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Advanced Materials and Manufacturing – Implications for Defence to 2040

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EDTAS
EMERGING DISRUPTIVE TECHNOLOGY
ASSESSMENT SYMPOSIUM

Developed in partnership with

THE UNIVERSITY OF MELBOURNE

Noetic GROUP

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Advanced Materials and Manufacturing – Implications for Defence to 2040

THE FUTURE OF ADVANCED MATERIALS AND MANUFACTURING FOR DEFENCE

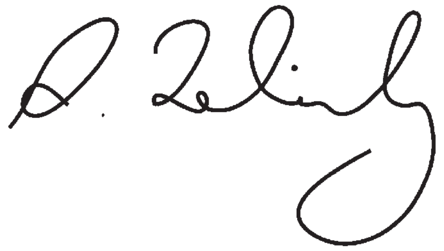
The Next Generation Technologies Fund announced in the *2016 Defence White Paper* focuses on game changing capabilities that have a disruptive effect on Defence and national security. One program within the Next Generation Technologies Fund is the Emerging Disruptive Technology Assessment Symposium (EDTAS) series which is designed to provide key insights and information on emerging and potential technologies over the longer term. In this context technology foresighting is a critical function required to understand the strategic environment we find ourselves in and the opportunities that science and technology may pose in minimising or exploiting disruption.

Defence Science and Technology (DST) is actively partnering with Defence stakeholders, industry, academia and international defence research agencies on technology foresight studies to identify opportunities and obtain insights on potential game-changing effects of new technologies. A number of symposiums have been held with the focus on biotechnologies and advanced manufacturing. This report provides observations, insights and strategic opportunities in the field of advanced materials and manufacturing out to 2040.

Advances in materials and manufacturing will have a profound effect on Defence and national security over the coming decades. Driven by the desire to continually seek lighter, stronger and more durable structures, new metals and alloys will be used for both Defence and civilian applications. Cheaper and lower energy production and manufacturing techniques will see increased use of specialised materials such as titanium and carbon fibre. Other specialised materials such as amorphous metals and superalloys will open up new opportunities with special magnetic properties and high-temperature resistance. The ability to produce metals with specific degradation qualities and deformation characteristics should enable novel applications in aerospace and biotechnology that were previously considered unfeasible.

The use of novel materials with additive and hybrid manufacturing will make for more efficient, lower waste products, highly customised design and production, and embedded electronics and sensors. Additive manufacturing will have important ramifications for the capability acquisition process of the Australian Defence Force. For example, the Defence and Australian defence industry could apply novel manufacturing techniques enabling the collaborative, rapid design and manufacture of spare parts for weapons, combat vehicles, and other equipment. The ability to make small batch or even one-off products at low cost could revolutionise how the Australian Defence Force acquires assets, supporting iterative improvements.

I commend this report to the Defence research community and Australian industry to keep abreast of developments and possibilities in advanced materials and manufacturing.



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EXECUTIVE SUMMARY

The Emerging and Disruptive Technology Assessment Symposium (EDTAS) series is a technology foresighting program under the Next Generation Technologies Fund designed to provide key insights and information on emerging and potential technologies over the longer term.

Technology foresighting is critical to understanding the strategic environment we find ourselves in and identifying the opportunities that science and technology may offer in minimising or exploiting disruption. DST is actively partnering with Defence stakeholders, industry, academia and allied defence research agencies on technology foresight studies to identify opportunities and obtain detailed insights on potential game-changing effects of new technologies.

In November 2017, DST joined with Noetic Group and the University of Melbourne to hold an EDTAS on Advanced Materials and Manufacturing.

Advances in materials and manufacturing will have a profound effect on Defence and national security over the coming decades. Driven by the desire to continually seek lighter, stronger and more durable structures, new metals and alloys will be used in both Defence and non-Defence settings. Cheaper and lower energy production and manufacturing techniques will see increased use of specialised materials such as titanium and carbon fibre in many applications. Other specialised materials such as amorphous metals and superalloys will provide new opportunities with special magnetic properties and high-temperature resistance. The ability to produce metals with specific degradation qualities and deformation characteristics will also enable novel applications in aerospace and biotechnology that were previously considered unfeasible.

Advances in manufacturing techniques will underpin new technologies and the use of novel materials with additive and hybrid manufacturing will make for more efficient, lower waste products, highly customised design and production, and embedded electronics and sensors.

Additive manufacturing will also have important ramifications for the capability acquisition process of the Australian Defence Force (ADF). For example the ADF and Australian Defence industry could use novel manufacturing techniques for collaborative, rapid design and manufacture of next generation weapons, combat vehicles, and other equipment. The ability to make small batch or even one-off products at low cost could revolutionise how the ADF acquires assets, allowing iterative improvements from one purchase unit to the next.

This report captures the key insights from the symposium, and identifies strategic opportunities for Defence in the field of advanced materials and manufacturing out to 2040.

The following are identified as key areas of research and development in the 2040 timeframe:

- Nanomaterials
- Metamaterials
- Materials for energy storage and generation
- Multi-functional materials.

The following are identified as gaps in research, as well as potential opportunities for Defence going forward:

- Cross disciplinary teams for novel materials
- Rapid modelling
- Mass customisation
- Sustainable manufacturing
- Smart products
- The Maker Movement
- Integrated computational materials engineering.

Additive manufacturing, nano-scale energetics, structurally reactive materials and metamaterials are identified as significant opportunities for Defence with the potential to offer substantial benefits in terms of savings, efficiencies and capability.

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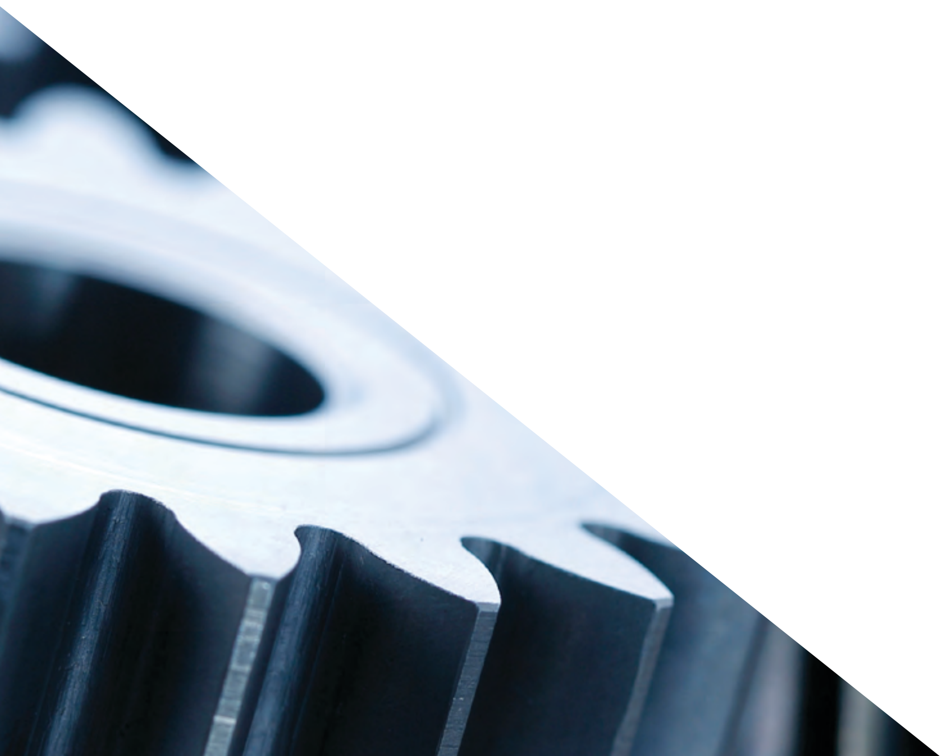

Advanced Materials and Manufacturing – Implications for Defence to 2040

1. INTRODUCTION

New and improved materials are being discovered and developed at a rapid pace. In the next 20 to 30 years, advanced metals and composites will become increasingly used in strong, lightweight structures, while applications of nanomaterials, metamaterials, novel superconductor and self-healing components will have emerged. Advances in manufacturing techniques will underpin new technologies and the use of these materials, with additive and hybrid manufacturing making more efficient, lower waste products, highly customised design and production, and embedded electronics and sensors. The application of these technologies was the primary focus of the Emerging Disruptive Technology Assessment Symposium (EDTAS) on the future of Advanced Materials and Manufacturing.

In realising and adopting the technologies of the future, society will navigate many challenges. Technological advances may see a rapid proliferation of new products, vehicles and components that government policy and regulation must cover. It will also present opportunities and risks for Australia's society and economy. Australian technology companies and manufacturers will have opportunities to design, produce and sell high value, niche products and materials, causing new demand for skills and applied research. Alternatively, Australia may fall behind if education, research and government policy cannot support these shifts in the economy.

