneurship

A project:
Co-funded by the European Union
2021-1-RO01-KA220-HED-000027527

Document title

Year

2023

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HACKTEX project was co-funded by the European Union through the grant 2021-1-RO01-KA220-HED-000027527.

Content

Introduction

This lesson (LU2.1) about *Raw materials for (functional) passive textiles* is enclosed in the Learning Unit 2, which corresponds to *Raw materials and products for functional and smart textiles*.

Passive smart textiles are materials that can only sense environmental conditions, being their interaction with the surroundings extremely limited.

In this lesson, you will learn about electrical conductive materials and materials that can conduct light. Moreover, photocatalytic materials will be also described.

1. Electrically conductive materials for textile applications

For the production of certain smart textile-based solutions it is necessary the use of materials that can provide electrical connections as well as flexible electronic components. Due to this, the obtention of electrically conductive materials with textile properties—such as lightness, flexibility, stretchability or transpirability, e.g.—but also with a good washability and durability is key for the development of new wearables and smart garments. In this sense, the two main approaches to reach such properties are to impart conductivity to textile materials though using *conductive fibres*—to obtain yarns that can be used for fabric production or embroidery, for instance—, or *conductive coatings, pastes and inks*—to obtain a thin conductive layer on the surface of fabrics and yarns—.

1.1. Conductive fibres

Depending on the type of conductive material they are made of, **conductive fibres** can be classified into:

- ***metal-based*** fibres
- ***carbon-based*** fibres
- ***conductive polymer-based*** fibres

On the other hand, they can be *inherently conductive*—if the fibres are made entirely of a conductive material—or *extrinsically conductive*—if the fibres are made of a non-conductive material to which another conductive material has been added—. Depending on where the conductive material is found, extrinsically conductive fibres can be classified as:

- *Coated fibres*: being the conductive element on the outside (fibre surface).
- *Composite fibres*: being the conductive element inside the fibres (composites including conductive metallic, polymeric or carbon particles, mainly in the form of nanoparticles or nanofibers).

The electrical conductivity of conductive fibres will depend on the nature of the conductive material used, being the metallic fibres the ones that can lead to higher conductivities, followed by the carbon-based and the conductive polymer-based, as shown in Figure 1. Moreover, there are multiple techniques for their production like wet spinning, electroplating or spray-coating, among others (Li et al., 2022).

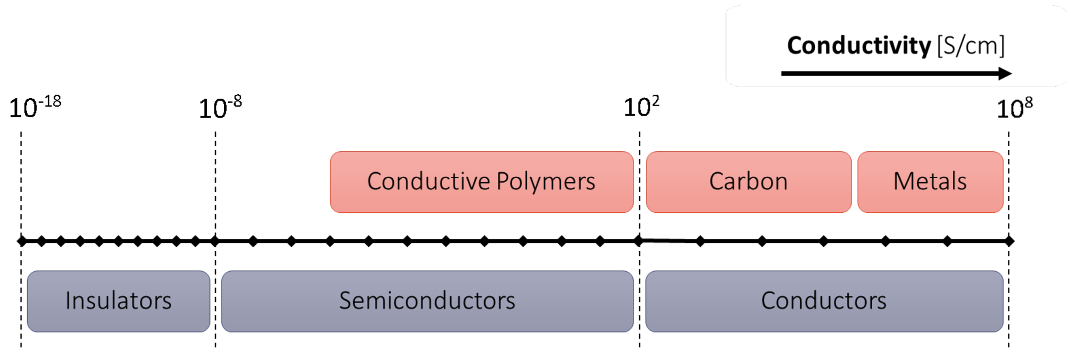

Figure 1. Electrical conductivity of the materials used for conductive fibres

Metal-based fibres

Intrinsically conductive metal-based fibres or metallic fibres

Metallic fibres are produced from materials such as ferrous alloys, nickel, stainless steel, titanium, aluminium or copper, among others. The most common ones are the stainless steel fibres, which present a conductivity of ~10^6 S/cm. These fibres can be found with diameters around 8 µm to 22 µm. Their density (7.9 g/cm^3) and melting temperature (1,380 ºC) are clearly higher of the conventional fibres. These fibres are highly conductive, but also brittle, stiff and heavier than most textile fibres. Some examples of commercial stainless steel fibres are Bekinox® fibres from Bekaert, AISI 316L fibres from IMATTEC, and R.STAT/S fibres from R.STAT.

