DEVELOPING FIBROUS MULTIFUNCTIONAL STRUCTURES FOR TECHNICAL APPLICATIONS

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Abstract

This paper describes a quick prototyping unit for fibrous multifunctional structures which has been set-up at the University of Minho. This unit provides for fast development of technical samples for a variety of special applications, mainly in the areas of health and well-being, sports goods, personnel protection, techno-fashion, the civil construction and building industries, composite materials, and so on.
The unit works systematically through the areas of conceptualisation, design and simulation, development, manufacturing and testing of technical and intelligent textile materials and structures, providing solutions for technical problems.
New structures are developed for specific applications where special requirements are needed.
It provides the best solution in terms of materials, structures, technologies and cost. The technologies involved include advanced CAD systems, FEA (finite element analyses), testing of mechanical properties, permeability, conductivity, microscopy, as well as small-scale-computer controlled manufacturing of yarns, nonwovens, wovens, warp & weft knits, braids and hybrid structures. Special finishings and surface treatments, coating and lamination are also possible.
The unit is used for research, education and to provide services for companies in emerging markets for advanced textile materials.
Examples of the novel products developed are provided.

Key words:

multifunctional structures, intelligent materials, nano-technologies, finite element analyses, simulation, modelling, specialty products, mass customisation

Introduction

Mass customisation has been defined as the organising principle of business in the 21st century. Because it is characterised by small lot production, timely delivery, competitive cost, and a move away from centralised manufacturing, mass customisation is fast becoming the *modus operandi* of companies seeking to obtain or maintain a competitive edge in today's marketplace.

Mass customisation is characterised by total market segmentation (1 customer per segment), and can be viewed as the quick & personalised design, manufacturing and delivery of products. In the case of textiles, customisation includes personalising the fibre, the yarn, the fabric, the finishing, the accessories, the style of the garment, the delivery and so on.

Many specialty products have to be customised for technical reasons, to suit a particular application or customer, for example, a vest to monitor the vital functions of the human body requires fitting and tuning of sensors in a customised way.

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The rapid prototyping of fibrous multifunctional structures is viewed as a model for customising specialty products for technical applications, that is, making samples. It may, of course, also be used for the development of advanced fashion products (techno-fashion).

The technologies involved include advanced CAD systems, FEA (finite element analyses), testing of mechanical properties, permeability, conductivity and microscopy, as well as small-scale computer-controlled manufacturing of specialty yarns (fancy yarn twister), specialty non-woven fabrics (60 cm wide non-woven line), specialty woven fabrics (two 100 cm wide rapier looms with multiple weft insertion, one of which has an electronic Jacquard and the other a special weft insertion to handle difficult yarns), specialty warp knitted fabrics (a 100-cm wide electronic Raschel machine), specialty weft knitted fabrics (two 120-cm wide electronic Jacquard flat machines with special feeding units to handle difficult yarns), specialty braided fabrics (vertical and horizontal machines) and hybrid structures. Specialty finishings and surface treatments, coating and lamination can also be developed on a small scale.

Multifunctional fibrous structures

The development of multi-functional textile structures and systems may be approached in two ways:

1. Developing structures with well-defined geometrical areas, each having a different pre-defined property;
2. Developing structures which, on the whole, have an array of different pre-defined properties.

Developing functional and multifunctional textile materials

In textile material science, the approach to developing functional materials can be divided into two areas:

1. The development of functional fibres to be used in the fabrication of the textile structures;
2. The development of functional finishings to be applied to or embedded in the textile structure.

In each case, the objective is to develop specific properties which will enable these materials to perform a particular task in the final product in a better way.

Examples of these are the development of special intense odours (such as insect repellents, perfumes, etc), anti-bacteria, anti-mildew, water repellents, water proofing, wind proofing, breathability, colour change (for example, thermochromic, photochromic, electrochromic), heat creation and exchange (such as phase change), shape change (for example, shape memory), high strength, high or low stiffness, low density, high electrical conductivity, high thermal insulation, high absorption, high permeability and so on.