In the context of Defence, the increasingly rapid development of new technologies and deployment of new capabilities present both an opportunity and a potential threat. The rate of development in materials and manufacturing will require Australia to be able to quickly adopt, or quickly counteract, new technologies and capabilities. It also presents an opportunity to more easily build sovereign capabilities and to insert more Australian suppliers into the Defence sector by developing high value, specialised components.

Until recently, large conglomerate corporations were the mainstay of industry. The rise of the Maker movement and the 4th industrial revolution (Industry 4.0) is challenging this hegemony and allowing for greater diversity of input from industry to Defence capability. For example, in the UK the Queen Elizabeth class Aircraft Carrier program has been utilising the efforts of hundreds of small and medium enterprises to deliver the revitalised capability [1].

Another example is additive manufacturing, which became a game-changing method for rapid prototyping in the 1980s when the first commercial technologies methods became available [2]. While still small-scale, additive manufacturing is being used across numerous industries, including automotive and aviation, to enable rapid spare development.

A report by the Dutch bank ING suggests that advanced manufacturing (such as additive manufacturing) could boost the production of locally manufactured goods, and diminish global trade by 40% leading up to 2040. The report [3] also claims that 'if the current growth of investment in 3D printers continues, 50% of manufactured goods will be printed with this figure possibly being achieved as early as 2040'.

In many ways we are now at a crossroads in materials science. With the congruence of multiple technologies from smart polymers to programmable matter the future applications of new materials will allow traditional industries to adapt and grow and develop solutions to huge challenges that were previously insurmountable. Figure 1 from Professor Graham Schaffer's presentation to the Advanced materials and manufacturing symposium [4] shows the considerations and factors that allow materials to perform in certain ways, described as the 'Materials Paradigm'.

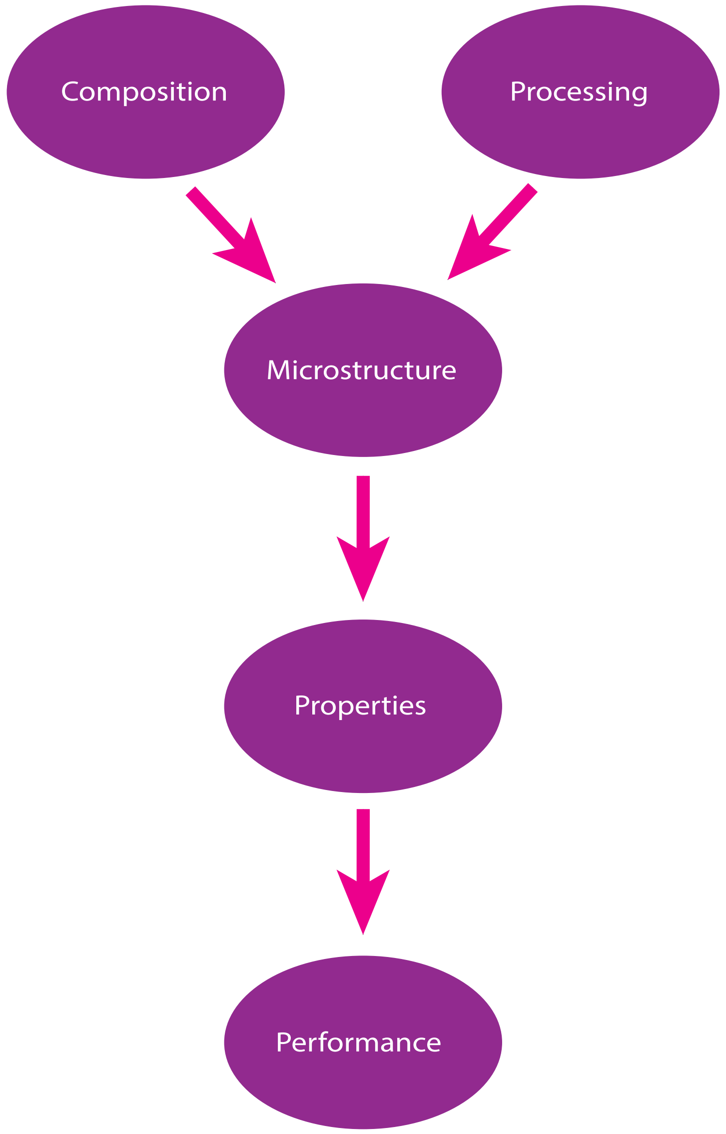

Figure 1. The Materials Paradigm

In addition to the key factors of performance and cost, a further consideration for future materials is the environmental impact, both to the ecosystem as a whole and health impacts on humans. Future materials will need to be seen to be both green and clean before being used in many areas. The experiences of high volume plastics and asbestos are too fresh in the memory to allow for the kind of unrestricted development.

Sustainability will also be a key input to future manufacturing. Thus materials which can be easily reused, or which are self-replicating will be a major avenue of research. 'How will manufacturing materials vary in the future when we have significant renewable energy... when we're not trying to minimise the energy because everything's free from the sun? How might that change the sustainability piece in terms of recycling or the materials we choose to use?' [5].

During the course of the campaign for this EDTAS, biomaterials were mentioned on a number of occasions, particularly during the symposium itself. A conscious decision was made to exclude this topic, as it will be examined in the EDTAS theme of Human Biotechnologies [6].

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2. MILITARY AND NATIONAL SECURITY CAPABILITY AREAS

To break down the broad domain that is advanced materials and manufacturing (AM&M) into a manageable size that is relevant to national security, DST has defined five key Defence capability areas impacted by AM&M, each of which was the subject of a workshop at the symposium. The five areas are detailed below.

2.1. Extreme environments

The ability of vehicles and people to travel and operate in the full range of extreme environments, from under the water to outer space, is significantly impacted by the materials used, and the methods of manufacture. The properties of the materials and the methods of construction could potentially enable novel deployment techniques, durability and endurance.

2.2. Uninhabited aerial vehicles

The utility of uninhabited aerial vehicles (UAVs) is well known, and in the national security context their ability to maintain a hidden surveillance of a potential threat makes them extremely useful to Defence. The ability to fly further, faster and for longer is advantageous from a commercial and national security context. Maintaining uninterrupted surveillance is vital for law enforcement to maintain an unbroken ‘chain of evidence’, and a longer endurance UAV has great commercial potential for agriculture, media, and general infrastructure inspection.

2.3. Power and energy storage

The rise of automated devices and 'wireless' sensors throughout society has increased the demand for smaller and lighter batteries with a longer endurance. Devices for use in the national security domain also benefit from these characteristics, especially if the device is to remain in place without interference for extended periods of time. Whether these are surveillance devices, security devices or UAVs, long endurance battery power is vital. This research area looks at advances in materials to make batteries, or materials and manufacturing techniques to harvest energy in other ways.

2.4. Survivability

The ability of equipment to withstand damage from either the environment or intentional damage from an adversary makes survivability an important research area for AM&M in Defence. This survivability can be achieved either by avoiding detection, or by making the structure of the equipment more durable.

2.5. Sensor systems

The ability of sensing systems to detect objects depends significantly on the materials from which they are made. Advances in these materials, and the manufacturing techniques used to make them, will greatly enhance the spectrum coverage and detection performance of these systems. Commercial sensors for automated vehicles, sensors for UAVs and other vehicles, and personal sensing systems will all benefit from advances in AM&M.

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3. NOVEL MATERIALS IN 2040

Materials have been instrumental to the development of human civilisation, so much so that we categorise entire epochs of our history by them. From the beginning of the Bronze Age around 5000 years ago, through the process of manufacturing iron and steel into the Modern Age, humans have shaped the world around them using materials that occur in nature.

Developments in advanced materials involves many fields of science including traditional materials science related to physics and chemistry, and engineering approaches including computer modelling, simulation, testing and fabrication. Advanced and novel materials have a huge spectrum of application areas covering everything from materials for energy to composites and coatings for the aerospace sector and biomedical materials to treat cancer. Nanomaterials in particular, where new materials are grown at the atomic and molecular level, have tremendous potential across a wide range of military applications.

This section identifies key future concepts and developments in advanced materials. The information has provenance in a number of areas, in accordance with the EDTAS campaign of events at Annex A.

3.1. Nanomaterials

Nanomaterials can be characterised as those materials which have structured components with at least one dimension less than 100 nm. Two principle factors cause the properties of nanomaterials to differ significantly from other materials: increased relative surface area and quantum effects. These factors can change or enhance properties such as reactivity, strength and electrical characteristics. Graphene is one of the best known nanomaterials and has a number of unique properties. It is an allotrope of carbon in the form of a two-dimensional, hexagonal lattice in which one atom forms each vertex (Figure 2). It is one of the strongest materials ever tested and also conducts heat and electricity very efficiently.