Extrinsically conductive metal-based fibres

With respect to the metal-coated fibres, the most common are the silver-coated ones. Usually, these fibres have a polyamide core (similarly to the shown in Figure 2) and, apart from conductivity, they also present antibacterial properties. Their conductivity is around 10^3 S/cm. Some examples of these fibres are the YLshielding™ silver fibres and silveR.STAT® fibres.

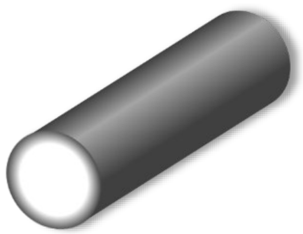

Figure 2. Schematically drawn coated fibre in which the core (white) is the base fibre and the surface (dark grey) is the conductive coating.

Other metal coatings can be copper, nickel, aluminium, gold, magnesium or titanium, among others. In some cases, the coating are metallic salts like copper sulphide coated fibres R.STAT/N and R.STAT/P fibres with a core of polyamide or polyester respectively.

Carbon-based fibres

It is widely known that the pure carbon fibres—such as those used in composite materials, which are made entirely of carbon—are intrinsically conductive. Their conductivity is very high, around 10^6 S/m. However, due to their high stiffness, they are not widely used for textile applications in garments. In many cases, the most used ones are the extrinsically conductive fibres, which are obtained using carbon particles and its derivatives—such as carbon black (CB), carbon nanotubes (CNTs), graphene (G) or reduced graphene oxide (rGO), among others (Chen et al., 2022)—, although their electrical conductivity is not as high as that of pure carbon fibres.

Typically, carbon-based conductive fibres are made of polyamide (PA) or polyester (PES) fibres in which the carbon component is mixed—if placed in the core of a composite fibre (Figure 3)—or coated—if placed on the fibre surface of a coated fibre—. When coated with carbon, PES or PA often reach conductivity values around 10^{-3}-10^{-7} S/cm, whereas when compounding with carbon particles the fibres often reach conductivity values around 10^{-6}-10^{-7} S/cm. Some of the most known examples of commercial carbon-based fibres are Resistat® fibres from Shakespeare Company, Belltron from Kanebo Japan, and Nega-stat® from Barnet.

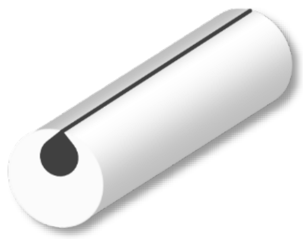

Figure 3. Schematically drawn carbon-based composite fibre with a conductive core (dark grey) surrounded by non-conductive polymer (white).

Conductive polymer-based fibres

Conductive polymers can conduct charge due to a combination of favourable bond configuration and dopants. On the one hand, in the conjugated backbone—alternating distribution of single and double bonds (Figure 4)—, all bonds contain a σ-bond that ensures the bond strength, whereas double bonds also have a π-bond that eases an electron delocalisation. On the other hand, the properly oxidation or reduction with dopants introduces the charge carrier into the system by adding or removing electrons to/from the polymer chain and properly delocalizing them. Thus, the combination of both factors eases the electrons jump within and between the chains of the polymer (Balint, Cassid, & Cartmell, 2014).

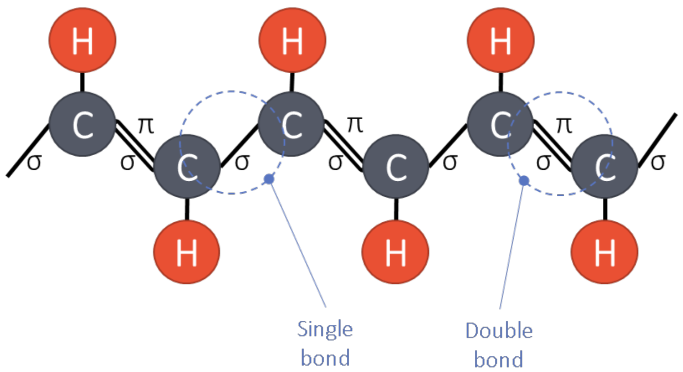

Figure 4. Simplified schematic of a conjugated backbone, containing alternating single and double bonds.

Image adapted from (Balint, Cassid, & Cartmell, 2014).

