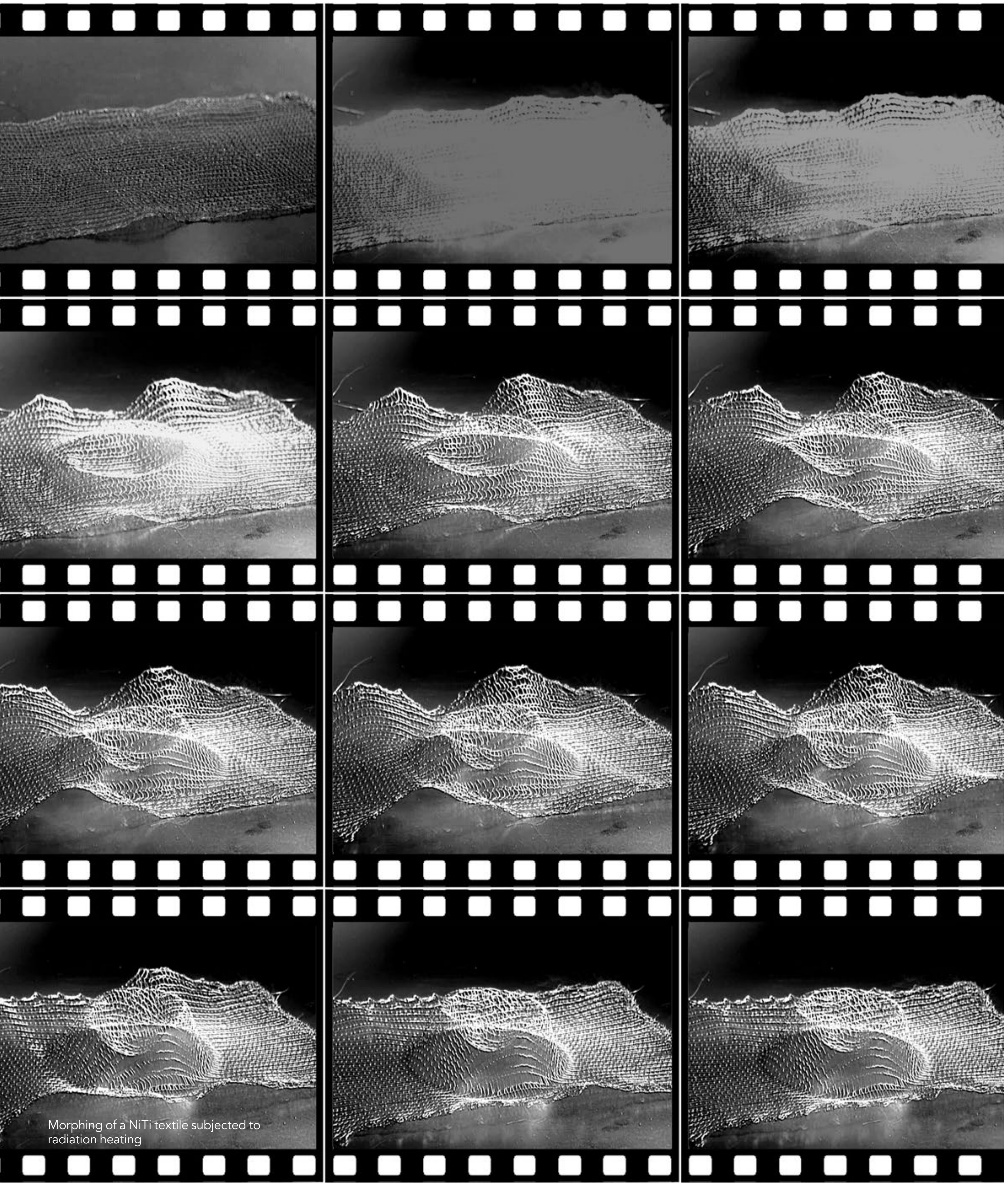


Morphing of a NiTi textile subjected to radiation heating

Functional textiles driven by transforming NiTi wires

Weaving textiles from nickel-titanium (NiTi) wires offers a way to give garments a 'shape memory' where they can return to their original shape after being deformed by applying heat. **Dr Ludek Heller** and **Dr Peter Sittner**, at the Institute of Physics of the Czech Academy of Sciences, have found new ways to make and process wires to take advantage of the numerous, exciting applications of their NiTi wire technology, including in the manufacture of protective clothing for firefighters and astronauts.