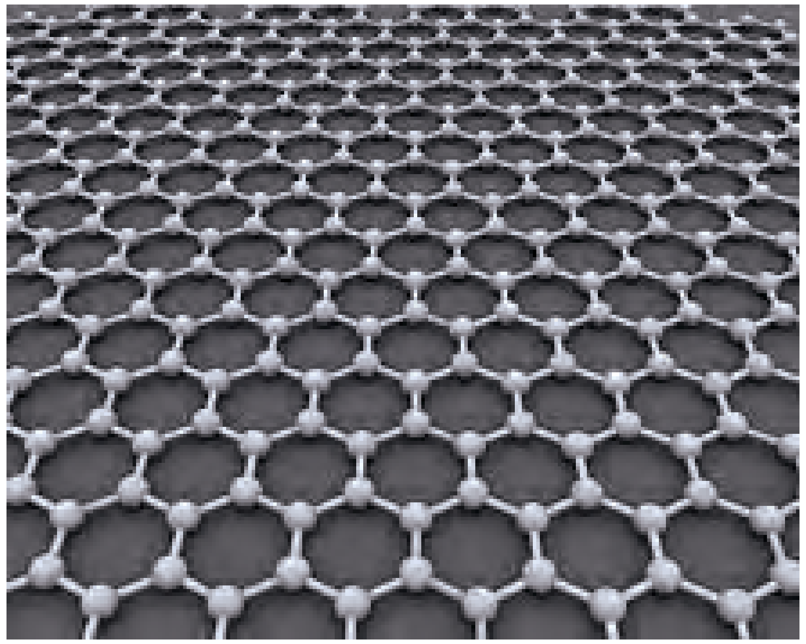

Figure 2. Graphene

3.1.1. Bibliometric analysis

Bibliometric analysis using Scopus, the largest database of peer-reviewed literature, and SciVal shows that scholarly output related to nanomaterials is strong and growing roughly linearly in recent years. The key topics in the field are shown in Figure 3, with nanoparticles, graphene and nanostructured materials being the fastest growing in recent years.

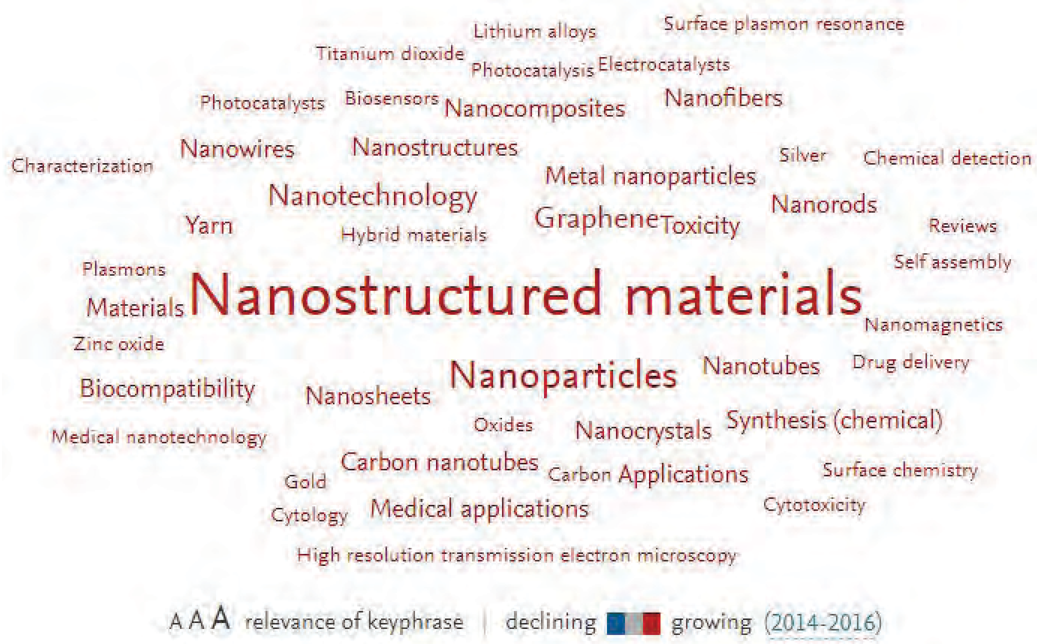

Figure 3. Nanomaterials key topics.

3.1.2. Military and national security implications

It has long been recognised that the key to building new materials is to work at the microstructure level, potentially leading to new alloys and high entropy steels with a broad range of military impacts. Opinions from the Advanced Materials and Manufacturing symposium reinforced this view and pointed out the impact on the development of nanowires for multi-spectral imaging, graphene-enhanced polymers for potentially stronger composites for vehicles and stronger and lighter body armour, and nanomaterials for anti-corrosion coatings and point of sampling medical diagnostics. Although a number of speakers at the symposium identified the potential overhype of graphene and carbon nanotubes (for example, see [7]), functional nanomaterial products are beginning to emerge on the market (for example, see [8]). A current low technology readiness level (TRL) example is the development of nanowires for multi-spectral imaging [9].

The recent fabrication of graphene foam is an example of how 3D graphene materials are being developed.graphene foam. The foam was fabricated using multi-walled carbon nanotubes and 2D graphene to produce a graphene 'rebar' (reinforced bar) in the shape of a screw. This material has exceptional mechanical strength as well as being highly conductive [10]. By 2040 this area of research is likely to have produced a number of novel materials and also see the incorporation of other two dimensional nanomaterials such as silicene, germanene or stanine into a very wide range of products.

Silicene, germanene and phosphorene are particularly interesting because (in contrast to graphene) they are semi-conductors. This opens the way for their use in nanoscale electronic circuits with a wide variety of applications and also potentially a way of enabling 'smart dust'. Smart dust has been conceived as a system of millimetre scale autonomous devices that form the basis for massively distributed wireless sensor networks. Recent advances in nanomaterials manufacture [11] potentially permits nanoscale electronic circuits to be grafted onto a particle such as a grain of sand to manufacture a material that in the future could provide novel wide-area surveillance capabilities.

3.1.3. Challenges and collaboration opportunities

Synthesis of nanomaterials is one of the most active fields in nanotechnology, and there are numerous methods for synthesising nanomaterials of various characteristics. Two general challenges in this area relate to atomic and molecular control of the structure of nanomaterials and in the control and definition of the spatial placement of such materials in bulk for industrial applications.

An implementation challenge relates to safety. A bibliometric search of Scopus data indicates almost 6000 of the 85 000 scholarly articles related to nanomaterials refer to 'toxicity'. These articles are evenly spread across the main subject areas of materials science, pharmacology, engineering, environmental sciences and chemistry. Analysis also shows that the term 'toxicity' has grown by 24% in the scholarly output over the last five years. Uncertainties about nanomaterial and its safety for human health and the environment are still hampering a more widespread exploration of its potentials. One of the challenges is in defining the means for the implementation of a safe, integrated and responsible approach for nanoscience and nanotechnologies.

Bibliometric analysis indicates that Monash University, CSIRO and the University of Queensland are active in scholarly publications in this area.

3.2. Metamaterials

3.2.1. Technology description

A metamaterial is a synthetic composite material with a structure such that it exhibits properties not usually found in natural materials [12]. For materials in nature, the basic building blocks are atoms and molecules, but for metamaterials, these are cells called 'meta-atoms' that are artificially designed and fabricated to achieve specific wave properties over a range of wavelengths. These artificially structured metamaterials are periodic, with feature sizes that are typically less than the size of the wavelength to be controlled. When the wave enters the metamaterial, it interacts with the structure, and the wave can be manipulated, often in highly counter-intuitive ways.

Employing metamaterials to alter how objects interact with the electromagnetic spectrum opens up the possibility of cloaking applications. A metamaterial cloak is a device that directs the flow of light smoothly around an object, without reflection, rendering the object invisible. At the moment cloaking is limited to passive structures but the symposium discussed how this might change as tuneable structures become employed at optical and terahertz frequencies. It is expected that this area will grow strongly in importance and have significant application areas for metasurfaces, especially in the area of novel optical coatings technology and for reconfigurable and tunable metamaterials.