Some of these materials may be active or passive. Passive materials' characteristics are quite stable (e.g. Young's modulus). However, in active materials there is a change of characteristics (e.g. colour, heat creation and exchange, electric conductivity) in response to an external agent (such as temperature or a magnetic field).

It should be stressed that a particular material may normally have only one specific but robust functionality. To have a single material that is a "jack-of-all-trades and a master of none" and has all sorts of functionalities does not seem to be the way ahead. However, if a variety of specific functions are desired for the final product, molecular blending, particle blending and fibre blending may be a way to develop multifunctional materials and products for a number of applications.

For other applications, however, other methods are being devised. This is the case of the current work, which follows a different path in the development of multifunctional textile products, i.e. the development of multifunctional textile structures and systems from single-function and multi-function material elements.

Nano-technologies

There are limits to the classical technologies used to develop textile materials. However, with the advent of nano-technologies (10^{-9} m), it is possible to create and develop super-materials in which the performance is many times that of the classical ones (one example is increasing the strength of a rope exponentially whilst decreasing its linear density exponentially). This is done by designing materials at the very essence of matter, that is, the atom and the molecule. With nano-technologies it is becoming possible to extrude nano-fibres and manufacture nano-particles with specific super-properties. These may be used to manufacture extremely strong and extremely light textile structures, as specific properties like the modulus of elasticity of the fibres may be extremely high and the density extremely low. If fibres can be spun to the diameter of a macromolecule, then the axial alignment of the molecule in the fibres can be ideal, and the modulus of elasticity much increased. With such fibres it would be possible to develop super-structures of extremely high strength, stiffness, toughness, permeability and so on at extremely low density. Nano-particles could be embedded to enable super-properties in all types of active materials.

Some of the applications may include multi-functional filters (dust, bacteria, virus), ballistic products, fibre-reinforced composites, surface-modified textiles, membranes for lamination and coatings, medical and well-being textiles, techno-fashion and so on.

Developing Multifunctional Fibrous Structures

The basic concept of developing multi-functional textile structures is one of assembling different types of robust high performance material elements (for example fibres, particles, microcapsules, additives, and so on) in a particular pre-defined way to perform various specific tasks.

The use of yarn and fabric engineering design concepts is essential, together with the most advanced yarn and fabric-forming and -finishing technologies.

Starting with functional materials A, B, C, D, E…..these may be assembled as shown in Figures1 to 4.

As concerns linear multifunctional structures, the possibilities are many. However, some examples of the two fundamental ways of developing them are given below:

- a multifunctional linear structure with a homogeneous effect, as shown in Figure 1;
- a multifunctional linear structure with a localised effect, as shown in Figure 2.

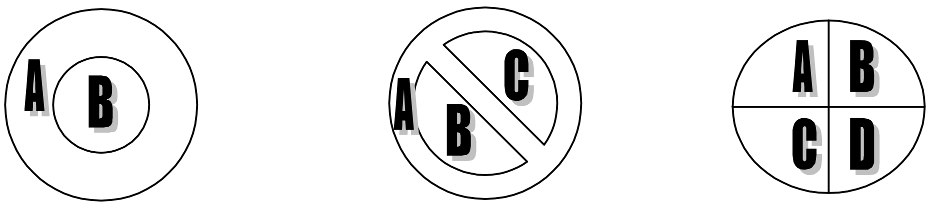

Figure 1. Schematic diagram of multifunctional linear structures with a homogeneous effect (shown in cross-sections)

The examples given in Figure 1 may be achieved by twisting and braiding.