Conductive polymers can reach a broad range of conductivities between 10^{-10} to 10^{5} S/cm (Grancarić, et al. 2017), but in general their conductivity is lower than the provided by metals and carbon materials (see Figure 1). However, conductive polymers are lighter hence more appropriate for textile applications. Among all the intrinsically conductive polymers, the ones that are the best candidates for the development of polymer-based conductive fibres are polyaniline (PANI)—with a conductivity of 30-200 S/cm—; polypyrrole (PPy)—with a conductivity of ~10^{3} S/cm—and poly(3,4-ethylene-dioxythiophene) (PEDOT)—with a conductivity of 0.4-400 S/cm— (Grancarić, et al. 2017).

Although conductive polymers can be relatively easy to synthesize, their transformation in fibres is still a challenge, and the fibres present poor mechanical properties for textile applications. It is because this that, despite many papers can be found related to the development of fibres with conductive polymers, there is a lack of commercial fibres. In fact, in the commercial solutions, conductive polymers are used as coatings rather than as fibres. In this sense, natural and synthetic fibres, yarns and fabrics can be coated with conductive polymers on their surface (Grancarić, et al. 2017) with different coating techniques like wet or vapour polymerization, or dipping and drying, among others.

1.2. Conductive coatings, printing pastes and inks

Fibres can allow to impart conductivity to yarns and fabrics in a highly integrated way, but sometimes it necessary to take another approach, by applying conductive layers on top of the fabrics. The use of **conductive coatings** directly applied on the textiles through different techniques is another solution to produce conductive fabrics. In this case, the electrical functionality is imparted directly onto regular yarns or fabrics, enlarging the development of conductive materials without the limitation of using conductive fibres. Some of the conventional systems for coating textiles—like spray coating, vapour phase deposition, padding or dipping—can be used to impart electrical conductivity to textiles.

Conductive pastes and inks consist of a dispersion of highly conductive particles—such as carbon, silver, silver/silver chloride, gold, copper or graphene—and binders—i.e. suitable resins such as polyester or epoxy, for instance—in an organic or inorganic solvent. In some cases, conductive pastes and inks may require encapsulation for being washable, and often require additional curing or sintering processes. The main difference between conductive pastes and conductive inks is their viscosity, since the pastes are much more viscous than inks. Due to this, they might be applied by means of an appropriate method such as screen-printing for pastes and inkjet printing for inks.

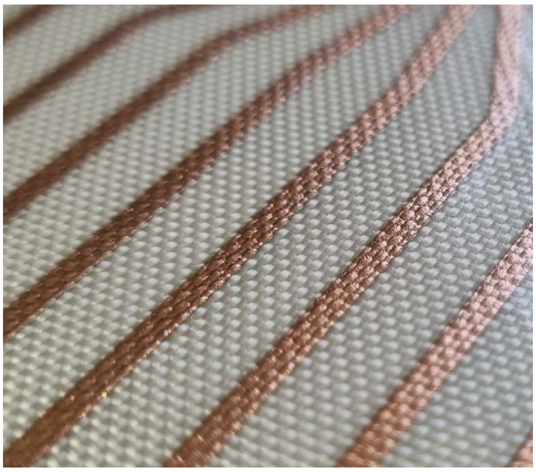

Figure 5. Conductive areas (copper lines) printed on a fabric.

Conductive coatings, printing pastes and inks have to be compatible with the textile materials and have good adhesion and washing durability. Moreover, due to the stretching capability of textiles, rigid paste/ink systems should be avoided. In this sense, some stretchable conductive pastes—based on silver or PEDOT-PSS polymers—are available in the market.

Want to learn more about this topic?

In the book *Smart Textiles Production: Overview of Materials, Sensor and Production Technologies for Industrial Smart Textiles* (Gehrke, Tenner, Lutz, Schmelzeisen & Gries, 2019) you can read more about conductive fibres.

Also, in the research papers *Conductive polymers for smart textile applications* (Grancarić et al., 2018), *Electrically Conductive Textile Materials—Application in Flexible Sensors and Antennas* (Krifa, 2021) and *Electrically Conductive Coatings for Fiber-Based E-Textiles* (Chatterjee, Tabor & Ghosh, 2019), you can learn more about the conductive materials used for smart textiles.