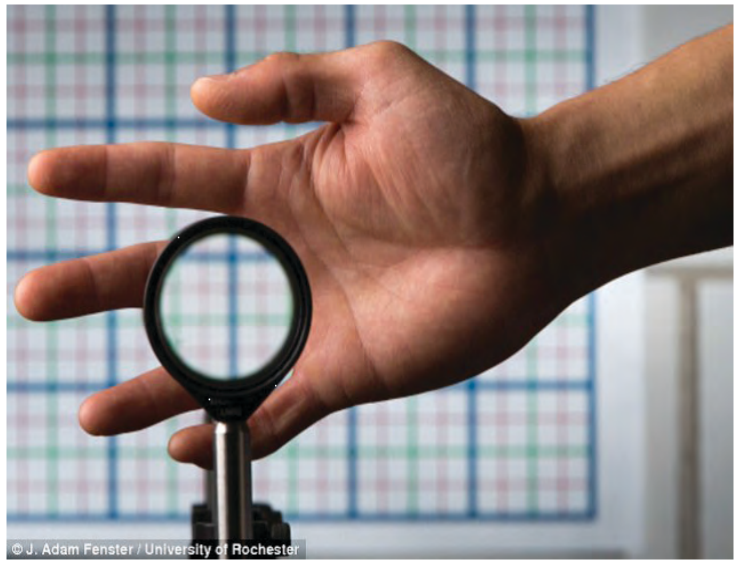

Figure 4 University of Rochester invisibility cloak (Copyright J. Adam Fenster / University of Rochester)

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3.2.2. Bibliometric analysis

Based on 16 621 publications the top 50 key phrases by relevance for metamaterials are shown in Figure 5. This analysis also indicates that metamaterial antennas are the fastest growing concept area in the field over the last five years.

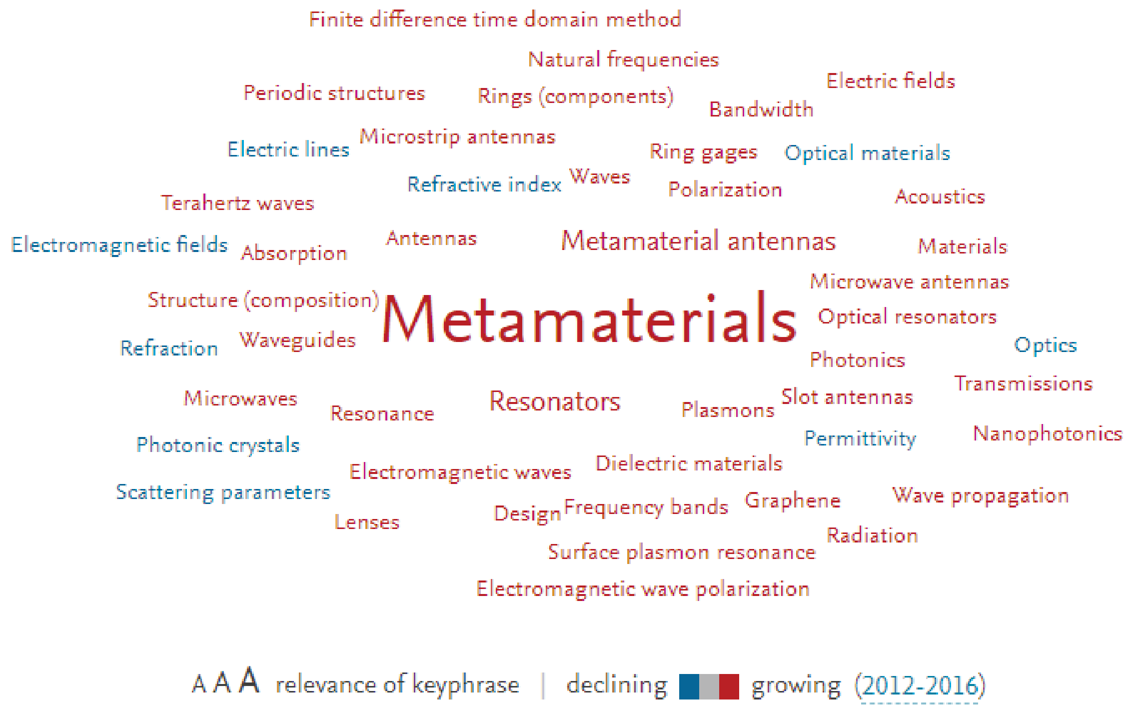

Figure 5. Metamaterials key topics

3.2.3. Defence and national security implications

The ability of metasurfaces to achieve ultra-broadband coherent perfect absorption has been demonstrated at a very low TRL level with implications for electromagnetic stealth technology for airframes in the future.

Researchers at Duke University have built a synthetic aperture radar using metamaterials, which makes it more flexible, more efficient, and cheaper than anything built before while maintaining the same image quality as traditional synthetic aperture radar systems.

Metamaterial-based antennas use metamaterials to improve performance such as enhanced antenna radiated power. Metamaterials can also allow for properties such as small antenna size, high directivity and tuneable frequency.

In the infrared spectrum metamaterials are being explored to control the direction of thermal emission. One potential application for this is a metasurface used for thermal management on a satellite to achieve high thermal emissivity from the satellite and, at the same time, high rejection of heat input from the sun.

3.2.4. Challenges and collaboration opportunities

In a recent review Kadic et al. [13] described how the metamaterial concept also applies to thermodynamics and classical mechanics (including elastostatics, elastodynamics, acoustics, and fluid dynamics). This indicates this is a field with rapid growth potential into new areas of research and application. For example controllable metamaterials that lead to smart structures and smart fabrics are a key trend in the next phase of metamaterial development.

Challenges involve binding the structural and functional properties of metamaterials more closely together and coping with the physical constraints around engineering metamaterials with acceptable mechanical, thermal, and environmental properties.

Bibliometric analysis indicates that the Australian National University (ANU) is the top Australian university in scholarly publications in this area.

3.3. Materials for energy storage and generation

Achieving higher energy densities in batteries in the 2040 timeframe emerged as one of the key areas in the symposium related to Defence applications involving both novel materials and manufacturing. However the average increase in the rate of the energy density of secondary batteries (such as Li-ion) has been about 3% in the past 60 years [14], and future progress is expected to be incremental. The ability to harvest energy from the ambient environment was also discussed in a variety of contexts. Energy harvesters typically provide a very small amount of power for low-energy electronics but they may have application in a longer time frame.

3.3.1. Technology description

Gradually evolving Li-ion batteries will provide continued growth in battery energy density, through incremental innovations like higher-voltage cathodes and electrolytes, paired with higher-capacity active materials such as silicon-based composites.

Solid-state batteries are one emerging technology in this space, where the liquid or polymer electrolyte found in current lithium-ion batteries is replaced with a solid. Lithium-sulphur and lithium-air are other emerging battery types with use in the 2040 timeframe dependent on energy density, cost, safety and weight.

Energy-harvesting materials refer to a broad range of technologies that are able to generate power from their operating environment, including light, heat, kinetic and organic. Theaim of these technologies can be either to act as a primary power source (e.g. photovoltaics) or capture and reuse small amounts of energy typically wasted during operation (e.g. kinetic energy recovery systems in Formula 1 cars), thus reducing the burden on the primary power source.

The most mature energy harvesting materials are photovoltaics. These materials, classically treated silicon, absorb photons and emit electrons, thus convert sunlight into an electric

current. Perovskite-structured solar cells are a recent emerging technology that offers an economically and environmentally viable option to traditional silicon-based technology and have exhibited efficiency levels of the order of 20% [15].

Piezoelectric materials convert mechanical stress into power. Systems exploiting piezoelectric materials are commonly used, although typically for non-energy harvesting applications. Nonetheless, stand-alone, closed-loop electronic devices with power consumption < 10 mWs can be manufactured cost-effectively today [16]. There are a large number of proposed commercial products under development based on piezoelelectrics, including pacemakers, wearables, and wireless sensor networks.

3.3.2. Bibliometric analysis

Based on 83 188 publications the top 50 key phrases by relevance for batteries are shown in Figure 6. This analysis also indicates that electric batteries are the fastest growing concept area in the field over the last five years.

