Industrial Interest in Materials Science

C. Walsh
KTN/ESP

July 25, 2017

1 Introduction

Materials Science is an intrinsically interdisciplinary field. It provides an avenue for the testing of condensed matter theories, whilst focussing on a more macroscopic picture than condensed matter itself. It provides a materials science based approach to nanotechnology through nanomaterials research. As much as physicists and engineers in other fields must make use of materials science, materials scientists must makes use of methods from the fields of physics, chemistry and engineering, whilst the field is also related to metallurgy and solid state physics from which it arose.

2 Current Research

2.1 Nanomaterials

Nanomaterial is the term used to describe materials which are used at the nanoscale. This is usually defined by having a unit size of 1-100nm. Materials science based approach to nanotechnology. This field has seen recent advancements in biomedicine such as incorporating antibodies into nanoparticles for tumor treatment [1]. Nanomaterials are particularly useful in many sectors as they display properties superior to those of the materials that were previously used.

An important class of nanomaterials are fullerenes, which are thin carbon sheets with a spherical geometry. This includes the well known and hugely promising example of carbon nanotubes. One of the publicised potential applications of such technology is the idea of a space elevator, an elevator stretching all the way up into space [2]. Carbon nanotubes have been demonstrated to exhibit the strength required for but at present are limited by length scale, the largest having been created by researchers from Tsinghua University in Beijing in 2013, which had a length of 550 mm. [3]

There is a project at the Helmholtz-Zentrum Geesthacht Centre for Materials and Coastal Research (HZG) on polymer-based nanocomposites which is looking to increase material applications by incorporating carbon-based nanoparticles (nanotubes (CNT), nanofibres (CNF), and nanosheets or exfoliated graphite (CNS)) into polymer materials [4]. They also are developing nanoparticle reinforced magnesium composites with the HZG Magnesium Innovation Centre MagIC [5]. In 2008, a group of researchers published some research on carbon nanotubes as a potential candidate as a hydrogen cryosorber for potential use in future particle accelerators and synchrotrons. [6]

HZG have an Institute of Materials research, within which operates the Materials Technology division (Nanotechnology), in addition to a Nanochemical and Nanoengineering department, a research topic within Hybrid Materials on nanomaterials, and a Micro-/Nanotechnology department within Institute of Biomaterial Science [7] [8][9][10]. Their research focus is for use in biomedicine, and centres around polymers.

2.2 Biomaterials

Biomaterials are the engineered materials for use in the medical field, for example in prostheses. These are selected based on the biocompatibility. Other examples are artificial organs, wound dressings, and implants. Biodegradable implants made from magnesium reduce discomfort for patients, and negate the need for a second surgery to remove the implant [11].

As previously discussed, HZG have a Biomaterial Science Institute, which includes some research into shape memory materials for medical applications [12]. Other research includes the Polymers in Regeneration department looking into the interaction between biomaterials and cells [13]. They further have a Metallic Biomaterials division researching and developing magnesium and titanium based materials for implants [14].

In 2012 HZG held a conference on 'Advances in Functional Polymers for Medicine' in Italy, amongst which topics of discussion included Micro and Nanoparticles for Drug Delivery, Cell-Material Interactions, and Biopolymer/Biomimetic Polymers [15].

2.3 Smart Materials

Smart materials are materials that alter their properties in response to an external change. An example could be a temperature change, a magnetic field change, or applied stress. Piezoelectric materials experience a voltage change under stress, whilst shape-memory materials exhibit pseudoelasticity under temperature change; that is, they may undergo a reversible deformation through the action of heating or cooling. Magnetic shape memory materials have the same principle, but respond to magnetic field changes. [16] [17]

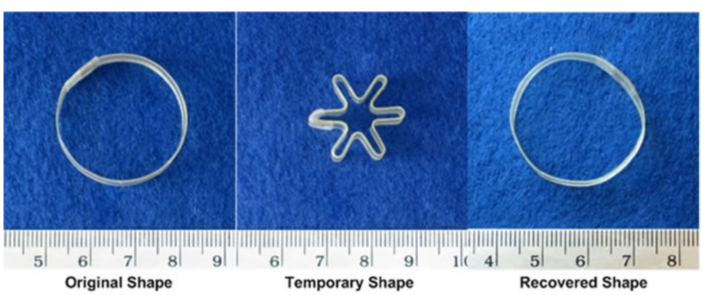

Figure 1: Showing the deformation and subsequent shape recovery of a shape memory material. [18]