Moreover, in the following links you will find information about some commercial conductive fibres and coatings:

100% stainless steel fibres

- Bekaert (2023). *Conductive fibers and yarns for smart textiles - Bekinox® fibers*. Available at: https://www.bekaert.com/en/products/basic-materials/textile/conductive-fibers-and-yarns-for-smart-textiles
- R.STAT (n.d.). *Products and Solutions: Stainless steel fibres - R.STAT/S fibre*. Available at: http://www.r-stat.fr/uk/stainless-steel-fibre.php
- IMATTEC International (2020). *Stainless Steel: Stainless steel (and other metals) technical yarns, fibres and fabrics for high-temperature and conductive applications (smart textiles, PPE, etc*.).: https://imattec.com/en/stainless-steel.php
- SWIIT (n.d.). *Stainless Steel Fiber: Product description.* Available at: http://www.swiit-fiber.com/product/stainless_steel_fibers/stainless_steel_fiber/

100% silver coated fibres

- YLshielding™ (2021). *Functions and Advantages of Silver Fiber.* Available at: https://www.ylshieldingtex.com/ blogs/functions-and-advantages-of-silver-fiber.html
- R.STAT (n.d.). *Products and solutions: Silver fibre - silveR.STAT® fibres*. Available at: http://www.r-stat.fr/uk/silver-fibre.php

Metallic salt coated fibres

- R.STAT (n.d.). *Products and Solutions: Copper fibre - R.STAT/N and R.STAT/P fibres*. Available at: http://www.r-stat.fr/uk/copper-fibre.php

Carbon-based conductive fibres

- SWICOFIL (n.d.). *BELLTRON - Kanebo Belltron fibres*. Available at: https://www.swicofil.com/commerce/products/carbon/228/belltron
- BARNET (2021). *Static Control with Nega-stat® - Nega-stat® fibres*. Available at: https://www.barnet.com/products/nega-stat/
- SHAKESPEARE (2023). *Conductive fibres: Nylon – Resistat® carbon suffused fibres*. Available at: https://shakespeare-pf.com/product/nylon/

Stretchable conductive inks

- Saralon (2023). *Stretchable Conductive Inks: Saral StretchSilver Inks.* Available at: https://www.saralon.com/en/blog/latest-stories-stretchable-conductive-inks/

2. Light conductive fibres

2.1. Optical fibres

Optical fibres are a type of light conductive fibres that are used to transmit light and light signals over long distances, with minimal loss of signal strength. The basic principle behind optical fibres is the phenomenon of total internal reflection, where light entering an optical fibre is reflected off the inner surface of the fibre and kept confined within it (Figure 5). To this end, optical fibres consist of a core—the central part of the fibre through which the light travels—surrounded by a cladding material, which helps to keep the light contained within the core. Moreover, for certain applications such as data transmission, optical fibres can also have an external protective coating, which is an outer layer that helps to protect the fibre from damage.

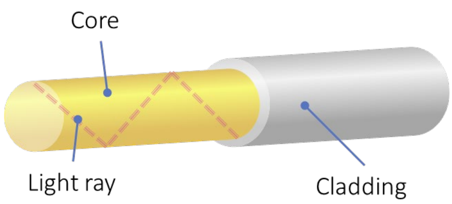

Figure 5. Scheme of an optical fibre and a light ray travelling along the core and reflecting on the cladding.

Total internal reflection is achieved by means of a change on the refractive index of the core and cladding materials. Given that the cladding has a lower refractive index than the core, it reflects the light back into the core whenever it tries to escape. However, a change on the internal reflection angle can lead to a light leakage through the fibres, generating a sidelight emission. The main methods to generate sidelight emission are based on changing the angle of the internal reflection, allowing hinder the total internal reflection. This can be achieved by adding dopants—also known as bulk scattering—, by bending, by surface perforation or damaging the cladding, and by adding luminescent particles (Figure 6).

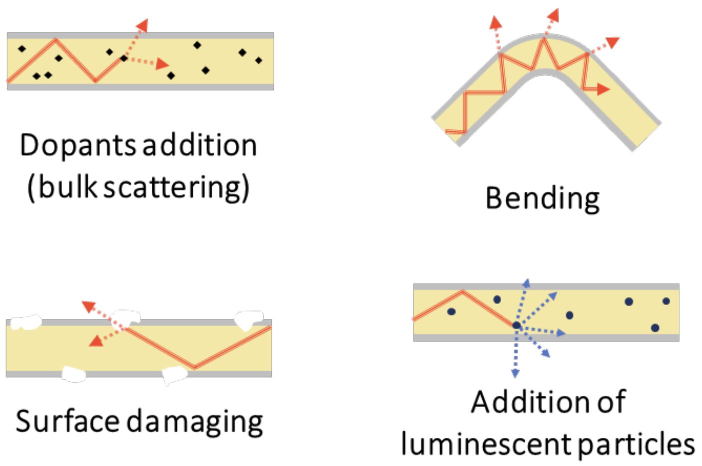

Figure 6. Methods to generate sidelight emission in optical fibres.
Image adapted from (Kallweit et al., 2021).