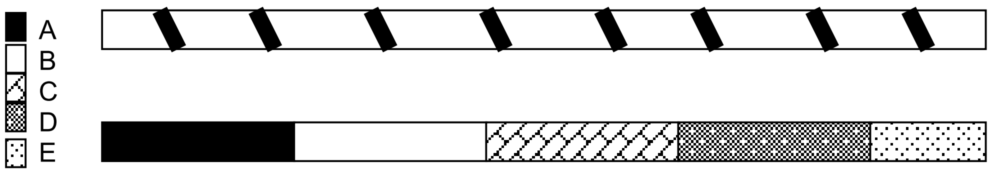

Figure 2. Schematic diagram of multifunctional linear structures with a localised effect (shown lengthwise)

The examples given in Figure 2 may be achieved by spraying and space printing.

With respect to planar multifunctional structures, there are also two fundamental ways of developing these:

- a multifunctional planar structure with a homogeneous effect or layered structures, as shown in Figure 3;

- a multifunctional planar structure with a localised effect or patchwork structures, as shown in Figure 4.

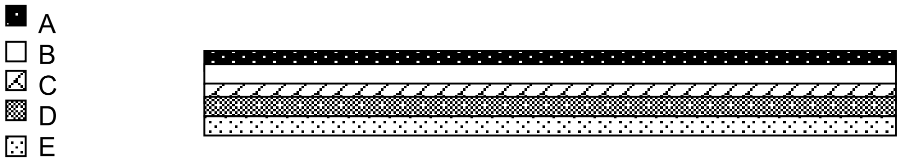

Figure 3. Schematic diagram of a multifunctional structure with a homogeneous effect or layered structure (shown in cross-section)

The example given in Figure 3 may be achieved by knitting (e.g. plaiting, sandwich fabrics), weaving (e.g. multi-layered, spacer fabrics), non-woven technologies, coating, printing, laminating or combinations of these.

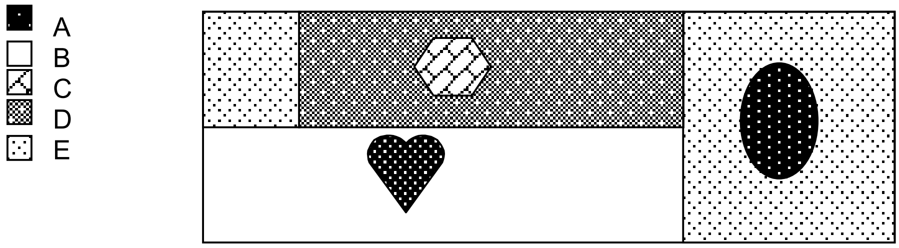

Figure 4. Schematic diagram of a multifunctional structure with a localised effect or patchwork structure (technical face shown)

The example shown in Figure 4 may be achieved by knitting (e.g. intarsia, Jacquard), weaving (e.g. interchangeable double fabrics, Jacquard, multiple weft insertion), embroidery, printing, spraying, flocking or combinations of these.

Combinations of the various approaches are also possible.
Depending on the application, the most suitable materials, structures and technologies to achieve the desired result should be selected.

In this context, fabric structure takes on a new dimension, as weaves and stitches have to be studied in the context of combining different functionalities (rather than just colour or pattern). In this way fabrics with novel properties may be developed, whose patterns may take the form of electrical circuits, transistors, resistors, capacitors, sensors, actuators and so on. The scaling down of all these components may be achieved through the development and application of nano-technologies.

<u>Setting up a specification for a health monitoring vest</u>

The structure being developed for use in apparel for the purpose of monitoring the vital functions of the human body should be comfortable, washable and flexible.

In order to achieve thermo-physiological comfort the structure should keep the body dry, at constant temperature and be able to breath in order to transfer body's excessive moisture. It should be able to support sensors, a display, a CPU, a transponder and a power supply in order to monitor the vital functions of the human body, communicate and be positioned by GPS.

