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Lamination of Nanofibre Layers for Clothing Applications

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Abstract
Nanofibre membranes and nanofibre products represent break-through technology in many fields of industry. They are used for air or liquid filtration, and their unique properties are suitable for many new health products or when manufacturing clothes etc. Their biggest advantage is their high porosity and fineness. On the other hand, the disadvantage of these membranes is the fact that it is not a homogenous material/foil, but a layer of fibres or rather several fibre layers (hereafter we will always use the term nanomembrane). This structure has a very negative impact on some of its properties i.e. strength, abrasion resistance, pressure resistance etc. This work introduces a 2-layer-laminate and 3-layer laminate where one of the layers is made of nanofibres with a view to their use in the manufacturing of clothes for sport and outdoor activities. The nanofibre membrane laminate must protect the wearer from weather conditions like rain and snow and, at the same time, enable transferring of liquid moisture from the wearer's body to the outside environment. Using lamination, we can connect the fine nanofibre membrane to a resilient textile material (knitted, woven or non-woven). This stronger textile material protects the more fragile nanomembrane from the outside environment (abrasion, friction etc.) while not diminishing its good comfort properties, like being windproof, waterproof and having good steam-permeability. The result of this work is a laminate with a high level of steam permeability, with minimum air permeability and a water column higher than 5000 mm. The tests carried out proved that during repeated washing cycles no delamination occurred and hydrostatic resistance decreased by approximately 20%.

Key words: *nanofibre layer, nanofibre membrane, lamination, Nanospider, outdoor.*

Introduction

There have been many scientific studies which have proved that a nanofibre membrane has got a small pore size, low fabric weight and high porosity. These properties make them suitable for use in many specific fields. For this reason, nanofibre membranes are expected to have high breathability, especially permeability to air and steam, which is important for high-performance clothing. One possible disadvantage of a nanofibre membrane is its low resistance to abrasion. Despite having so much potential, these above-mentioned bad mechanical properties make nanofibre membranes unsuitable for use in the textile industry [1-6]. To overcome this problem, a composite fabric with a nanofibre layer must be created which will withstand the possible surface damage of clothing during wear and sport activities. Lamination is a process which is carried out for the purpose of protecting nanofibres against mechanical damage, thereby reducing this disadvantage [7-8].

Lamination

In the textile industry the term lamination is used for the permanent connection of two or more woven, knitted or non-woven textile fabrics of the same or different composition and function (i.e. lining, face material etc.)

Liu [9] looked into the lamination of nanofibres between glass fibre fabrics. The polymer used for the nanofibre production was polyamid 6 with formic acid, trifluoroethanol and dimethylformamide. Electrostatic spinning with the use of a nozzle was applied. The laminate was clamped between two clamp jaws and put into an oven for two hours at a temperature of 120 °C. The aim of this work was to create a composite with better tensile and strength properties. The result showed that the nanofibres had no effect on those properties.

M. Munzarova [10] experimented with the lamination of nanofibres and non-woven fabric. She used 3-layer laminates, where a non-woven fabric was undertaken for the lining and face material. Dakota ethylen-vinyl-acetate-based powder adhesive was used for this lamination. Due to the fact that the final laminate was intended for face-mask filters, the mass per unit area/ fabric weight of the nanofibre layer was lower than 0.5 g/m^2. The process of lamination chosen in this work would therefore not be suitable for nanofibre layers with a higher fabric weight.

M. Mohamadian and A.K. Haghi [11] looked into the effect of the lamination temperature on a nanofibre layer. Their laminate was meant for clothing. The nanofibre layer was polyacrylonitrile created by electrospinning. A cotton fabric was used as the base material and a melting adhesive foil was utilised for the adhesion. The authors used an iron for the process of lamination, which was heated to temperatures ranging from 58 °C to 150 °C. Their experiment showed that an increase in the lamination temperature decreases the material's air permeability while at the same time increasing the adhesion between the nanofibre layer and textile material. It proves the claim that temperature affects the adhesion of the materials connected. This way of lamination is completely unsuitable for clothing purposes as the use of a melting adhesive foil decreases not only the material's air permeability but also its steam permeability.