Optical fibres can be made of glass or of a polymer. The polymer optical fibres (POF) have to present high optical clarity to allow passing the light through the fibres. The most common POFs are made of poly(methyl methacrylate) (PMMA), polycarbonate (PC) and polystyrene (PS), being the PMMA ones have the highest transmission. POFs are more suitable to fulfil the fineness and flexibility necessary for being integrated into woven, knitted or nonwoven structures for smart textile applications.

Optical fibres have applications for smart textiles in sensing technology, data transmission and in lighting technology. Some examples of applications in smart textiles are:

- *Lighting:* Optical fibres can be used to create smart lighting in textiles, such as clothing or home textiles. The fibres can transmit light to different parts of the fabric, creating a variety of lighting effects (Figure 7).

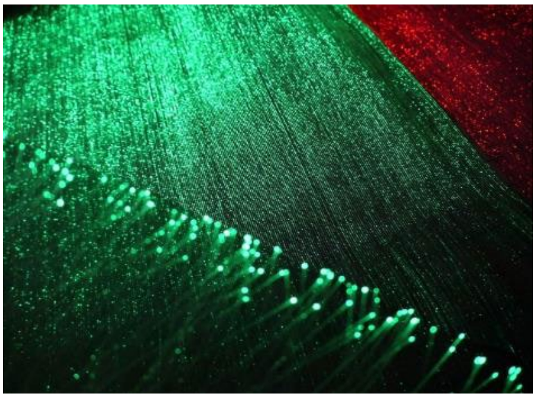

Figure 7. Light glowing fabric made with optical fibres.
Image credits: by Rain Rabit, CC BY-NC 2.0.
https://www.flickr.com/photos/37996583811@N01/17252720903/in/photostream/

- *Sensing:* Optical fibres can be used as sensors to measure changes in temperature, pressure, or other physical properties. When the fibre is subjected to a change in the environment, the light signal transmitted through the fibre is altered in a way that can be detected and measured. Therefore, they can be integrated into clothing to monitor vital signs, such as heart rate, breathing rate, and body temperature.
- *Data transmission:* Optical fibres can be used to transmit data between textiles, such as in a network of wearable devices. The fibres can be woven into the fabric of the textiles and used to transmit data through the fibre optic network.

Want to learn more about this topic?

In the book *Polymer Optical Fibres: Fibre Types, Materials, Fabrication, Characterisation and Applications* (Bunge, Beckers & Gries, 2016) you will find information about polymer optical fibres (POFs), form their basic principles to their production and market.

In the research papers *An overview on fabrication methods for polymer optical fibers* (Beckers, Schlüter, Vad, Gries & Bunge, 2015) and *An Overview on Methods for Producing Side-Emitting Polymer Optical Fibers* (Kallweit et al., 2021) you will find some information about the production of optical fibres.

3. Photocatalytic materials

Photocatalytic materials are substances that can cause a photochemical reaction—induced oxidation and reduction reactions—when exposed to light. This can lead to interesting applications such as on photodecomposition of hydrogen, degradation of organic pollutants, or reduction of carbon dioxide, among others.

Textiles can be treated with these photocatalytic materials for different purposes, being the most common to develop self-cleaning applications, or decontamination and purification applications for air or water treatment. Some common photocatalytic materials used in textiles include titanium dioxide (TiO_2), zinc oxide (ZnO), and tungsten oxide (WO_3). Usually, these oxides are deposited as a thin film, and doped with some precious metals—e.g. silver, gold or platinum—or transition materials—e.g. chromium, cobalt or vanadium—to improve the photo-catalytic efficiency. Other methods for increasing the photocatalytic activity are introducing silica, like for TiO_2/SiO_2 composites.