The Nanochemistry and Nanoengineering group at HZG have a focus on smart materials due to their wide range of applications. In 2013, they produced the first shape-memory plastics to reversibly change with repeated temperature change. [19]

The European Spallation Source (ESS), which is currently under construction and expected to begin operation in 2020, will have a diffractometer dedicated to materials research with a beam magnitude of one or more orders greater than current diffractometers. This is under the Beamline for European materials Engineering Research project, or BEER, which was proposed in part by HZG. It is anticipated the project will attract a wide range of researchers and industrial manufacturers. Research on shape memory alloys, which have valuable uses in sensors and biomedical components, is among the possible applications once the project is complete [20].

Under the frame of the Heinz Maier-Leibnitz Zentrum (MLZ), which is the collaboration between the Helmholtz centres (FZJ and HZG) with the Technische Universität München (TUM), the centres are conducting research at FRM II (the leading German research reactor). In 2015 they published results taken using the SPODI instrument on a faster method for structure determination of magnetic shape-memory alloys [21] [22].

Last month's edition of the journal Advanced Materials featured a piece on research done on a self-regulating iris based on light-actuated Liquid Crystal Elastomer (LCE) [23]. The researchers also published a paper on a light-driven caterpillar robot using LCE in the journal Macromolecular Rapid Communications in May [24].

2.4 Metamaterials

Similarly to smart materials, metamaterials are classed as materials that have been specifically designed to have a specific property. However there is a distinct difference in that these properties arise less from the materials with which it is made and more from the periodic structure of the materials. They incorporate elements into the structure that are on a scale smaller than the wavelength of the light interacting with it. For example, metamaterial cloaking [25]. Several universities are doing research on this topic, including the University of Birmingham, Cambridge University, the University of Exeter, Imperial College London, King's College London, Oxford University, and more [48].

2.5 Journals

There are a multitude of journals reporting on recent advancements in materials science. These can be ordered by an impact factor based on the number of citations to articles published that year. The impact factors given to figures taken from 2016 are shown in figure 2.

Journal	Impact Factor
Advanced Materials	19.79
Advanced Functional Materials	12.12
Advanced Energy Materials	16.72
Small	8.64
Advanced Electronic Materials	4.19
Advanced Engineering Materials	2.31
Advanced Healthcare Materials	5.11
Advanced Materials Interfaces	4.27
Advanced Optical Materials	6.87
Advanced Science	9.03
Macromolecular Materials and Engineering	2.86
Particle	4.47
Steel Research International	1.23
Advanced Materials Technologies	New Journal
Advanced Sustainable Systems	New Journal
Small Methods	New Journal
Solar RRL	New Journal

Figure 2: Journals listed by impact based on data from 2016 [26].

It can be seen from the figure that the journals Advanced Materials, Advanced Functional Materials, and Advanced Energy Materials have the greatest impact based on this criteria.

3 Industry

The main materials exploited by industry are ceramics and glasses, composites, polymers (for example, HZG have polymer research institute [47]), and metal alloys. Semiconductors represent a significant part of materials science in industry. Popular choices for materials are silicon, gallium arsenide, and germanium. They have uses in diodes, transistors, LEDs, and electrical circuits. Some of the main sectors with applications are healthcare, IT, automotive, communications, electronics, and aerospace and defence [48].These applications are developing further to other sectors as materials become more advanced and cost effective.

The research centre MLZ contribute to the semiconductors market, including use of their silicon doping system for commercial production and by carrying out neutron source testing of the functional life of semiconductors. Their doped silicon is used in high power electronics and in the automotive industry. [27]

3.1 Smart Materials

Smart materials have a broad range of applications in industry, from automotives to biomedicine. Shape memory materials may even have nanotechnology applications as they have been shown to exhibit the shape memory effect in even nano-sized systems [28]. The main sectors in which smart materials can be utilised are industrial, defence and aerospace, automotive, healthcare, and consumer electronics [43] . Some of these are detailed here.