Lately there has been a focus on creating a nanofibre laminate with good mechanical properties.

In their work, K.A. Hong et al. [12] tried to explain the production of nanofibre laminates with a higher resistance to abrasion and higher waterproofness. The samples used in this experiment were treated with a resin layer. For the laminate production a hot-melt dot-lamination process using a gravure coating machine was applied. This experiment proved that the choice of a suitable base fabric is the decisive factor for keeping the resin within the fabric structure and for maintaining the mechanical strength of the treated fabrics.

An important part of the lamination process is delamination, a process where the two layers of a composite textile material separate. This undesirable process should be suppressed during production. T.M. Brugo et al. [13] studied the delamination process of nanomembrane composite materials used in construction engineering. They used a polyamide 6 nanomembrane. Brugo and his team concluded that if we wish to increase the tenacity of a material, we must use a nanomembrane with a higher mass per unit area.

In their research work, S. Lee et al. [14] showed the very good mechanical and functional properties of nanomembrane composite materials. They found out that the use of thermo-compression at a suitably chosen temperature leads to retaining the good mechanical and functional properties of nanomembranes even after ten washing cycles without any morphological changes in the laminate. The overall results of this study proved the suitability of nanomembrane laminates for applications in outdoor wear.

Ragaišienė A. [15] inserted a web of nanofibres into the inner structure of a knitted fabric and in this way protected the web from mechanical damage. Her goal was to fix this nanofibrous web between the thread systems of the knit.

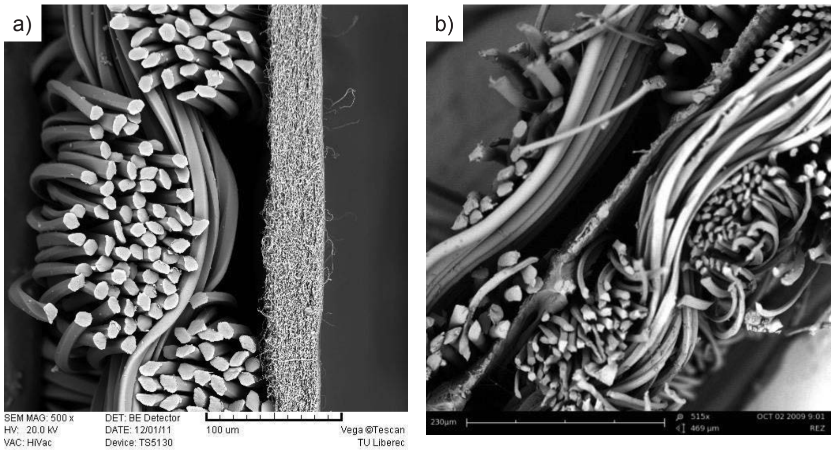

Figure 1. *Cross-sections: a) two-layer laminate, b) three-layer laminate.*

H. Lee [16] produced WO3-based nanofibres used as photocatalysts. He successfully fabricated WO3 nanofibres with palladium oxide (PdO) particles by combining electrospinning and chemical deposition processes. This led to the improved photocatalytic efficiency of the nanofibres compared to the WO3 nanofibres without PdO normally used.

[17] This author also produced nanofibres with terpolyester of isosorbide, ethylene glycol, 1,4-cyclohexane dimethanol, and terephthalic acid (PEICT) using electrospinning. The nanofibres have a higher glass transition temperature than other polyester-type polymers. They also show a better tensile property than other bio-based nanofibres, such as chitosan and gelatin. They can be used in tissue engineering, wound dressings and health care devices.