Imagine a dress that, no matter how much you crumpled it up or wrinkled it, could pop back to its original shape, just with a little heat. Imagine clothing that could move and morph designs, just by changing the temperature of the environment. All of this can now be achieved in the era of 'smart' or 'technical' textiles, where new technologies are being combined with traditional textile manufacturing to create high performance materials with a whole variety of exciting applications.

It is not just high fashion and design that has been making use of the rapid development of technical textiles. Sportswear manufacturers are very interested in novel textiles that help better regulate body heat, or offer better protection in extreme weather conditions. These applications are not just limited to clothing either – technical textiles can now be found in bandages that have enhanced antibacterial properties to reduce the probability of post-operative infections.

Among these, one of the most exciting developments is the use of shape memory alloys in technical textiles. These are materials that can be set into a shape and, no matter how they are distorted, they will return to their original shape on heating. This is how 'animated' dresses can be created that seem to move of their own free will.

Dr Ludek Heller and Dr Peter Sittner, at the Fyzikální ústav AV ČR, are experts in this highly interdisciplinary area. Their research is about finding new ways to combine nickel-titanium wires with traditional textiles to achieve many of the proposed novel applications. Dr Sittner describes their role as being, "physicists – metallurgists – mechanical engineers, that, coupled with textile manufacturers, make hybrid metallic textiles".

PROPERTIES OF NITI

Why is NiTi the alloy of choice for making the wires that are combined with traditional yarns? NiTi (sometimes called NiTiNOL, an acronym derived from its composition and place of discovery – Naval Ordnance Laboratory) is the most commercially successful shape memory alloy. NiTi wires and thin filaments have functional and structural properties outperforming other shape memory alloys.

NiTi is relatively easy to process into wires that range in diameter from a few to tens of microns thick – roughly the thickness of a human hair. They can be combined with traditional yarns made from cotton or wool to make a variety of different fabric types. The stretchability of the NiTi wires (due to their superelastic functional property) is fairly similar to the blended yarns so the overall fabric is suitable for use in items like clothing.

It is the superelasticity and shape memory properties of NiTi that Dr Heller and Dr Sittner are most excited about. Much of their work has been on characterising the thermomechanically induced martensitic transformations that give the NiTi wires their unique physical properties, and on finding new ways to transform these properties into smart and functional properties of NiTi textiles. Martensitic transformations involve the movement of atoms within the material in such a way that the crystal structure is changed. There are technological issues arising from incompatibilities between NiTi wires and textile yarns (such as temperature resistance, friction coefficient, bending stiffness) that had to be overcome. For example, the low friction of the wires has made it challenging to make stable fabrics, as the warp and weft threads slide over each other, meaning the fabric distorts with handling and wear. By using a traditional weaving technique called leno, where the warp yarns are twisted around the weft, they have successfully created stable woven fabrics.

MARTENSITIC TRANSFORMATIONS

All exciting properties of NiTi stem from the reversible solid state martensitic transformation that takes place in the material when temperature and stresses are properly changed. The word reversible is of key importance here as martensitic transformations are common to other materials such as steels. In steels, however, when a crystal lattice of the parent (austenite) phase transforms into a different crystal lattice of the lower symmetry phase, the reversibility is lost because of the dislocation slip at the interface and lattice volume changes introducing defects and internal stresses. The way back for the atoms to the initial sites of the parent phase is thus lost and therefore there is no shape memory effect.