A specially designed three-layered knitted structure could be as follows:

1^{ST} LAYER: an open thick structure made of a hydrophobic fibre to be worn close to the skin, in order to keep the body dry and prevent moisture formation near to the skin of the human body, thus creating discomfort by sweat and thermal stress; an elastomeric fibre should be mixed in a small percentage for snugness;
2^{nd} LAYER (in the interface 1^{st} layer/ 3^{rd} layer): sandwiched between the 1^{st} and 3^{rd} layers is a layer of electrically conductive fibres to conduct electric current from a power supply to the sensors, display unit, CPU and transponder. The sensors and the display unit have micro-antennas for wireless

communication with the CPU, which also includes a micro-antenna and thus forms a LAN. The signals from the sensors are processed in the CPU, and the measured values are displayed in the display unit and sent by wireless means wherever required. The transponder enables GPS positioning; it should be finished with a micro-encapsulated PCM (phase change material) with a melting point of 28ºC in order to create an active thermal barrier between the human body and the atmosphere.

3rd LAYER: a highly hydrophilic fibre to be used away from the skin to absorb body moisture with little contact with the human body; it should be porous for breathability, and anchored by small channels to the 1st layer to help moisture transfer by capillarity.

■ - 1st layer composed by 5% spandex and 95% polypropylene
□ - 2nd layer composed by metal fibres to conduct electric current to embedded electronics + PCM
☒ - 3rd layer composed of highly hydrophilic cotton

1 – sensors with micro-antenna,
2 – display with micro-antenna
3 – transponder
4 – CPU with micro-antenna
5 – power supply (ex battery)
6 – moisture transfer channels

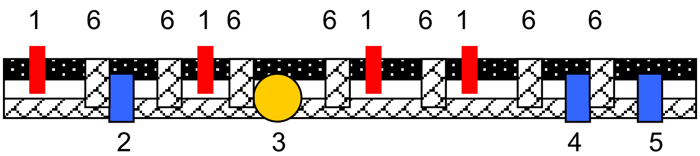

Figure 5. Schematic diagram of a multifunctional structure with embedded electronics for health monitoring (cross-section)

Other samples may be developed using different fibres:
- conductive fibres, based on polyaniline and polypyrole (2nd layer); or
- fibres with special surface finishing and an odd cross-section to induce wicking (3rd layer).

Figure 6 shows a variety of multi-layered structures produced in a flat-bed knitting machine.