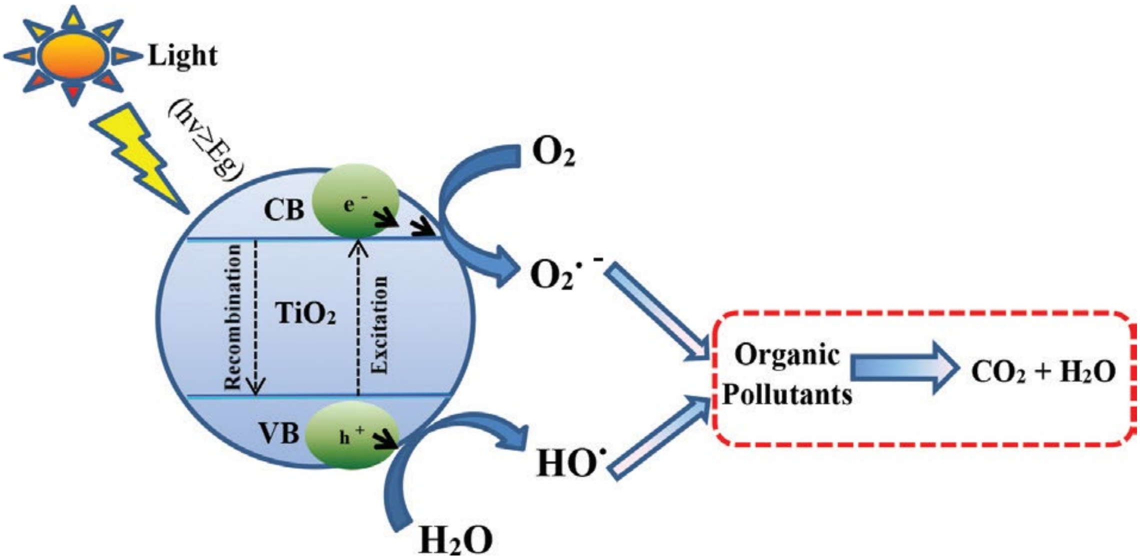

Figure 6. Schematic illustration of photocatalytic activity of TiO_2.

Image credits: By Emy Marlina Samsudin, Sze Nee Goh, Ta Yeong Wu, Tan Tong Ling,Sharifah Bee Abd. Hamid & Joon Ching Juan - Evaluation on the Photocatalytic Degradation Activity of Reactive Blue 4 using Pure Anatase Nano-TiO2, CC BY 4.0, https://commons.wikimedia.org/w/index.php?curid=99563290

These materials are applied to yarns or fabrics using the techniques typically used for industrial finishing of textiles—such as dipping or spraying the fabric into a solution containing the photocatalytic material—or by other coating techniques using printing pastes or inks. Other most advanced techniques—like magnetron sputtering, sol-gel techniques or plasma assisted processes—, which allow coating the textiles with a very thin layer to avoid changing the textile properties, are promising. For example, the magnetron sputtering has been used to deposit Ag/TiO_2 composite films on polyester fabrics. Sol-gel technology has been used successfully to prepare self-cleaning cotton textiles with water and oil-repellent properties. The multifunctional textiles can be prepared without affecting comfort properties.

As aforementioned, photocatalytic textiles have a range of potential applications, including air purification, water purification, and those to react with light and break down organic compounds that come into contact with the fabric. For example, photocatalytic materials can be used in smart textiles to break down bacteria, viruses, and other pollutants that are in contact with the fabric. This can help to reduce odours and improve the overall cleanliness of the fabric.

Want to learn more about this topic?

In the research papers *Advances in photocatalytic self-cleaning, superhydrophobic and electromagnetic interference shielding textile treatments* (Pakdel, Wang, Kashi, Sun & Wang, 2020) and *Photocatalytic property of polyester fabrics coated with Ag/TiO2 composite films by magnetron sputtering* (Yuan et al., 2020) you will find some practical applications to know more about photocatalytic textiles:

Besides, in the following link you will find a video presenting a self-cleaning textile developed by scientists from the National Institute of Chemistry and the Faculty of Natural Sciences and Engineering at the University of Ljubljana:

- Wash-resistant water and oil-repellent self-cleaning cotton textile: https://www.ki.si/en/for-industry/licensing-opportunities/advanced-materials-and-engineering/self-cleaning-cotton-textiles/

Summary

In this lecture you have learned the basics about (1) electrically conductive fibres, (2) light conductive fibres and (3) photocatalytic materials to design passive smart textiles. The classification of electrically conductive fibres as well as the main characteristics and commercial metal-, carbon- and polymer-based fibres and coatings have been described. Optical fibres, and more specifically the ones based on polymers, have been described. Finally, the main photocatalytic materials used for textile finishing have been reviewed.