Hoik Lee [18] also studied nanofibres with terpolyester of isosorbide, ethylene glycol, 1,4-cyclohexane dimethanol, and terephthalic acid (PEICT) using electrospinning. The results of his work show that these nanofibres have a higher glass transition temperature (Tg) than other polyester-type polymers. Nanofibres with a smaller diameter have a higher Tg than those with a larger diameter. Increasing the diameter of the nanofibres also enhances their strength.

Subramanian S. studied experimental results of investigations of mechanical properties of nanocomposite mats produced by the method of core-shell electrospinning.

Textile laminates which have a nanofibre layer can be classified into two basic categories:

a) two-layer laminate – consisting of outer face material and a nanomembrane
b) three-layer laminate – consisting of outer face material, a nanomembrane and an inner lining

Two-layer laminate

This composite consists of an outer textile layer and nanofibre layer (***Figure 1.a***). Its big disadvantage is the fact that the nanomembrane is not protected and this can be damaged by abrasion or soiling (e.g. by sweat), which leads to a significant decrease in its functionality.

Three-layer laminate

The lamination of a layer of outer textile material, a nanofibre layer and an inner textile layer is the most common type (see ***Figure 1.b***) because it decreases the possibility of damaging the nanomembrane. The nanomembrane layer is very well protected from dirt and also from friction, which leads to its abrasion.

Membranes for clothing purposes

The purpose of membranes is to increase the comfort of a garment no matter whether it is a jacket, pair of trousers, gloves or shoes. Every kind of textile material has its natural limitations. By inserting a membrane between the top face-material and bottom lining-material (the lining material is not always necessary), we can improve these limitations and consequently the resulting composite material can serve its purpose for a longer time while the wearer experiences a higher level of comfort. The membrane in clothing enables three functions: steam permeability, wind- and waterproofness.

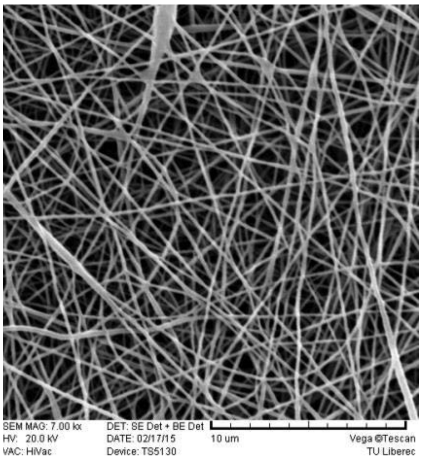

Figure 2. *Nanofibre membrane.*

Figure 3. *Polymer dot on lining created during the coating process.*

Electrospinning

One option for producing a nanofibre layer by electrospinning is a setup with a vertical capillary and collector placed under it. The polymer solution drips from the capillary because of gravitation and an electrical field and forms submicron fibres (in the range of 1000 nm) which are deposited on the surface of the collector. During this process, a high intensity direct electrostatic field is used to create a charged stream of the polymer solution or melt. One electrode has the form of a narrow capillary and is connected directly to the polymer solution, while the other (often called the collector) has the form of a plate, which is positioned with its flat side opposite the tip of the capillary at a certain distance. The polymer solution is exposed to a high electrical voltage, which results in the surface layer of the solution becoming charged. When the voltage is sufficiently high, it overcomes the surface tension of the liquid and Taylor cones begin to form on its surface. The charged liquid is pressed out, forming a charged liquid jet which is elongated and split on its way to the collector. The solvent agent evaporates and dry solid fibres deposit on the collector in a nanofibre layer [19].

Experimental part

Material

Two- and three- layer laminates were produced for this experiment.

The following fabrics were used for the face material:

1) Woven fabric, yarn 100% polyamide, thread count – weft 36 threads/cm, warp 53 threads/cm, mass per unit area – 70 g/ m^2
2) Woven fabric, 100% cotton yarn, thread count – weft 82 threads/cm, warp 82 threads/cm, mass per unit area – 190 g/m^2

In the three-layer laminate, a warp knitted fabric made of 100% polyester (11 wales/columns per cm, 17 courses/rows per cm, mass per unit area 27g/ m^2) was used as the third layer (lining). The nanomembrane had a mass per unit area of 5 g/m^2.