In contrast, when NiTi transforms to the product martensitic phase, the atoms never lose their way back even after extensive complex deformation, since the accompanying plasticity is marginal and the interface remains highly mobile. In these exciting alloys, the transformation proceeds smoothly in

Imagine clothing that could move and morph designs, just by changing the temperature of the environment. This can now be achieved in the era of 'smart' or 'technical' textiles using NiTi wire technology

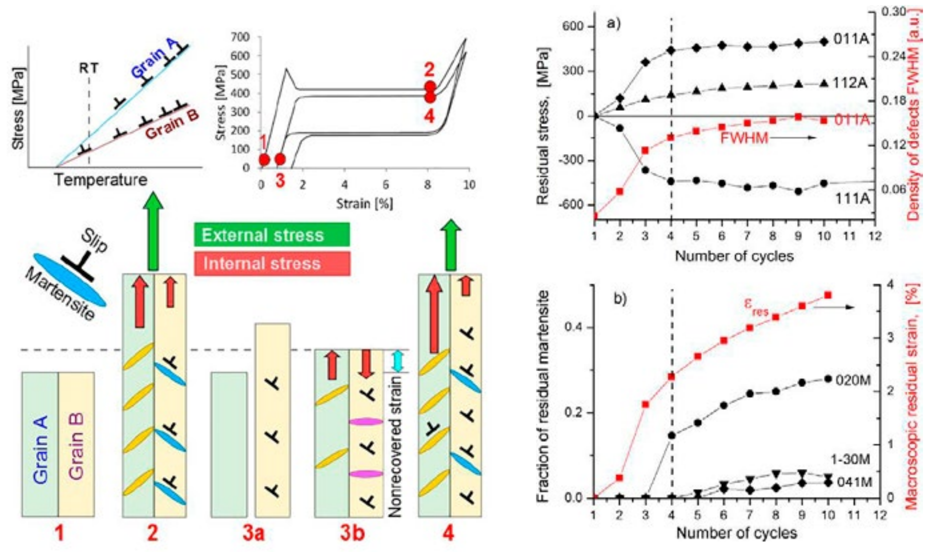


Figure 1: High energy synchrotron x-ray diffraction helps to detect accummulation of residual stress and residual martensite upon superelastic cycling of thin NiTi filaments due to concurrent martensitic transformation and plastic deformation by slip

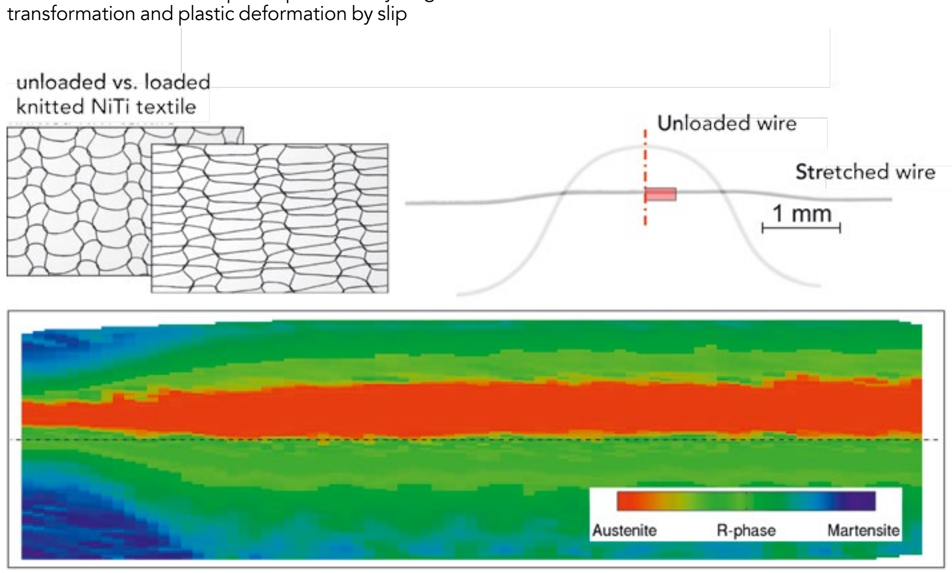


Figure 2: Reversible straightening of a single knit loop made from a 100 um NiTi wire subjected to tensile loading. The straightening is accommodated via a solid state transformation of the initial austenite phase. This deformation mechanism was tracked using microdiffraction tomography revealing the spatial distribution of martensite and R-phase induced by bending dominated loading

response to stress and temperature variation with negligible lattice volume changes but high lattice distortions giving rise to highly reversible strains (up to 10%). In addition, the product martensite phase can easily deform through cooperative translation gliding of entire planes of atoms (twinning) giving the martensite so-called pseudoplastic behaviour. But again, pseudoplastically displaced atoms of martensite will find their way back to the initial sites of the parent austenite phase by heating. This is where the memory of shape comes from.