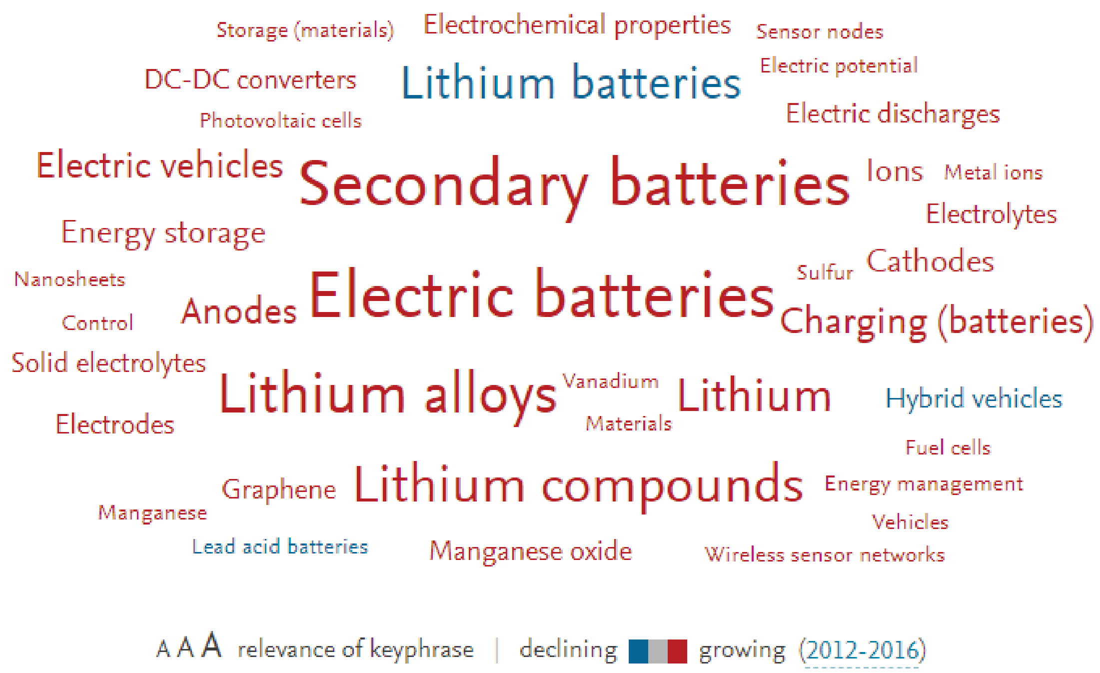

Figure 6. Batteries key topics

Research related to batteries represents by far the quickest growing concept in the scholarly literature related to batteries.

3.3.3. Military and national security implications

A common theme from some of the symposium workshops was a need for one to two orders of magnitude increase in battery energy density. This includes providing power for long-life uninhabited vehicles and long-life sensor systems. More generally this is a central issue in the strong global trend towards electric vehicles and in the need for storage of electricity for dwellings with solar panels. Hence large commercial players such as Toyota and Tesla are leading the way here.

The use of photovoltaic modules on military equipment, particularly long-duration drones, is a rapidly developing. An Australian company is using solar cells encapsulated in the material the drone is composed of to provide much increased endurance without loss of efficiency [17]. And the need to minimise the Army's logistics footprint is leading to the development of lightweight and flexible solar panels to obviate the need to carry bulky battery re-chargers in an operational setting. Reports of R&D progress in the US indicate that solar panels in the form of amorphous silicon thin film on plastic in the fabric of tents can potentially deliver up to 1 kilowatt of energy, which is enough to power fans, lights, radios or laptops [18].

3.3.4. Challenges and collaboration opportunities

The growing use of electric vehicles is the driving force behind much of the R&D in this field but the biggest challenge remains in achieving substantially higher energy densities over the next 20 years or so. This has to be achieved within the constraints of producing a battery that is safe, cheap, light, and able to be resourced from available materials. Without a breakthrough in battery chemistry we expect incremental progress in this area in coming decades.

Bibliometric analysis indicates that the University of Wollongong, the University of New South Wales, the University of Technology Sydney and the ANU are active in scholarly publications in this area.

3.4. Biomimetic materials

3.4.1. Technology description

Bioinspired or biomimetic materials are synthetic (man-made) materials that mimic natural materials and designs. Examples of bio-inspired materials include light-harvesting photonic materials that mimic photosynthesis; superhydrophobic (water repellent) surface coatings that mimic a lotus leaf; and hardness graded materials that mimic squid beaks.

The adaptability of biological organisms enables a level of flexibility in system design and performance that before now was impossible with synthetic materials and industrial manufacturing processes. Natural materials have evolved over time to perform a wide variety of functions such as light-harvesting, sensing and structural strength and use self-assembly and self-organisation to successfully adapt to an environment.

Based on nature's designs, methods of fabrication of biomimetic materials includes tissue engineering where peptides are used as building blocks by other biological structures and artificial muscles created using using electroactive polymers. The most immediate application for tissue engineering is in the area of human health for purposes of healing, replacement and augmentation. And artificial muscles are able to produce large movements in response to an applied electric field and have potential in robotics, sensors and actuators.

The new field of biomimetic materials has sparked the development of tiny robots that take on human or animal features, and tissue engineering to build machines powered by living muscle tissue or cells. These hybrids made up of natural and man-made materials are known as biobots and are fabricated by growing living cells, usually from the heart or skeletal muscle of rats or chickens, on platforms that are safe for the cells.

3.4.2. Bibliometric analysis

Based on 4434 publications the top 50 key phrases by relevance for biomimetic materials are shown in Figure 7. This analysis also indicates that 'functional polymers' and 'tissue engineering' are the fastest growing concept areas in the field over the last five years.

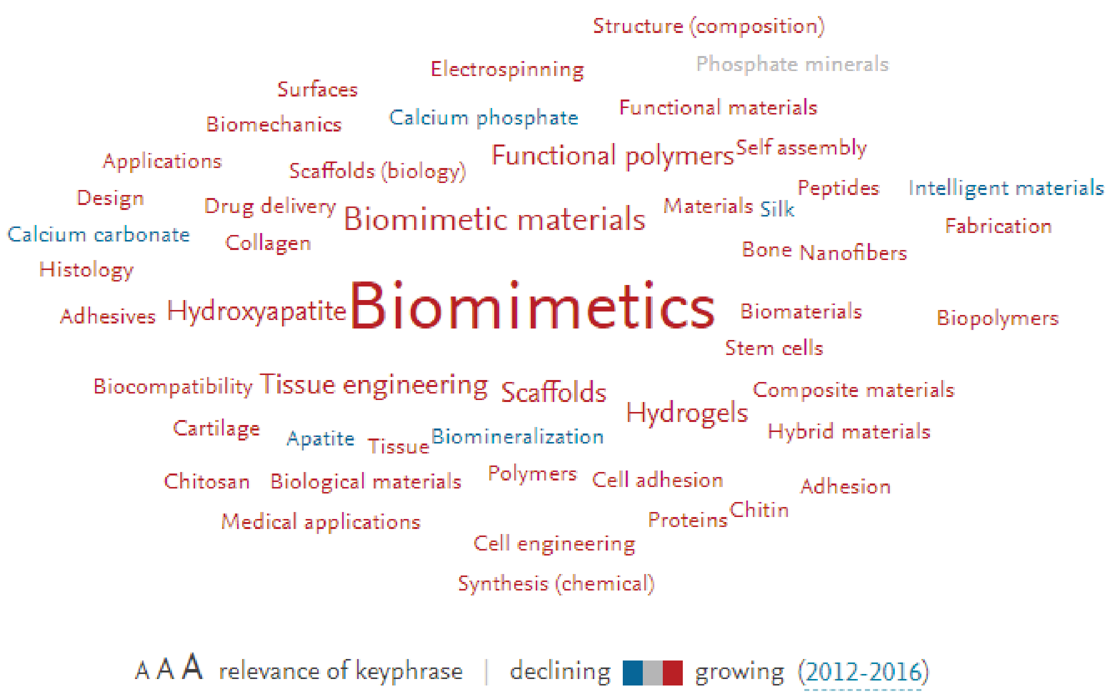

Figure 7. Biomimetic Materials key topics

3.4.3. Military and national security implications

Key biomimetic materials themes are mostly focused around the potential for improved adaptability to operational conditions. These include:

- Flexible electronic device designs inspired by natural materials and living organisms. These consist of nature-inspired structural materials that accommodate large mechanical deformation while maintaining the functionality of the devices, which have various applications such as mechanical sensing and energy harvesting.
- Self-healing, a natural process common to all living organisms that provides increased longevity and the ability to adapt to changes in the environment. A key requirement for the ADF in the 2040 time frame and beyond are new synthetic materials with extended longevity that are capable of restoring mechanical integrity (and other additional functions) after being damaged.
- Tissue engineering, a multi-disciplinary field that aims at the development of biological substitutes that restore, maintain, or improve tissue function. It has applicability in the treatment of wounds including the treatment of severe burns, and the growing of replacement limbs and muscles.

3.4.4. Challenges and collaboration opportunities

As discussed in Section 3.4.3., combining advanced fabrication techniques with techniques from synthetic biology could result in the construction of integrated systems across multiple length scales, achieving structures that are dynamic and responsive in ways similar to their natural counterparts; however translating biological concepts to manufacturable prototypes or products has yet to occur on a large scale. The challenges involve both the novelty of the biomimicry design process that involves prospecting nature for inspiration and selecting the correct functions to imitate, and the research and development process that typically involves activities across a number of disciplines to find a way to artificially mimic those functions efficiently in a device or system.

Bibliometric analysis indicates that CSIRO, the University of Sydney and Monash University are active in scholarly publications in this area.

3.5. Multi-functional materials

3.5.1. Technology description

Multi-functional or adaptive materials are those which provide additional functionality beyond their primary role, for example, a structural material that is also insulating, protecting, sensing, healing, actuating, and power generating. Given the broad range of technologies over which this concept sits there is also a wide range of technical maturity, i.e. some are more advanced than others. For example, structural sensing [20] or self-healing [21] compared to power generating [22].