Polymer solution preparation

Polymer solution for the production of polyurethan nanofibre membranes was prepared by stirring 115 g of Larithane LS 14086 into a solution containing 50 g of dimethylformamid (DMF), 55 g of saturated solution of bromine in DMF and 5 g of distilled water. This solution was then stirred using an electric stirrer.

Creating a nanofibre layer

A polyurethane nanofibre layer was produced by electrospinning. This polymer was chosen due to its easy spinability and high speed of spinning. A nonwoven fabric of the spunbond type with a mass per unit area of 30 g/ $m^2$was used as the support material. Its production in a laboratory using the Nanospider machine. The polymer solution was added to a basin with a rotating roller. This solution was exposed to an electrofield of U = 76.1 kV voltage. A collector was placed above the basin at the distance of 175 mm. The speed at which the base material was moving was set at v = 0.1 m/min. The relative humidity in the spinning chamber was regulated at 21%. The humidity sensor was not placed directly in the spinning chamber, but in the tube bringing air to the chamber to ensure proper sealing. The turning of the roller (driven by a rotor) in the basin created a thin polymer solution layer on its surface, from which, in turn, nanofibres were formed due to the high voltage and collected on the support-material. The mass per unit area of the nanofibre layer created was 5 g/m^2 and the nanofibres diameter 150 nm. An image of the nanofibre membrane on its own is shown on ***Figure 2***.

Nanospider is a technology created at and patented by the Technical University of Liberec in 2004 (Department of Nonwoven Textiles). This technology enables the mass production of individual continuous nanofibres from various polymers. The method is based on the fact that Taylor cones can be created on a thin layer of polymer solution. This method does not use any nozzle or spinning capillary, but does use an electrode in the form of a rotating cylinder, which is partially immersed in a polymer solution and rotates slowly. The opposite electrode, the collector, is placed above it. A support textile material moves across the collector electrode. The high voltage causes the occurrence of Taylor cones on the surface of the rotating electrode, which, in turn, produce nanofibres. The nanofibres are transported towards the collector and form a nonwoven nanofibre fabric on the support-material.

Creating a laminate

The above-mentioned laminates are produced during a process called lamination. Lamination is carried out in two steps:

- coating – the application of an adhesive
- lamination – the bonding of two layers

Coating

Coating is the application and bonding of an adhesive layer onto textile material (face fabric or lining). The mass per unit area and structure of the base textile must correspond to the quantity and size of adhesive points applied, to achieve the best possible properties of the final laminate e.g. a soft-touch feel and good durable adhesion, and to minimise the risks of the adhesive penetrating the base fabric.

Generally we can say that the adhesive layer can be continuous or partial (full-surface coating or patterned/dot coating). In the production of laminates, dot-coating is more common as it leads to low stiffness, a soft-touch feel and good steam permeability of the final laminate, which are important properties for clothing fabrics.

The following methods are used for creating a partial adhesive layer:
- scatter coating – an irregular distribution of adhesive
- gravure roll coating– a regular distribution of adhesive
- gravure roll and scatter coating – bi-component points
- hot melt coating

Gravure roll coating was used for the production of experimental samples. Adhesive was applied in the form of dots (see ***Figure 3***). This method is commonly used in the clothing and footwear industry. The advantages of this process are the even distribution of the quantity of the adhesive applied on the base textile, the easily controllable coating process, and the soft-touch feel of the laminate.

First the base fabric is warmed up by being run between two steel rollers heated to 170 °C. These rollers together with the fabric are pressed against a gravure print roller heated to 138 °C. A doctor blade wipes the gravure roller clean and thus ensures that an exact amount of adhesive powder is applied. When the warm base fabric touches the gravure roller, the adhesive agglomerates are transferred from the gravure cells to the fabric's surface. These powder agglomerates are consequently heated in an infrared field, which leads to their melting and the creation of adhesive dots bonded to the base fabric. The temperature of the infrared field was 170 °C.