Shape-memory materials (SMM) can be used in actuators. such as in the previously mentioned research from HZG published in 2013. The actuators could become the basis of a heat engine, or the shape memory material could be used in temperature-sensitive blinds [19]. Actuators have applications in biomedicine for use in active cancellation of tremor devices [29]. Biomedicine has further SMM applications, such as stents and remotely controlled switchable implants [30] [31]. Most recently, the University of Colorado presented their shape-memory alloy actuated biomimetic robot at the 2017 International Conference on Robotics and Automation. The robot makes use of nine SMA-actuators in the form of springs. This has the potential to revolutionise colonoscopy treatments by hugely reducing the risk factors associated with current devices. [32]

Research done at the University of Calabria, Italy, on shape-memory alloys is being utilised in a collaboration with the CERN for use in the High-Luminosity Large Hadron Collider (HL-LHC) project, for applications in vacuum sealing. The material can be installed at room temperature (at which it is a larger ring shape) and then heated, causing it to contract around the vacuum chamber. This will be easier to install and remove than existing technology [33].

Figure 3: Showing a shape-memory actuator for the Ultra High Vacuum chambers of the HL-LHC. [33]

Photochromic molecules have the potential to be implemented in the making of smart optoelectronic devices such as sensors, which was the aim of some research conducted at HZG that was published in 2011, which used a photoswitchable transparent conductor with a selective Photobleaching gas nose as a multifunctional device [34].

Magnetic smart materials can be used as dampers in everything from bridges to washing machines and prosthetic limbs. They can also be utilised as a reusable catalyst in depolymerisation of plastic waste for recycling, in addition to separation of metallic waste and liquid sealing such as ferrofluids in hard-drives. [36]

Horizon 2020 has been involved with several projects utilising smart materials. Among these were the ADAM4EVE project (ADaptive And smart Materials and structures for more Efficient VEssels), and the ShopInstantShoe project, which incorporated the shape-memory alloy Nitinol (composed of Nickel and Titanium) into a material for shoes that would be fitted to the wearer and hold their shape. This became available in 2015. [37] [38]

Nitinol, which is an NiTi alloy, was again used in a H2020-funded project that created a prototype medical tool to reduce cross-contamination in addition to being flexible and able to exploit the shape memory effect to return to the original shape. [39] InnoSMART, an ongoing H2020 FET project, proposes using shape-memory alloys as a structural coating which could extend the life expectancy of bridges and planes. Other FET projects are looking into new materials and their applications in new technologies. [40]

The University of Bolton, a world leading centre for materials science research, have developed flexible piezoelectric fibers with a huge number of potential applications. The material combines the mechanical-energy-to-electrical-energy conversion of piezoelectric materials with the light-to-electrical-energy conversion property of photovoltaic materials, and is capable of converting energy from sunlight, wind and rain. The material can be placed in carpet to harvest energy from commuters walking, used in stealth technology to detract radar, used to recover energy in railway sleepers, use in tires as harvesting energy and sensing tire wear, or even used in sails to convert energy from the elements. They could be the basis for energy harvesting synthetic trees where solar panels cannot be placed, clothing that charges devices or a shirt that can be worn by pregnant mothers and monitor a baby's heartbeat at all times. They formed the company Fibrlec in 2013 in order to bring their commercial applications to life. [41] Piezoelectric materials are highly useful and have broad range of applications: as actuators, in printing, speakers, welding, micro-valves, sensors, sonar, ultrasound, and accelerometers. [42]

According to the 'World Smart Material Market-Opportunities and Forecasts, 2015-2022' report produced by Allied Market Research, the smart materials market is predicted to exhibit a Compound Annual Growth Rate (CAGR) of 12.9% between 2015-2022. It is valued at $72.63 billion over the same period. [43]