Although the martensitic transformation in NiTi alloys is theoretically perfectly reversible, when NiTi wires are loaded cyclically they gradually get longer – a sign of irreversible processes. That irreversible processes proceed in cyclically loaded NiTi wires was shown by recent in situ x-ray diffraction studies led by Dr Sittner (Figure 1). The irreversible processes are of particular concern for fatigue performance of NiTi wires and are currently the focus of Dr Heller's team. Better understanding of the mechanisms leading to premature fatigue is key to further applied use of NiTi alloys.

MANIPULATING MARTENSITIC TRANSFORMATIONS IN NITI

When fine NiTi wires arrive from production by cold drawing they behave elastically just like stainless steel wires. This is because the microstructure is heavily deformed with a high density of crystal defects preventing shape memory functionality. Therefore, microstructure recovery by heat treatment must be done to restore them. Ten years ago, Dr Pilch from Dr Heller's research team developed a unique method of thermal treatment using short electric current pulses. The method allows a wide range of desired microstructures and properties to be set to NiTi wires. Functional properties of NiTi wires can be customised for a given application, particularly to elastic modulus, reversible strain, ductility, strength etc. This method has been extended to continuous annealing where the thin filaments are being respooled from one spool to the other while being annealed (heated then slowly cooled), which is of particular interest for textile applications.

SHAPE SETTING OF NITI TEXTILES

Imagine textiles that look like a normal fabric but have shape memory properties. For this, textile processing combining both the NiTi wires and common yarns has been successfully tested. Applying the heat treatment while the textile is constrained in a desired shape allows researchers not only to induce shape memory properties in NiTi but also to shape-set NiTi wires creating the shape of the entire fabric (see main image). This process of the constrained heat treatment of NiTi wires is called shape setting. The complex internal architecture of NiTi textiles is created partially by weaving (knitting) and partially by the shape setting treatment. In addition, the macroscopic shape of the 2D textile can be set as well. The key issue when shape setting hybrid NiTi textiles is to heat treat the NiTi wires while protecting the surrounding heat-sensitive yarns. Shape setting at moderate temperatures is the only way to achieve that. Dr Heller and Dr Sittner's research team has been exploring how to shape-set NiTi wires at temperatures as low as 250°C, employing the stresses arising naturally in NiTi wires from the reverse martensitic transformation driven by the supplied heat.

Shape-set NiTi wires embedded in textiles have wavy geometry due to their interlacing with the textile patterns. This wavy geometry allows for large deflections due to wire bending. This deformation mechanism is further assisted by martensitic transformations, which in this case proceed in more complex ways than straight wires being simply stretched. Dr Heller's team systematically makes use of diffraction techniques to track in situ martensitic transformations in NiTi wires undergoing thermomechanical loadings. To

Q&A

What are the properties that make NiTi wires so special?

Of course the most fascinating property is the memory of shape upon heating. It has been transferred from 1D to 2D by textile technologies. From the mechanics point of view the most striking is that a NiTi wire can behave plastically so that it remains in any shape given to it yet at just a slightly higher temperature it becomes stiffer and highly elastic – the original shape is restored upon unloading. One can switch between both material states by changing temperature. When stretching NiTi wire in the superelastic state one can feel and even hear how the phase transition proceeds in the material giving rise to ~5% of deformation that is induced suddenly when reaching a critical stretching force. All unique properties of SMAs derive from the martensitic phase transformation in solid state – diffusionless rearrangements of atoms within the material. Among SMAs, NiTi are unique in the ability to undergo large recoverable strains up to 10% and are commercially by far most successful. NiTi wires can reversibly change the stiffness, recover strains, and exert tensile stresses hundreds of MPa by changing temperature by a few tens of degree Celsius within the range from -50°C up to 100°C. All these properties may be utilised in NiTi wires that can be easily shape set into any tortuous shape.

What inspired the idea of using NiTi wires in textile applications?