A Villars AG coating machine and gravure roller with mesh 17 were used in this experiment. A powder adhesive with particle size 80-200 µm was used for coating. The diameter of the adhesive dots was 0.77 mm, and the amount of adhesive applied was 8-10 g/m^2. The final dot is shown in ***Figure 3***.

Producing a laminate

Two-layer laminate

For the production of a two-layer laminate, a face fabric with adhesive lamination dots and a nanofibre membrane on a support material is needed.

When laminating the face textile and nanomembrane, we created samples of 50 x 50 cm. First the nanomembrane was placed on the face textile on the side of the lamination dots. These two layers were placed on the bottom part of the Kannegiesser coating machine unit. On the top part of the unit, the following conditions were applied for 15 seconds: pressure 3 bar, temperature 120 °C. After the laminate had cooled down, the support material was removed by hand (see ***Figure 1.a***)

Three-layer laminate

For the production of a three-layer laminate, a face fabric with lamination dots and a nanomembrane were used again, but also a lining fabric with lamination dots applied just as they were on the face fabric.

The procedure was at first the same as when creating the two-layer laminate. After creating the two-layer laminate and removing the support material, a lining textile was placed on the nanomembrane on the side with the lamination dots, and this three-layer structure was again run through the coating machine under the same conditions (see ***Figure 1.b***).

4 kinds of samples were produced:
- 2-layer laminate P2: face textile polyester + nanomembrane
- 2-layer laminate C2: face textile cotton + nanomembrane
- 3-layer laminate P3: face textile polyester + nanomembrane + lining
- 3-layer laminate C3: face textile cotton + nanomembrane + lining

Properties of the individual materials are presented in ***Table 1***.

Table 1. Properties of the original materials.

Property	Material – mean value (standard deviation)			
	Polyester fabric	Cotton fabric	Nanomembrane	Lining
Air permeability, l/m^2/s	3.3 (0.03)	177 (4)	48.5 (1.2)	569 (0.5)
Steam permeability Ret, Pa.m^2.W^{-1}	0.84 (0.05)	5.04 (0.05)	<0.1	0.5 (0.05)
Hydrostatic resistance, mm	241(28)	289 (9)	–	–
Thickness, mm	0.14 (0.05)	0.51 (0.05)	–	0.26 (0.05)

Table 2. Measurement results for laminate samples.

Property	Material – mean value (standard deviation)			
	P2	P3	C2	C3
Air permeability, l/m^2/s	2.144 (0.022)	1.666 (0.013)	2.684 (0.07)	2.19 (0.02)
Steam permeability Ret, Pa.m^2.W^{-1}	0.92 (0.083)	3.16 (0.114)	5.26 (0.114)	7.3 (0.122)
Hydrostatic resistance, mm	5812 (222)	24405 (1388)	5250 (311)	31522 (883)
Mass per unit area, g/m^2	79 (0.052)	230 (0.023)	150 (0.069)	270 (0.048)
Thickness, mm	0.146 (0.011)	0.382 (0.008)	0.51 (0.007)	0.782 (0.013)

The following properties, which relate to thermo-physiological comfort, were measured on samples of the 4 different kinds of laminates using the equipment stated below:
- hydrostatic resistance – instrument SDL Atlas M018 Hydrostatic Head Tester; the instrument works in accordance with ISO 800818 [20]
- air permeability – instrument Fx 3300 Labotester III; the instrument works in accordance with ISO 9237 [21]
- steam permeability – instrument Permetest the instrument works in accordance with ISO 11 092 [22]
- thickness of sample – instrument Alambeta

Results

This work investigates the influence of an added lining and the type of face fabric on the comfort properties of the final composite material. Air permeability, steam permeability and thickness were measured 5 times and the hydrostatic resistance 4 times for each sample. The resulting data were processed using statistic software – QC Expert version 2.7. Two factor analysis of variance was used and the effect of interactions was also monitored. The significance level was chosen at $\alpha = 0.05$. The mean values and standard deviations are stated in ***Table 2***. The thickness of the laminate is also given there.