3.2 Nanomaterials

Nanomaterials have received increasing attention in multiple industrial sectors. Among these are aerospace and transportation, energy, and the medical industry [44]. One type of nanomaterial is called an aerogel. Aerogels are highly porous and lightweight and are currently being used in 'smart' window and glasses technology, in which the glass darkens in response to changes in the levels of sunlight, and insulation in buildings. Due to their structure structure, aerogels can hold a significant amount more energy and hence could also be used as separator plates in batteries. Batteries with nanocrystalline materials in would theoretically have a longer lifespan before needing to be recharged than conventional batteries. Nanocrystalline phosphors can be used as a low cost, high resolution display, such as those used in laptops. Nanocrystalline materials can further be used in catalytic converters, in which they react with pollutants due to their high chemical activity. Magnets composed of nanocrystalline materials possess magnetic properties that make them extremely useful in applications such as quieter submarines, power generators, ship motors, ultra-sensitive analytical instruments, and magnetic resonance imaging (MRI) technology. Nanocrystalline sensors are highly sensitive to environmental changes. They can be made into smoke detectors, sensors on aircraft wings designed to detect ice, and engine performance sensors in the automobile industry. They have further automobile applications in a prototype spark plug with a longer lifespan, and potential applications in more fuel efficient engines by coating the cylinders within the engine in nanocrystalline ceramics, which retain thermal energy much more efficiently than conventional engines. In a similar way, aerospace components made of nanocrystalline materials can function at higher temperatures and for longer than those made of other materials, in addition to being stronger, making the aircraft more efficient. The high temperature strength means they can also be used in spacecraft applications. The list of applications is endless, and includes more from the fields of weapons, more efficient satellites, more wear resistant medical implants (such as artificial heart valves) which require less frequent surgeries and hence reduce the associated risk, and ceramics. [45]

3.3 Biomaterials

The main applications of biomaterials are within the field of biomedicine, as one would expect. These include in orthopaedics, dentistry, cardiovascular, and cosmetic. The global biomaterials market is predicted to show a Compound Annual Growth Rate (CAGR) of 15.73% between 2016-2021, according to the Global Biomaterials Market report by Azoth Analytics [46].

3.4 Metamaterials

Industrial sectors in which metamaterials prove particularly useful include healthcare, manufacturing, energy, electronics, telecommunications, and IT. According to BCC, by 2018 the metamaterials market should reach $1.7 billion based on a CAGR of 22.5% from 2013-2018. [48]

3.5 Other Topics

Other important topics of interest include graphene and 2D materials. These have the potential to revolutionise electronics through wearable technology, sensors, photonics, and energy storage devices. Current applications include graphene touch screens. [49]

3.6 Companies

Several companies have already begun manufacturing advanced materials for industrial applications. Fort Wayne Metals are the world's leading melt-to-finish source for Nitinol to be used in medical instruments, and offer the material in different forms for various applications. Their website even plays host to a bimonthly highlight hinting at the activities of their R&D department, usually on shape memory alloys, of which the July issue was on shape-memory yarn for use in textiles [50]. The main markets in which Fort Wayne are active are medical devices, aerospace and defence, and industrial [51]

Advanced Cerametrics offer a series of piezoelectric fibers and composite materials. The flexibility of the piezoelectric fiber allows the harvesting of energy and also vibration dampening. Their materials have been used in 'active smart' sporting equipment, aircraft, automobiles, motorcycles, wireless sensors, industrial equipment, infrastructure and clothing [52]. They are a key player in the global piezoelectric smart materials market [53]

The company TDK created a piezoelectric component called CeraPlas that can be used to generate cold plasma very efficiently, with better performance compared to existing technology. It is the world's first component capable of acting as both a transformer and generating plasma, and as such has a long list of applications including sterilisation of machines that handle food or medical instruments and wounds [55]. Their main sectors are electronics, automotive, and information and communication technology [54].

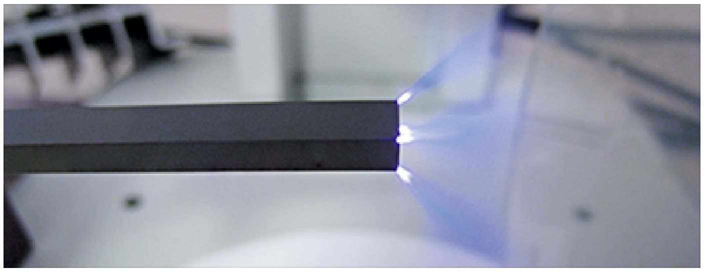

Figure 4: Showing air plasma being generated by CeraPlas and ignited. [55]

The CTS corporation specialise in piezoelectrics. They deliver materials for a broad range of applications such as bimorphs and high frequency sensors. These can be used in micro-actuation, where they require high accuracy and are frequently found in computer hard drives. High performance piezo actuators have further applications in the military industry. CTS are a leading manufacturer of sensors, actuators and electronic components for the aerospace and defence, medical, industrial, telecommunications and IT, and transportation markets [42].