Actually, when you touch a fine NiTi wire this idea comes naturally. The fine NiTi wires possess the magic shape memory properties and are even stronger than bars or thick wires. So why not combine multiple thin wires using textile processing technologies to make superelastic cables or textiles with memory of shape or roughness? Indeed, by setting a densely wrinkled shape on a flat textile, it will remember its surface roughness, etc. From another perspective, textile internal architecture can be modified by shape setting. A variety of textile patterns may be advantageously introduced into already woven or knitted textiles to improve or modify their properties. But we must note that NiTi textiles have already been used in the form of braided NiTi stents when we started this research 13 years ago within the frame of the large-scale European project, AVALON.

How do you decide which types of textile processing are likely to give you the behaviour you want from the NiTi wires?

Requirements of the textile to be engineered dictate the choice of the type of NiTi wires, textile pattern, shape setting, and textile processing. This makes the design of each end product rather complex as there are many variables to play with, and one variable may condition the other. For example, if large stretchability beyond the limits of NiTi wires is required then one has to go for suitable knitted patterns that allow for enlarged stretchability. But in knitted patterns NiTi wires are loaded in bending, giving the textile compliant mechanical characteristics that are very different from woven structures with two perpendicular sets of nearly straight wires that are much stiffer in plane deformation, reproducing the tensile properties of NiTi wires. Another example, when a 3D shape is required, shape setting is advantageous as it can replace time-consuming 3D textile-processing methods – one can start from a flat pattern and extend it into 3D using shape setting. The shape setting has a side effect – it releases all deformation energy stored in wires when they are being interlaced into textile patterns. It is positive for knitted patterns that, thanks to it, are not prone to unravelling.

Do you think it will ever be commercially viable for NiTi textiles to become commonplace?

Because thin NiTi wires are rather expensive, need special treatments, and are not fully compatible to common yarns, one cannot expect wide scale application – for example, in apparel or geotextiles. I think the use of NiTi filaments in textiles is justified only in cases where they provide textiles with unique properties that cannot be achieved otherwise and these novel functional materials can be applied in a manner which justifies the money spent.

In other words, for the time being only high-added-value NiTi textiles have a chance on the market e.g., in medical devices or special products. Our experience is that even if we demonstrate attractive functionalities of NiTi textiles, commercialisation of the end product is very difficult. On the other hand, as there are no other materials showing such a combination of structural and functional properties, there are no competitors…

Which of the potential applications of these NiTi textiles do you think will be most exciting?

Applications where we utilise both the shape memory properties and the ability to be shape-set. 3D-shaped textiles such as spacer fabrics being able to sense temperature and repeatedly react upon that by a change in stiffness and shape even against external pressure. I think no other material can equal NiTi textile in providing this combination of properties. For example, a compliant low profile patch of NiTi textile embedded in thermally protective clothes becomes larger, stiffer, increasing the space between the extreme heat and human body in a fraction of a second because NiTi senses the temperature and reacts immediately.

Dr Heller and Dr Sittner look at 'shape memory' alloys. These are materials that can be set into a desired shape, and no matter how they are distorted up to limits given by the nature of martensitic phase transformation, they will return to their original shape on heating

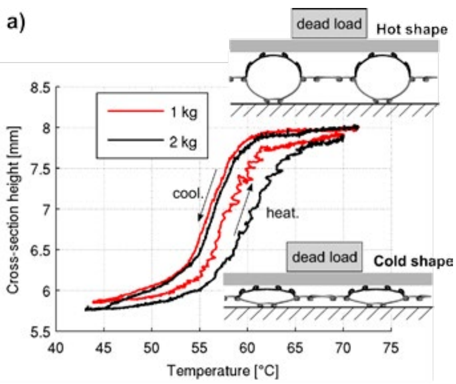
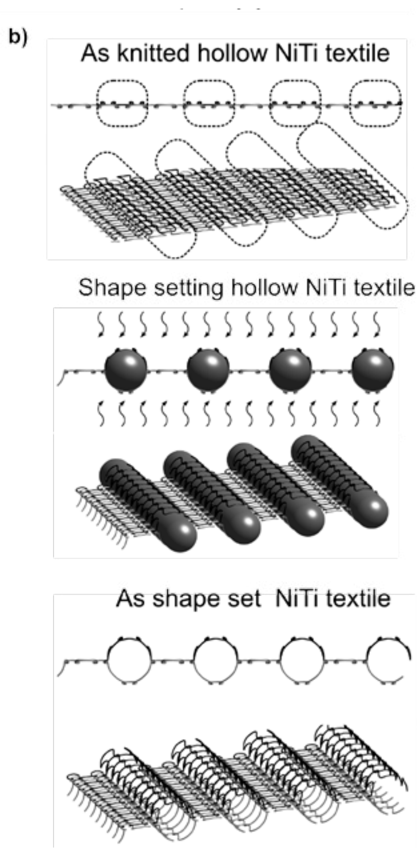