Two-factor analysis of variance with interactions was used for monitoring the combined effect of the number of layers (added lining) and face textile used. For all the properties monitored (steam permeability, air permeability and hydrostat-

__Table 3.__ Hydrostatic resistance after 5 washing cycles.

Property	Material – mean value (standard deviation)	
	C2	C3
Hydrostatic resistance, mm	3990 (102)	23 980 (453)

ic resistance), their effect was confirmed for the significance level chosen. The interaction effect was significant only for the hydrostatic resistance.

Steam permeability results show that laminates made with polyester as well as cotton are exceptionally steam permeable. The steam permeability of the nanomembrane is of such a low value that it is below the measuring range of the Permetest machine used, which proves that the steam permeability of the nanomembrane will have a minimum negative effect on that of the final laminate. The results stated in ***Tables 1*** and ***2*** show that the worsening of the steam permeability of the two-layer laminates was below the level of 10%. The more substantial steam permeability changes for three-layer laminates must therefore be caused rather by the third layer (lining) than the nanomembrane.

A noticeable effect of the nanomembrane, or the nanomembrane with a lining, can be observed with hydrostatic resistance, which rose from centimeters of the water column to 5 m thereof for two-layer laminates and more than 20 m for three-layer laminates. This high hydrostatic resistance together with the good steam permeability indicates that a membrane made from nanofibres can be used for outdoor clothing (e.g. jackets). The air permeability values are very low for two-layer laminates as well as for three-layer laminates. Low air permeability is not important when windproof clothing is required.

Resistance of laminates to washing

Laminates with cotton face fabric C2 and C3 were tested for their resistance to washing cycles. The samples underwent 5 washing cycles and their delamination tendencies were monitored. Changes in hydrostatic resistance in samples C2 and C3 were also monitored.

Washing conditions used:
Detergent: Perwoll Sport & Active
Washing machine: Miele Professional W 6071
Washing time: 30 min.
Temperature: 30 °C
Spinning speed: 800 rpm

Results: No delamination occurred on the C2 and C3 samples after 5 washing cycles. ***Table 3*** shows the values of hydrostatic resistance after washing. Comparing the values in ***Tables 2*** and ***3*** shows a decrease of about 25% in hydrostatic resistance for both samples.

Conclusions

The goal of this work was to create a laminate suitable for outdoor clothing where one of the layers will be made of nanofibres. A broader goal was to create a laminate which enables the use of nanofibre membranes in such an environment where the demands on tensile strength and abrasion resistance are high. A procedure was designed and verified which shows that it is possible to create a laminate where the nanofibre layer functions as a membrane which guarantees good hydrostatic resistance, steam permeability and windproof properties. The nanofibre layer was made of polyurethane. Two types of fabric with a different mass per unit area and different composition were used for lamination with the nanomembrane. One was cotton textile and the other polyester. In the 3-layer laminate a warp knitted polyester fabric was used as the third layer.

The minimum steam permeability values reached in this study were from Ret = 1 $Pa.m^2.W^{-1}$ for two-layer laminates and from Ret = 3 $Pa.m^2.W^{-1}$ for three-layer laminates. The results show that the effect of the nanomembrane on the steam permeability was minimal.

Air permeability values ranged from 1.5 to 2.7 $l/m^2/s$, which is a substantial decrease compared with those for the face textiles on their own. It is relatively low air permeability.

Minimum values of hydrostatic resistance were over 5 000 mm of the water column for the two-layer laminate and over 24 000 mm of the water column for the three-layer laminate. A value of 10 000 mm of the water column is considered the limit value for outdoor activity clothing. Our results show that the three layer laminate would be suitable for such purposes.

The durability of the laminates was tested through repeated washing. No delamination occurred after 5 washing cycles and the hydrostatic resistance decreased by approximately 25%.