Piezosystem Jena, in Germany, produce products for piezo micro-positioning, piezo nano-positioning and metrology for supply to the semiconductor, microscopy, optics, and synchrotron industries. [56]

Smart Material Corporation in Germany develop piezo-composite materials as actuators and sensors, for energy harvesting and for use in ultrasounds. The main application areas of focus are in actuation, sonar, non-destructive testing, structural health monitoring, energy harvesting, and aerospace. They are in research cooperation with Fraunhofer IKTS and NASA's Langley Research Center to advance new material technologies. [57]

The company Wright use Nitinol staples to distribute force evenly in their FUSEFORCE™ fixation system, with their main sector of focus being healthcare [58]. They are a global leader in the biomaterials market [46].

The company Haydale manufacture graphene and 2D materials. They operate in a number of markets, including inks and coatings, polymers and composites, energy, electronics, and transport, providing tailored materials for each purpose. They are working in collaboration with Alex Thomson Racing to produce a boat with the strength to sail around the world in addition to being as light as possible, and improve performance. [59]

Applied Graphene Materials are a world leader in the manufacture of graphene and graphene materials such as graphene nanoplatelets. Applications include supercapacitors and batteries, inks and 3D printed materials, coatings, and advanced composites and polymers [60]. The main sectors of operation are Polymers & Composites, Paints & Coatings, and Functional Fluids, and they are currently working with the largest independent paint manufacturer in the UK, HGM Paints [61].

XG Sciences are a graphene industry leader. They manufacture high quality nanoplatelets for the sectors of transportation, energy storage, electronics, sports, aerospace, infrastructure, defence, and biomedicine [62].

Another company that are active in the field is QinetiQ, which is working with DSTL, Exeter and Southampton to develop advanced materials [48]. They mainly operate in the defence, security and aerospace sectors [63]. The Global Marine Technology Trends 2030 report produced with aid from QinetiQ examines advanced materials, including nanomaterials, for future maritime industry applications [64].

3.7 Conferences

There are a series of existing conferences on smart materials and materials research within materials science. One such is the yearly Materials Research, during which the 2017 event had speakers from Helmholtz and HZG in addition the the University of Bolton's Fibrlec team. Another is Ceramics, which took place in Spain this year. A few others are Smart Materials, which will take place in Austria in 2018, and Smart Materials &Structures which will take place in the US next year. The ACTUATOR conference in Bremen attracts experts, suppliers and users in the field of actuators to present their work. The International Conference & Exhibition on Advanced & Nano Materials (ICANM) will take place in Toronto, Canada, in August of this year. Next March, London will play host to the yearly conference Nanomaterials and Nanotechnology, with such topics as nanoparticles, nanoelectronic devices, and nanoscale materials. The Graphene and Semiconductors conference is taking place this July in Chicago, Illinois. Another example is the Composites and Advanced Materials Expo this September, which Haydale are attending. The 8th International Conference on Metamaterials, Photonic Crystals and Plasmonics, META'17, was held in Seoul, South Korea, in July. [65] [66]

4 Conclusion

The materials science market has seen some vast developments in recent years, and they have a high potential at this stage to be used further in future applications as materials advance and become more sensitive and efficient. Advanced materials continue to outperform conventional materials and find new uses in a wide range of sectors.

References

[1] D. Chu, X. Dong, Q. Zhao, J. Gu, Z. Wang, Adv. Mater. 2017, 29, 1701021. $https://doi.org/10.1002/adma.201701021$

[2] Lisa Zyga, 'Long, Stretchy Carbon Nanotubes Could Make Space Elevators Possible', $https://phys.org/news/2009-01-stretchy-carbon-nanotubes-space-elevators.html$, January 23, 2009, [accessed 17/07/2017]

[3] 'Growth of Half-Meter Long Carbon Nanotubes Based on Schulz-Flory Distribution', Rufan Zhang, Yingying Zhang, Qiang Zhang, Huanhuan Xie, Weizhong Qian, and Fei Wei, ACS Nano 2013 7 (7), 6156-6161, DOI: 10.1021/nn401995z