References

Balint, R., Cassidy, N. J., & Cartmell, S. H. (2014). Conductive polymers: Towards a smart biomaterial for tissue engineering. *Acta Biomaterialia*, 10(6), 2341–2353. https://doi.org/10.1016/j.actbio.2014.02.015

Beckers, M., Schlüter, T., Vad, T., Gries, T., & Bunge, C. (2015). An overview on fabrication methods for polymer optical fibers. *Polymer International*, 64(1), 25–36. https://doi.org/10.1002/pi.4805

Bunge, C., Beckers, M., & Gries, T. (2016). *Polymer Optical Fibres: Fibre Types, Materials, Fabrication, Characterisation and Applications*. Woodhead Publishing.

Bunge, C., Woyessa, G., Bremer, K., & Lustermann, B. (2017). Special fibres and components. In *Elsevier eBooks* (pp. 119–151). https://doi.org/10.1016/b978-0-08-100039-7.00004-x

Chatterjee, K., Tabor, J., & Ghosh, T. K. (2019). Electrically Conductive Coatings for Fiber-Based E-Textiles. *Fibers*, 7(6), 51. https://doi.org/10.3390/fib7060051

Chen, S., Li, X., Peng, Y., Zheng, Z., Li, J., & Zhong, F. (2022). Conductive Fibers. *encyclopedia.pub*. https://encyclopedia.pub/entry/22383

Gehrke, I.; Tenner, V.; Lutz, V.; Schmelzeisen, D.; Gries, T. (2019). Smart Textiles Production: Overview of Materials, Sensor and Production Technologies for Industrial Smart Textiles. In *MDPI eBooks*. MDPI AG. https://doi.org/10.3390/books978-3-03897-498-7

Grancarić, A., Jerković, I., Koncar, V., Cochrane, C., Kelly, F. M., Soulat, D., & Legrand, X. (2018). Conductive polymers for smart textile applications. *Journal of Industrial Textiles*, 48(3), 612–642. https://doi.org/10.1177/1528083717699368

Qi, K., Daoud, W. A., Xin, J. H., Mak, C. L., Tang, W., & Cheung, W. P. (2006). Self-cleaning cotton. *Journal of Materials Chemistry*, 16(47), 4567. https://doi.org/10.1039/b610861j

Kallweit, J., Pätzel, M., Pursche, F. G. W., Jabban, J., Morobeid, M., & Gries, T. (2021). An Overview on Methods for Producing Side-Emitting Polymer Optical Fibers. *Textiles*, 1(2), 337–360. https://doi.org/10.3390/textiles1020017

Krifa, M. (2021). Electrically Conductive Textile Materials—Application in Flexible Sensors and Antennas. *Textiles*, 1(2), 239–257. https://doi.org/10.3390/textiles1020012

Li, X., Chen, S., Peng, Y., Zheng, Z., Li, J., & Zhong, F. (2022). Materials, Preparation Strategies, and Wearable Sensor Applications of Conductive Fibers: A Review. *Sensors*, 22(8), 3028. https://doi.org/10.3390/s22083028

Pakdel, E., Wang, J., Kashi, S., Sun, L., & Wang, X. (2020). Advances in photocatalytic self-cleaning, superhydrophobic and electromagnetic interference shielding textile treatments. *Advances in Colloid and Interface Science*, 277, 102116. https://doi.org/10.1016/j.cis.2020.102116

Yuan, X., Liang, S., Ke, H., Wei, Q., Huang, Z., & Lang, J. (2020). Photocatalytic property of polyester fabrics coated with Ag/TiO2 composite films by magnetron sputtering. *Vacuum*, 172, 109103. https://doi.org/10.1016/j.vacuum.2019.109103

Partnership

Project coordinator
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HACKTEX project was co-funded by the European Union through the grant 2021-1-RO01-KA220-HED-000027527.

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KA2 – Cooperation for innovation and the exchange of good practice
KA220-HED - Cooperation partnerships in higher education
Grant Agreement: 2021-1-RO01-KA220-HED-000027527

Project duration: 01/02/2022 – 31/07/2024

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