We can conclude that two-layer and three-layer laminates were successfully created which are suitable for outdoor and sports clothing, where the nanofibre layer works as a membrane/barrier against bad weather and environment conditions. We assume as well that these laminates could also be used for air and liquid filtration in places where a nanomembrane on its own could easily be damaged.

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MUSEOEUROPE 2019
THE REGIONAL MUSEUM MARIBOR, Slovenia
invites you to take part in the international symposium

TEXTILE, THE CULTURE OF CLOTHING AND FASHION

The MUSEOEUROPE project was conceived in 2012 as part of the project MARIBOR 2012, European Capital of Culture. In 2014, our museum organised a symposium on the theme of The Applied Value of the Wooden Wheel. In 2015, the theme of the symposium was Meetings of Two Worlds. In 2016, on the 170th anniversary of Franz Liszt's performance in the Knights' Hall of Maribor Castle the symposium theme Europe at the Time of Franz Liszt was dedicated to this musical virtuoso. In 2017, the central focus is on kitchens, food and eating under the umbrella title of Kitchen Debate. The year 2018 was centred upon the general theme of the uniform as a reminder of social order and tradition.

The Regional Museum Maribor holds the country's largest and pivotal collection relating to fashion and textiles. The collection includes aristocratic and bourgeois fashion wear from the 17th century to modern times, women's, men's and children's clothing, footwear, headgear, various fashion accessories, fashion graphics, journals and textiles of various other uses. In 2019, the fashion and textile collection will be presented in a new depot setup, which will also include items from a visiting museum of the MUSEOEUROPE 2019 project.

For the MUSEOEUROPE 2019 symposium, we welcome research papers that reflect on the development, characteristics and functions of fashion and culture of clothing in different prehistorical and historical periods, on the role and significance of fashion, on design, development, textiles and technology, on the meaning of fashion as identity and its role in culture. It will be also interesting to hear about the experiences of fashion and textiles experts, dealing with the preservation of clothes and exhibitions. Papers will be grouped into four sections:

I. Role and meaning of the culture of clothing and fashion (historical reviews, the function of fashion and dressing culture, fashion as communication, fashion as identity, fashion as a symbolic and visual culture, the meaning and role of fashion in culture, fine art and aesthetics, the influence of dressing culture and fashion on politics, culture and everyday life)
II. Textiles and technology (history of materials, new materials, new technologies, fashion innovations, alternative sustainable solutions, concepts, development, testing, fashion in textile and clothing industry)
III. Tradition and crafts (daily dressing culture, development, role and importance of the folk costume, folklore, history and crafts development)
IV. Textiles, culture of clothing and fashion in museum setups and educational programs (exhibitions, preservation, restoration, handling, educational programs and projects)

We invite historians, arthistorians, ethnologists, archeologists, anthropologists, sociologists, cultural scientists, psychologists, communicologists, pedagogues, textile technologists and other researchers of textiles, culture of clothing and fashion, to participate.

The symposium will take place on **17-19 October 2019** in the **Knights' Hall of Maribor Castle**. Contributions should be in English and will be published in an electronic collection of papers. **The submission deadline** for the preliminary titles and abstracts comprised of up to 600 characters without spaces is **9 December 2018**. You will be notified of having been selected by 20 December 2018.
The selected authors should send their contributions in English to the following email address: museoeurope@museum-mb.si by 10 April 2019. English language revision of the contributions and their translation into Slovene will be provided by the symposium organiser. The selected papers will be presented at the symposium in Slovene and English. The duration of each presentation is 15 to 20 minutes. Registration Fee for Authors is 70 EUR. Additional information can be obtained by writing to museoeurope@museum-mb.si, by calling +386 (0)2 228 35 51 or on web site www.museum-mb.si/museo-europe/.

Warm regards on behalf of the Regional Museum Maribor.
Dr Mirjana Koren, Director

Maribor, 19 October 2018