[4] $https://www.hzg.de/science/eu\_projects/fp7/key/047575/index.php.en$

[5] Magnesium Innovation Centre MagIC, Magnesium Processing, $https://www.hzg.de/institutes\_platforms/materials\_research/magnesium\_technology/magnesium\_processing/index.php.en$ [accesssed 19/07/2015]

[6] F. Xu, M. Barberio, R. Vasta, P. Barone, A. Bonanno, and V. Pirronello, Phys. Rev. Spec. Top. Accel. Beams 11, 113201 (2008)

[7] HZG Materials Technology, Institute of Materials Research, https://www.hzg.de/institutes_platforms/materials_research/materials_technology/index.php.en, [accessed 17/07/2017]

[8] HZG Nanochemistry and Nanoengineering Dept, Institute of Polymer Research, $https://www.hzg.de/institutes\_platforms/polymer\_research/nanochemistry\_and\_nanoengineering/index.php.en$, [accessed 17/07/2017]

[9] HZG Hybrid Materials Research Topics $https://www.hzg.de/institutes\_platforms/materials\_research/materials\_mechanics/hybrid\_materials_systems/projects/index.php.en$, [accessed 17/07/2017]

[10] HZG Micro-/Nanotechnology Dept, Institute of Biomaterial Science, $https://www.hzg.de/institutes\_platforms/biomaterial\_science/interface/index.php.en$, [accessed 17/07/2017]

[11] 'Recent advances in research on magnesium alloys and magnesium?calcium phosphate composites as biodegradable implant materials', Katarzyna Ku?nierczyk, Micha? Basista, Journal of Biomaterials Applications, Vol 31, Issue 6, pp. 878 - 900, July 2016, 10.1177/0885328216657271

[12] Saatchi, M., Behl, M., Nchel, U. and Lendlein, A. (2015), Copolymer Networks From Oligo(?-caprolactone) and n-Butyl Acrylate Enable a Reversible Bidirectional Shape-Memory Effect at Human Body Temperature. Macromol. Rapid Commun., 36: 880?884. doi: 10.1002/marc.20140072

[13] HZG Institute of Biomaterial Science: Polymers in Regeneration department $https://www.hzg.de/institutes\_platforms/biomaterial\_science/biocompatibility/index.php.en$ [accessed 19/07/17]

[14] HZG Institute of Materials Research: Metallic Biomaterials Division, $https://www.hzg.de/institutes\_platforms/materials\_research/metallic\_biomaterials/index.php.en$ [accessed 19/07/17]

[15] HZG Conference, Italy, 2012, 'Advances in Functional Polymers for Medicine', $https://www.hzg.de/institutes_platforms/biomaterial_science/news/046106/index.php.de$, [accessed 19/07/2017]

[16] Innovate UK, *'Smart Materials'*, $https://connect.innovateuk.org/web/smart-materials/smart-design-guide$, [accessed 23/06/17]

[17] Matt Kenealy, 'Smart Materials', $https://sites.google.com/site/mattkenealysmartmaterials/piezoelectric$, [accessed 23/06/2017]

[18] Wei Min Huang, 'Shape Memory Polymers (SMPs)- Current Research and Future Applications', $http://www.azom.com/article.aspx?ArticleID = 6038$ [accessed 05/07/17]

[19] Marc Behl, Karl Kratz, Ulrich Noechel, Tilman Sauter, and Andreas Lendlein (2013), 'Temperature-memory polymer actuators', *PNAS* 110: 12555-12559.

[20] European Spallation Source (2014), 'The Future is BEER', $https://europeanspallationsource.se/building-europes-next-flagship-engineering-diffractometer-future-beer$

[21] Haile Yan, Yudong Zhang, Nan Xu, Anatoliy Senyshyn, Heinz-Günter Brokmeier, Claude Esling, Xiang Zhaoa and Liang Zuoa, 'Crystal structure determination of incommensurate modulated martensite in Ni?Mn?In Heusler alloys', *Acta Materialia* 88, 375 (2015)

[22] TUM, $http://www.frm2.tum.de/en/news-media/press/news/news/?tx\_ttnews\%5Btt\_news\%5D = 719\&cHash = de94a35178b2ff7bfc00933a8722b1d0$ [accessed 23/06/2017]

[23] H. Zeng, O. M. Wani, P. Wasylczyk, R. Kaczmarek, A. Priimagi, ?Self-Regulating Iris Based on Light-Actuated Liquid Crystal Elastomer?, Adv. Mater. 2017, 1701814.