Shape memory alloys (SMA) are an example of a multi-functional material that have been developed to market, primarily for use in actuators and motors. SMAs, the most common of which is NiTi, can revert their form to that of the original state when subject to some external stimulus Classically, that stimulus has been thermal, which can result in a sluggish high-frequency response. However, developments in magnetic actuation or thin-film SMAs shows promise in resolving this problem. Recent developments in using SMA wires embedded in composite structures is an example of a promising development in this field [24] and shows promise in generating larger, faster-actuating forces. There are substantial manufacturing hurdles limiting the broader commercialisation and application of SMA [25].

A wide range of multi-functional material concepts is based on structural composite materials. For example, through the inclusion of optical fibres or piezoelectric ceramics, damage monitoring of composites can potentially be achieved. Embedded fibres can also provide temperature [26] and strain monitoring. Additional work on self-sensing composite materials has demonstrated the potential for damage monitoring by the structural material itself (i.e. without the need for secondary embedded fibres) [27] potentially limiting the need for complex manufacturing processes associated with embedding fibres. Composite materials appear to be well suited to multi-functional concepts due to their multi-material nature, highly customisable manufacturing process, and relatively low-temperature manufacturing.

Nonetheless, improvements in architectured materials [28] and new nano-reinforcements should provide opportunities to expand the potential number of base materials.

Multi-functional materials also offer the potential for signature management across a number of domains, including visual, thermal, and acoustic. For instance, polychromic, chromogenic, and halochromic materials change colour due to external influences [29].

3.5.2. Bibliometric analysis

There is a very active research community working in this field, exhibited by the rapid increase in publications and patents in this area. Based on 10 922 publications the top 50 key phrases by relevance for adaptive or multi-functional materials are shown in Figure 8. This analysis also indicates that 'functional materials' and 'shape memory effect' are the fastest growing concept areas in the field over the last five years.

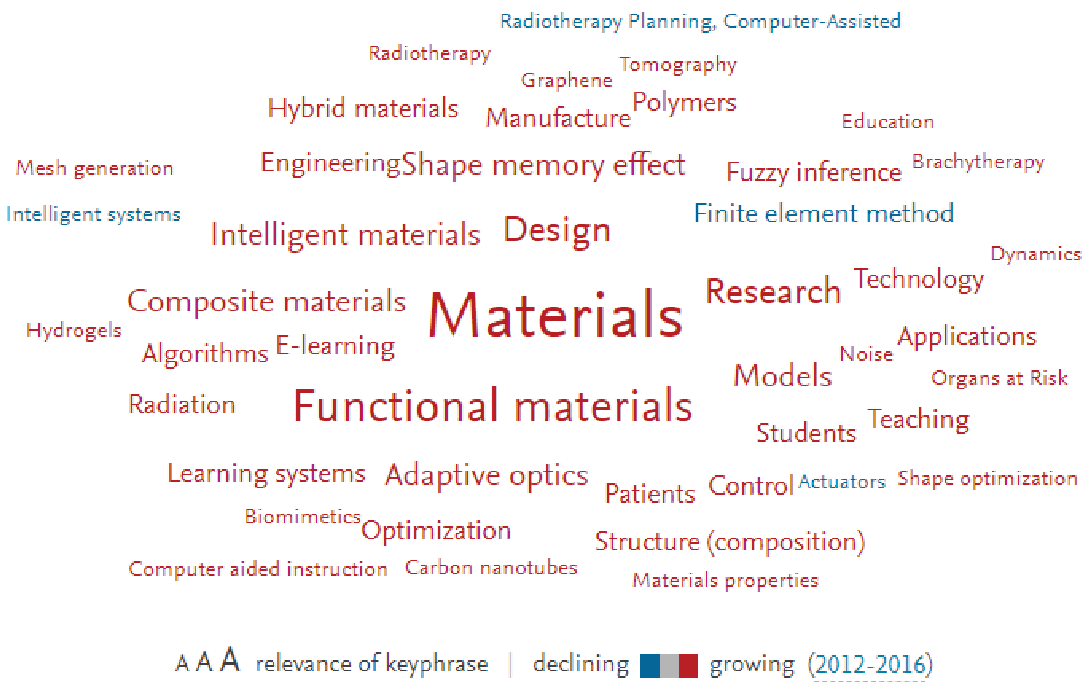

Figure 8. Adaptive or Multi-functional Materials key topics

3.5.3. Military and national security implications

A UAV skin and structure that could track damage through embedded sensing, and self-heal that damage, would have a disruptive effect on military capability. It was also evident from the symposium that adaptive materials, particularly self-healing and/or self-regenerating, are critical technologies in a number of Defence applications. For example, an 'infinite endurance' UAV would require the ability to heal impact damage and ongoing environmental degradation, as well as an ability to harvest and store energy from its environment. Smart and flexible materials offer great potential for novel clothing and

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textiles such as, bandages that detect infection and respond with an alert or medical response or fabrics that allows troops to stay dry during operations in extreme environments.

The issue of developing low-cost, sustainable platforms or systems also focused discussion on reusable materials. The discussion can be divided into two broad lines of implementation: (1) regenerative materials able to self-repair and thus sustain their integrity beyond the life of conventional materials, or (2) refurbishable materials, such as low-cost spray-on coatings, that could be reapplied as necessary to provide ongoing protection as necessary.

3.5.4. Challenges and collaboration opportunities

There are significant multi-disciplinary challenges in developing new multi-functional materials and implementing them in advanced systems. The R&D domain spans length scales from nano-structured materials to engineered land, air and space structures. CSIRO has significant expertise in smart clothing and bibliometric analysis indicates that the University of Sydney and University of Wollongong are active in scholarly publications in this area.

4. FUTURE MANUFACTURING IN 2040

4.1. Key approaches

Manufacturing is no longer simply about making physical products. Changes in consumer demand, the nature of products, the economics of production, and the economics of the supply chain have led to a fundamental shift in the way companies do business. With the proliferation of sensors and connectivity, 'dumb' products are turned into 'smart' ones, while products become platforms and increasingly move into the realm of services.

As technology continues to advance, the barriers to entry into the marketplace, commercialisation opportunities and manufacturing knowledge are diminishing.

While large-scale production will always dominate certain segments of manufacturing the symposium discussed the future impact of micro factories—manufacturing systems small and efficient enough that they can be set up in every community across the globe. These embody the concepts of decentralised, distributed manufacturing and are proposed for the recycling of e-waste into its constituent metals and other valuable products.

4.1.1. Additive manufacturing

A number of presentations [30–32] at the symposium referred to additive manufacturing (also known as 3D printing) and its ability to fundamentally change the way we manufacture everyday items. Although 3D printers are not new, their application and variants are likely to progress much further. Current versions of 3D printers are capable of printing material as small as 2.5 mm, while larger scale printers can produce one tonne of material per day.

This type of manufacturing with such a high level of precision and rate could theoretically be extended to large-scale production of entire tanks and submarine skins.

The material properties of additively-manufactured products in the future could be highly precise and individually customised. The emergence of techniques such as cold spray application could see the rapid production of high strength metal structures in shapes that are not currently possible, and lead to vast savings in materials used. Cold spray technology could also allow many new materials to be used and enable additive manufacturing to occur in new environments (see Figure 1).

A Delphi study [33] looking at the future of additive manufacturing explored the prospect of creating new business models. In one scenario explored in the study manufacturers become pure content providers of digital product files, outsourcing manufacturing to consumers.

From a Defence perspective, advanced manufacturing offers potentially very large benefits in terms of lower costs and timely delivery to the logistics and sustainment activities that underpin all operations. In the future, basic logistics runs may be routinely redirected to supply materials to outposts for direct-part manufacturing in the field to meet urgent needs while saving time and money. One such futuristic scenario is outlined in the US Air Force Future Operating Concept. A container of polymer for directly 3D printing parts is delivered by air to an isolated outpost. The digital file to print the needed part is processed by a 3D printer that generates the critical part within hours compared to days, potentially saving millions of dollars in the process.