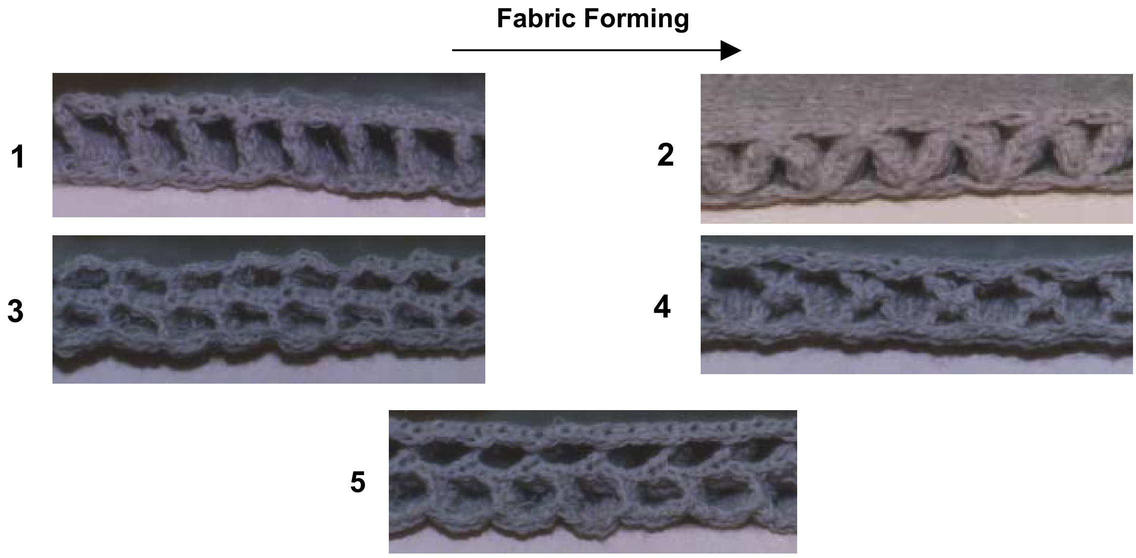

Figure 6. Multi-layered sandwich fabrics produced in a flat-bed knitting machine
(1) Rectangular core structure (connecting layer: rib)
(2) Triangular core structure (connecting layer: interlock)
(3) Honeycomb core structure (connecting layer: jersey combined with rib)
(4) Triple face structure 1 (connecting layers are not alternated)
(5) Triple face structure 2 (connecting layers are alternated)

Example of a layered structure developed to maximise thermo-physiological comfort

In the example shown in Figs. 7–9, the objective is to develop a structure with maximum thermo-physiological comfort in the wet state, according to specified reference values of some thermal properties, namely high thermal resistance and low thermal absorption.

1 – absorbing layer (cotton);2 – separation layer (polypropelene); 3 – suction channel (cotton)

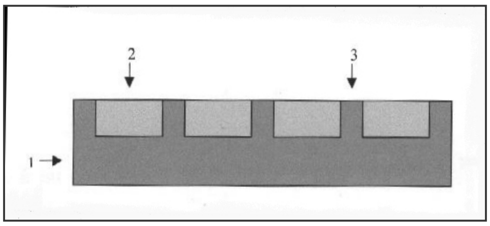

Figure 7. Schematic diagram of a two-layer structure with suction channels

1 – suction channels (cotton); .2 – separation layer (polypropilene)

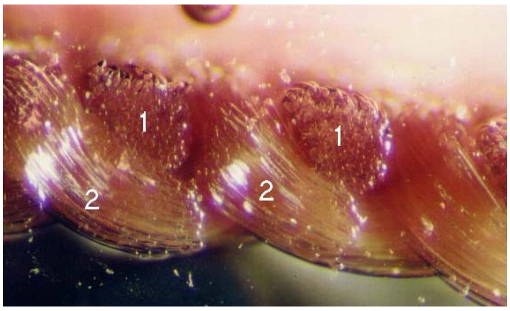

Figure 8. Microscopic view of the suction channels

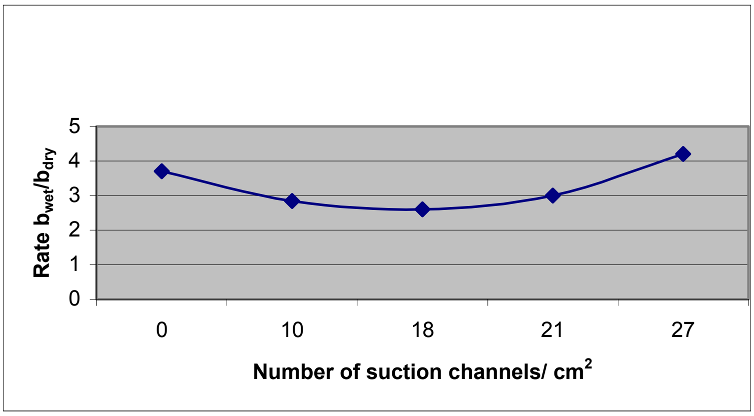

Figure 9. Optimised number of suction channels

Conclusions

The quick prototyping unit set-up at the University of Minho has been an invaluable tool for the development of novel multifunctional fibrous structures, thus contributing to the rapid development of technical samples for a variety of special applications.

The thinking behind the development of multifunctional structures has been systematised, thus providing a variety of possible solutions for solving specific problems.

Examples are given of multifunctional structures that are being developed for specialty products.

References

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