[24] H. Zeng, O. M. Wani, P. Wasylczyk, A. Priimagi, ?Light-Driven, Caterpillar-Inspired Miniature Inching Robot?, Macromol. Rapid Commun. 2017, 1700224.

[25] $http://www.iop.org/resources/topic/archive/metamaterials/$, [accessed 14/07/2017]

[26] '2016 Journal Impact Factors Materials Science', Advanced Science News, June 14th 2017, $http://www.advancedsciencenews.com/?p = 43742\#anchor$, [accessed 18/07/2017]

[27] FRM II, Industry & Medicine: Silicon Doping, $https://www.frm2.tum.de/en/industry-medicine/silicon-doping/$ [accessed 20/07/17]

[28] W.M. Huang, Z. Ding, C.C. Wang, J. Wei, Y. Zhao, H. Purnawali, 'Shape memory materials', *Materials Today*, Volume 13, Issues 7?8, July?August 2010, Pages 54-61

[29] A. Pathak, 'The Development of an Antagonistic SMA Actuation Technology for the Active Cancellation of Human Tremor', University of Michigan, 2010

[30] Lorenza Petrini and Francesco Migliavacca (2011), 'Biomedical Applications of Shape Memory Alloys', *Journal of Metallurgy*, vol. 2011, Article ID 501483, 15 pages, 2011. doi:10.1155/2011/501483

[31] HZG Biomaterials Science Group, $https://www.hzg.de/institutes\_platforms/biomaterial\_science/active\_polymers/profile/index.php.en$, [accessed 26/06/2017]

[32] Ortega Alcaide, J., Pearson, L., Rentschler, M., "Design, Modeling and Control of a SMA-Actuated Biomimetic Robot with Novel Functional Skin," IEEE International Conference on Robotics and Automation (ICRA), Singapore, June, 2017.

[33] Anas Schaeffer and Stefania Pandolfi, ' 'Shape memory' material provides a solution for the HL-LHC', https://home.cern/cern-people/updates/2016/04/shape-memory-material-provides-solution-hl-lhc, 2016

[34] Jamali, M., Hedayati, M. K., Mozooni, B., Javaherirahim, M., Abdelaziz, R., Zillohu, A. U. and Elbahri, M. (2011), 'Photoresponsive Transparent Conductive Metal with a Photobleaching Nose', *Advanced Materials*, 23: 4243?4247. doi:10.1002/adma.201102353

[35] AZO Materials (2001), 'Smart Materials', http://www.azom.com/article.aspx?ArticleID=123, [accessed 29/06/2017]

[36] Ioniqa Technologies, 'Applications of Magnetic Smart Materials', http://www.ioniqa.com/applications/, [accessed 29/06/2017]

[37] H2020, https://ec.europa.eu/programmes/horizon2020/en/news/instant-custom-fitted-shoe-technology-perfect-footwear, 2014, [accessed 29/06/2017]

[38] H2020, https://ec.europa.eu/programmes/horizon2020/en/news/innovative-system-shop-develops-new-customizable-female-footwear-based-intelligent-materials, 2015, [accessed 29/06/2017]

[39] H2020, https://ec.europa.eu/programmes/horizon2020/en/news/new-surgical-tool-minimises-cross-contamination-risk , 2014, [accessed 29/06/2017]

[40] H2020, https://ec.europa.eu/programmes/horizon2020/en/news/h2020-fet-projects-technologies-new-materials, 2014, [accessed 29/06/2017]

[41] Fibrlec, http://www.fibrlec.co.uk/ [accessed 04/07/17]

[42] CTS Corporation, http://www.ctscorp.com/, [accessed 04/07/17]

[43] https://www.reportbuyer.com/product/3992147/world-smart-material-market-opportunities-and-forecasts-2015-2022.html, [accessed 21/07/2017]