Figure 3: Prototype of a temperature-responsive 3D NiTi spacer fabric with the ability to reversibly increase and decrease its profile height and volume upon heating and cooling while being loaded by external pressure as illustrated in graph a). At lower temperatures the spacer fabric becomes compliant, deforming under pressure into a low profile thickness cold shape while becoming stiffer, thus forming a high profile thickness hot shape at higher temperatures. The 3D spacer fabric is based on a flat hollow knitted textile pattern that is 3D shape set as seen in b).



this end, synchrotron X-ray microdiffraction was used to identify martensitically transformed zones within a wavy 100 micron NiTi wire while being stretched, mimicking the NiTi wire loading in weft knitted NiTi textiles (Figure 2).

NITI TEXTILES

Embedding NiTi wires into textiles enables the engineering of a complex 3D structure thanks to the shape setting. Such NiTi structures can repeatedly undergo large strains thanks to both NiTi atoms shuffling back and forth, and wavy geometry of NiTi wires allowing for large deflections. These NiTi structures may be extremely compliant and soft at one temperature while becoming stiff and hard upon being heated by just a few degrees. The key for the successful design of NiTi textiles is to interlace NiTi wires into smart patterns. A collaborating textile engineer K. Janouchova, together with Dr Heller and Dr Sittner, has been working on designing lightweight, hollow 3D textiles using a unique weft knitting pattern. This forms a temperature-responsive spacer fabric that can triple its profile thickness when the temperature is changed by 30°C or lift up to 2000x its own weight. One application for this smart spacer fabric is as thermally protective cloth (Figure 3).

FUTURE CHALLENGES

The research group has already been awarded several patents for their work, including one for a low-profile stent graft (used to repair damaged blood vessels). The extreme thinness of the stent graft means the diameter of the delivery system catheter can be decreased. The graft is made from a unique woven textile incorporating 30 microns of NiTi wires combined with medical grade yarns that are low temperature shape-set into a tubular textile. Another patent is for developing a Velcro-like fastener that is made from an array of NiTi 'hooks' which open and close silently. This fastener is also immune to dirt and oil that can clog conventional Velcro fasteners stopping them from working.

At present, NiTi use has mostly been restricted to medical, aerospace and automotive applications due to the costs associated with manufacturing. Shape-settable hybrid NiTi textiles offer a wide range of new applications, for example in medical devices or wearable electronics. Key technologies have already been developed for textiles made from superelastic filaments. The work of Dr Heller and Dr Sittner represents a major breakthrough in NiTi textile production from drawn filaments with subsequent heat treatment for simultaneous adjustment of the functionality, textile architecture and shape. Incorporating NiTi wires into textiles on an industrial scale, however, still poses challenges due to the additional machinery wear and friction from working with the metallic alloys during textile production. However, given the exciting applications, NiTi textiles will become ever more attractive as time goes on.

Detail

RESEARCH OBJECTIVES

Dr Heller and Professor Sittner's research analyses textiles and materials using thin NiTi wires. Through their wire technology, they aim to revolutionise not only the textiles industry but the medical industry as well.

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- Technical University of Liberec (www.tul.cz)
- ELLA-CS (www.ellacs.eu) – Producer of health care devices
- D'Appolonia (www.dappolonia.it) – Provider of engineering services

BIO

Dr Ludek Heller's academic background has largely focused on mechanical engineering, having studied in both the Czech Republic and France. Dr Petr Sittner, after receiving his PhD in Solid State Physics from the Faculty of Mathematics and Physics Charles University in Prague, has made a long and distinguished career in the field of martensitic transformation and shape memory alloys. Together, they currently lead the SMA research at the Institute of Physics ASCR.

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