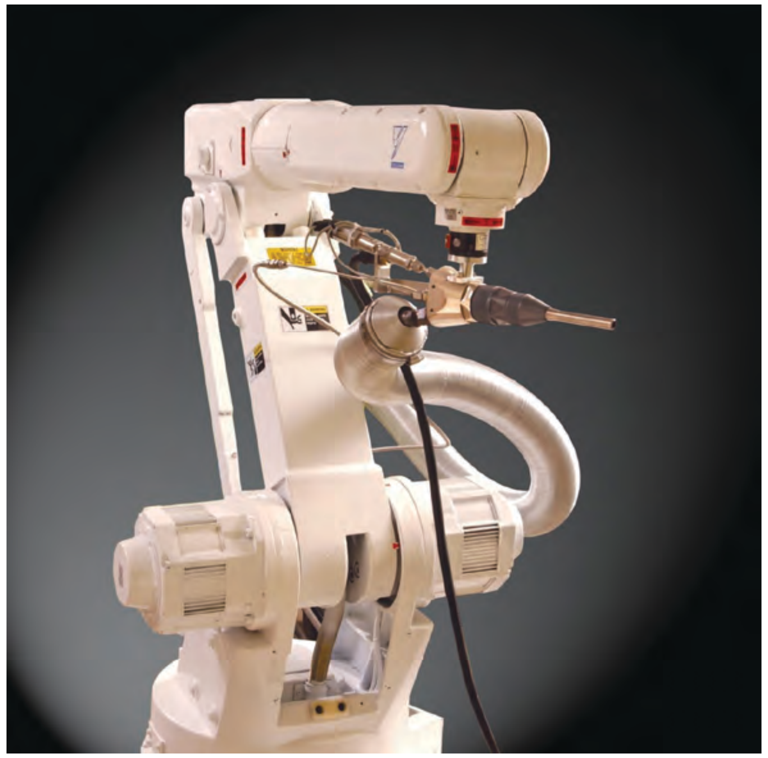

Figure 9. Spray nozzle on a robotic arm for complex additive depositionat Lab 22 (Copyright CSIRO, 2016)

4.1.2. Industry 4.0

Digitisation, automation and machine learning are driving Industry 4.0. At a high level, Industry 4.0 represents the vision of the interconnected factory where all equipment is connected online, and in some way is also intelligent and capable of making its own decisions. The ultimate goal may be thought of as a 'smart factory' with cyber-physical systems capable of autonomously exchanging information, triggering actions, and controlling each other independently.

The explosion in connected devices and platforms (sometimes referred to as the Internet of Things), combined with the abundance of data from field devices and a rapidly changing technology landscape, has made it necessary for companies to move from the physical world to a digital one.

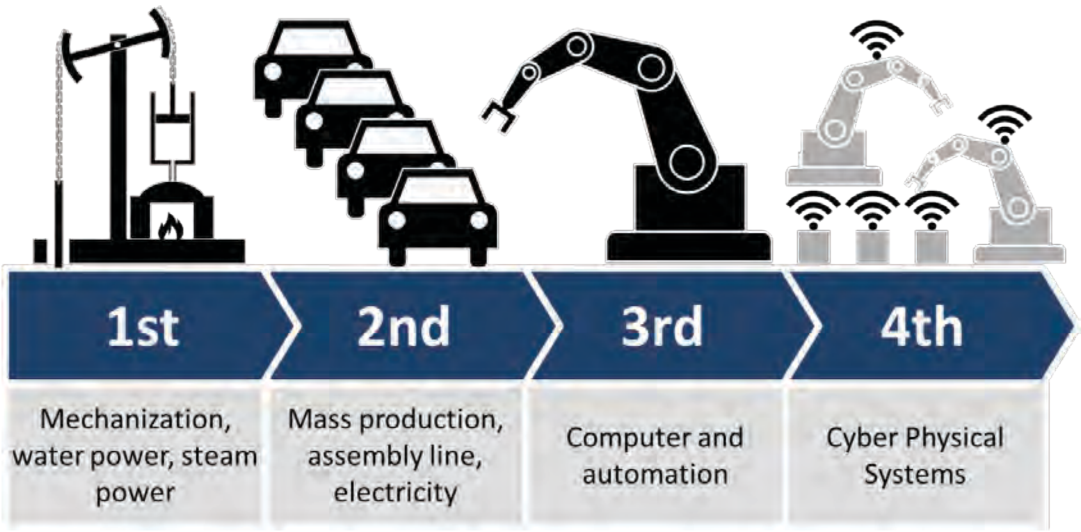

Figure 10. The four 'Industrial Revolutions' defined by the German Industry-Science Research Alliance (Source: Christoph Roser at AllAboutLean.com)

The benefits to Defence of the adoption of Industry 4.0 methods by commercial partners come through cost efficiency (for example in greatly improved asset tracking capabilities) and overall supply-chain effectiveness. Investments in the digital supply chain elements of Industry 4.0 will improve speed to market, lower production costs, and enable more collaborative innovation. And considering that a significant share of aerospace and defence products are supplier developed, it is investments like these that will prove to be critical enablers for industry and military leaders alike.

A greater benefit in the longer term from the move to digitisation of the product space will come from the flow-on and convergence effects of this revolution. These technologies will work in time with advances in data analytics and artificial intelligence, providing manufacturers with the ability to predict and react to ADF supply needs. Ultimately there may be pay-offs for operational commanders due to increased situational awareness provided by hundreds of connected and computer-enabled platforms and devices in the battlespace.

4.1.3. Robotic systems

Industrial robots have historically been used mostly for tasks requiring strength and precision, for example moving heavy items, bonding and welding, and semiconductor production. Now rising global labour costs and a new generation of cheaper, more capable, more flexible robots are changing the equation. The use of a new generation of lightweight, assistive robots will provide manufacturing enterprises with new options to improve their effectiveness and meet the challenges of high costs and a scarcity of skilled workers.

By 2040 we can expect to see increasing use of 'cobots' — robots that work directly and collaboratively with human beings in a manufacturing setting. In addition, there will be much greater use of soft robots that use pneumatic instead of mechanical power, reducing energy requirements and generally increasing safety.

Use of robots in an Industry 4.0 environment will increasingly lead to a 'lights out' or 'dark factory' production concept in which activities and material flows are handled entirely automatically. This is already being seen in, for example, a Philips factory that produces electric razors where robots outnumber the line workers by more than 14 to 1.

4.1.4. The maker movement and extreme manufacturing

Industry 4.0's range of new technologies, increased availability of design tools and data, and low barriers to entry to the fabrication and manufacturing fields have led to the emergence of the 'Maker Movement'. The Maker Movement represents a broad-based extension of DIY culture and results in the creation of new devices as well as tinkering with existing ones. One impact of this growing movement is that it is likely to lead to a shift in job creation; larger companies are becoming more and more automated – often involved in repetitive tasks done at scale; in contrast, the maker movement allows individuals to become creators of bespoke products. Over time it is likely that this will have major implications for company start-ups and job creation.

A key element of this movement is the use of open source hardware that opens the door for newcomers by challenging the branded foothold of a larger competitor. With design and technical specifications typically available online, hardware developers can modify existing hardware and do rapid prototyping and small-scale production runs. The dynamics of open source hardware are still evolving, but the implications are expected to become more important in the years ahead.

Big corporations are now exploiting the movement's techniques in an approach known as 'eXtreme Manufacturing'. This combines Scrum software development methodology and other software programming frameworks with lean manufacturing principles to rapidly design, build, test and iterate new products and technologies.

This more rapid and more atomised industrial landscape will see much quicker development and marketing of products, as well as a proliferation of customised, modularised and ever-changing manufacturing systems.

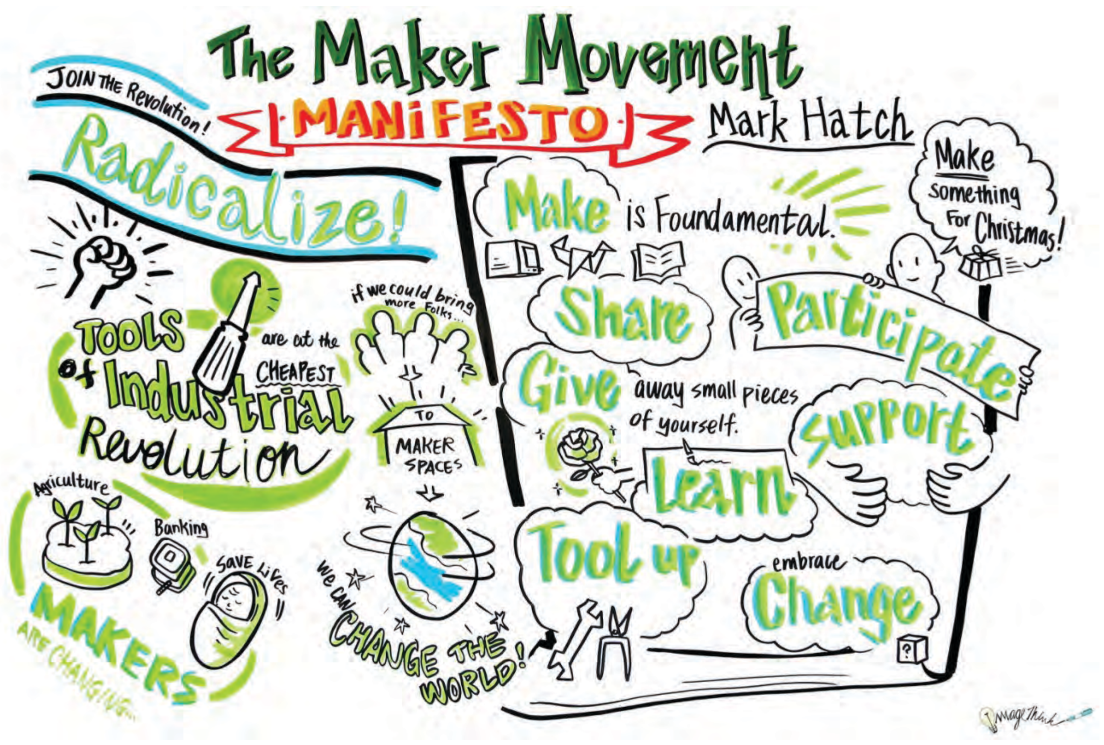

Figure 11. Maker Movement Manifesto (Source: ImageThink)

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5. ENABLERS AND BARRIERS

This section examines the barriers and enablers to the effective military exploitation of novel materials in the 2040 time frame.