[44] 'Manufacturing nanomaterials: from research to industry', Costas A. Charitidis, Pantelitsa Georgiou, Malamatenia A. Koklioti, Aikaterini-Flora Trompeta and Vasileios Markakis, Manufacturing Rev., 1 (2014) 11, DOI: https://doi.org/10.1051/mfreview/2014009

[45] AZoM, http://www.azom.com/article.aspx?ArticleID=1066, Nov 2001, [accessed 17/07/2017]

[46] Azoth Analytics, 'Global Biomaterials Market: Opportunites and Forecasts (2016-2021)', Report ID: 3891920, https://www.reportbuyer.com/product/3891920/global-biomaterials-market-by-type-by-application-by-region-opportunities-and-forecasts-2016-2021-by-material-type-polymer-ceramic-metal-by-application-orthopaedic-cardiovascular-plastic-surgery-wound-care-by-region-north-america-euro.html [accessed 21/07/2017]

[47] HZG Institute of Polymer Research, https://www.hzg.de/institutes_platforms/polymer_research/index.php.de, [accessed 17/07/2017]

[48] Steve Morris, Knowledge Transfer Network, 'A State of the Art Review of Smart Materials: A Review of Metamaterials in the UK', Dec 2015, https://connect.innovateuk.org/documents/2854053/3676905/A%20Review%20of%20Metamaterials%20in%20the%20UK, [accessed 17/07/2017]

[49] Future Markets, 'The Graphene and 2D Materials Global Opportunity Report', Dec 2016, Report ID: 4537885, *https://www.reportbuyer.com/product/4537885/the-graphene-and-2d-materials-global-opportunity-report.html* [accessed 21/07/2017]

[50] Fort Wayne Metals Bi-Monthly Highlight, *http://www.fwmetals.com/services/r-d/bi-monthly-highlight/* [accessed 05/07/2017]

[51] Fort Wayne Metals: Markets, *http://www.fwmetals.com/markets/*, [accessed 18/07/2017]

[52] Advanced Cerametrics, *https://www.linkedin.com/company/advanced-cerametrics-inc*, [accessed 18/07/2017]

[53] Infiniti Research Limited, 'Global Piezoelectric Smart Materials 2016-2020' *https://www.reportbuyer.com/product/3696574/global-piezoelectric-smart-materials-2016-2020.html*, [accessed 19/07/2017]

[54] TDK LinkedIn profile, *https://www.linkedin.com/company-beta/7505/* [accessed 19/07/2017]

[55] TDK CeraPlas, *https://en.tdk.eu/tdk-en/373562/tech-library/articles/applications---cases/applications---cases/cold-plasma-from-a-single-component/1109546*, [accessed 05/07/2017]

[56] Piezosystem Jena, *https://www.piezosystem.com/company_piezosystem_jena/*, [accessed 19/07/2017]

[57] Smart Material Corporation, *https://www.smart-material.com/aboutus.html*, [accessed 18/07/2017]

[58] Wright FUSEFORCE Fixation System, *http://www.wright.com/footandankleproducts/fuseforce-fixation-system-foot*, [accessed 26/06/2017]

[59] Haydale Case Studies, *http://www.haydale.com/working-with-us/case-studies/*, [accessed 28/07/2017]

[60] 'About Us', *http://www.appliedgraphenematerials.com/*, [accessed 19/07/2017]

[61] 'Understanding our business', *http://www.appliedgraphenematerials.com/investor-relations/understanding-our-business/*, [accessed 19/07/2017]

[62] XG Sciences, 'Nanomaterials Potential Applications', *http://xgsciences.com/library/nanomaterials-potential-applications/*, [accessed 19/07/2017]

[63] QinetiQ news release, *https://www.qinetiq.com/en-gb/news/2016/05/qinetiq-signs-10m-dstl-contract-to-maintain-uks-advanced-materials-superiority*, [accessed 20/07/2017]

[64] Andy Walker, *https://www.qinetiq.com/blogs/2015/09/advanced-materials-nanotechnology*, 10th Sept 2015, [accessed 18/07/2017]

[65] Conference Series, *http://www.conferenceseries.com/*, [accessed 26/06/2017]

[66] META Conferences, *http://metaconferences.org/ocs/index.php/META17/META17#.WXca4NPytTY*, [accessed 17/07/2017]