New initiatives in novel materials and manufacturing may require Government funding to kick-start development in key areas. In this regard, an appetite for high risk/high reward R&D enterprises is needed at a national level, and an ability to select areas that Australia can lead the world in research and development. A Defence CRC in novel materials and manufacturing is one possibility in this regard.

5.1. Expertise in nanotechnology

The symposium demonstrated that Australian universities along with DST have strong nanotechnology credentials that are seen as key enablers of novel material development and exploitation through to 2040. Nanomaterial fabrication is the key to building new materials and Section 2 pointed out the impact of nanomaterials on, for example, the development of nanowires for multi-spectral imaging and graphene-enhanced polymers for potentially stronger composites for vehicles and stronger and more lightweight body armour. Nanotechnology also has implications for energetic materials where it is likely that novel nanomaterial propellants, for example will allow munitions to travel further for a given payload.

A lack of skills and a suitable training pipeline both in the academic and industrial domains is a potential barrier to the development and manufacture of novel materials. This is particularly true for future materials that cut across existing academic disciplines and siloed expertise. The need for Defence consumers to be highly educated and informed on what is possible for forthcoming large Defence projects [34] is important and can be viewed as a barrier, though from a positive perspective this could also be seen as an enabler.

5.2. World class facilities

Large-scale facilities and equipment are needed for the study of surface science that underpin innovation in materials. For example, at the ANSTO synchrotron, a research team from the Walter and Eliza Hall Institute of Medical Research obtained the world's first 3D pictures of insulin in the process of binding to its receptor on the surface of cells [35]; facilities at the Australian Centre for Neutron Scattering are used to determine the internal structure of many classes of materials; and universities such as the University of New South Wales [36] use a field-emission scanning electron microscope to achieve ultra-high imaging resolution at the nano level.

5.3. Early identification of dual-use applications

Dual-use applications are novel uses of materials and manufacturing that have both commercial value as well as utility for Defence. More generally speaking, dual-use can also refer to any technology which can satisfy more than one goal at any given time. Early spotting of such applications gives advantages along the supply chain from commercial through to Defence use.

5.4. Natural resources

Australia has many natural resources that underpin advanced materials. To take one example, Australia is the highest world producer of lithium used in Li-ion batteries, and demand for this is expected to grow rapidly with electric vehicle production. In terms of biological resources Australia has very well-documented flora and fauna, and this is seen as an important enabler for the development of biomimetic applications.

5.5. Ethical and legal implications

There are ethical and legal implications associated with the development of bio-mimicry and bio-hybrid robots. Looking forward towards 2040, it is expected that robots and in particular biobots will become increasingly autonomous in operation. This move to autonomy has major legal and ethical consequences and inhibitors. The EDTAS on Trusted Autonomy [37] explored this in some detail. The use of synthetic biology as a mechanism to grow living tissue for use in biomaterials also has to be considered within the context of the ethical and legal frameworks in which we operate.

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6. COMMON THEMES

In the course of the EDTAS campaign of events a number of overarching themes appeared. This section addresses these themes.

6.1. Cross-disciplinary teams for novel materials and manufacturing

The symposium found that that novel or disruptive applications in nanoscale materials will likely depend on bringing together skills from a number of disciplines such as chemistry, life sciences, engineering and computer science. For example (as described in Section 3) biomimetics is the study of nature and natural phenomena to understand the principles underlying natural mechanisms and the application of those concepts to material uses in science, engineering, and medicine. This is not a new field (for example swimsuits inspired by the structure of shark's skin already exist), but with the increasing impact of synthetic biology in engineering tissues for biomimetic applications the field is likely to become more important and more cross-disciplinary. Synthetic biology involves concepts from biology and computer science and will likely have to be married with chemistry, physics and engineering skills in the research and development of novel biomaterials.

6.2. Mass customisation

Manufacturing is beginning to enter a new phase of customisation-oriented production that is less concerned with productivity and efficiency and more focused on agility and responsiveness. There will be an increasing emphasis on making to individual requirements, sometimes thought of as mass-customisation, rather than high throughput, low variability mass production. Greater consumer expectations are also causing a shift from mass production of goods to bespoke solutions. This will be seen in many market sectors such as health and medicine where biomaterials and bioengineering will allow for the generation of individualised products. A potential barrier is the cost of the customisation. While improved manufacturing techniques will offset this to some degree, it will be a major hurdle to overcome during implementation.

6.3. Sustainable manufacturing

Sustainable manufacturing is the creation of manufactured products through processes that minimise adverse environmental impacts. The growing understanding of the limitations on natural resources and the increasingly valued environmental, social and financial credentials of developing a sustainable business model are driving businesses to adapt. The ideal end state will be to create a closed loop manufacturing system. Currently we recycle 50% of aluminium, with a soft drink can taking around two months to go from refuse to reuse. The future will see advances in this area, with all inputs being designed and scoped from the earliest stages to be as reusable as possible, in the most efficient and economical way.

6.4. Smart products

Technological advances enabling modularity and connectivity are transforming products from inert objects into ‘smart’ devices, while advancements in materials science are enabling the creation of far more intricate, capable, and advanced objects, smart or otherwise. At the same time, the nature of the product lifecycle is changing, with many products transcending their roles as material possessions that people own to become services to which they buy access. Increasingly we will see manufacturers expanding their role in the value chain from making objects to developing integrated service-product bundles.

6.5. The Maker Movement

The Maker Movement outlined in section 5 represents an aspect of a democratisation of manufacturing and a blurring of the lines between producers and consumers. In 2040 the consumer trends towards personalisation, customisation, and creation will see more niche markets established where consumers will be able to find or even create products suited to their individual needs. In this environment, manufacturers producing large volumes of limited numbers of products will work alongside smaller makers of customised products.

6.6. Integrated computational materials engineering

Integrated computational materials engineering (ICME) is a holistic design method which considers the product design, the materials used and the processing methods to link them together. This has the potential to be a transformative discipline. It is currently focussed on metallurgical engineering, but in future will expand to other material categories. This systems approach to materials engineering will allow faster and more efficient materials design and production.

Many of the biomimetic and metamaterial concepts discussed during symposium require multi-scale design and manufacture. This spans material selection and structural design at the nanoscale through to the macro scale (e.g. ‘architecture materials’ [38]). Such multi-scale optimisation was expected to require improved computational tools, likely based on machine learning techniques. ICME covers the range of scales and methods used to optimise the performance of new materials. Lockheed Martin in Australia has experience in use of ICME for tailoring materials to specific purposes in infrared sensing platforms and chemical sensors. Techniques from artificial intelligence such as machine learning are expected to play a big part in the design and optimisation of new materials. Starting with laboratory data and computer modelling of known materials, machine learning techniques are used to identify and extract common patterns that are in turn used to guide prediction of new material properties. Chemists can then try to make novel material candidates for real world testing and experimentation.

7. KEY QUESTIONS

Based on the findings of Sections 5 and 6 the following key questions are raised with respect to the future of advanced materials and manufacturing.

On the development of Defence capability:

- How do we increase the pace at which new materials and manufacturing technology are identified and adopted in Defence capabilities?
- Where can agile manufacturing and rapid design and build approaches be applied in Defence capability?
- Can testing and verification be streamlined to facilitate advances in materials and manufacturing?
- How can Australia maximise its domestic capabilities in Defence-related industries?
- How can collaboration between Defence, research bodies and industry best enable the exploitation of new technologies in advanced manufacturing and materials?

On the impacts to Australia, its security and its economy:

- Can Australia's government, businesses and workers embrace the changing industrial environment, or will we fall behind?
- Can Australia's own natural resources lead to a strategic advantage in developing advanced materials and manufacturing?
- What strategic risks do we face from reliance on expensive, rare or imported resources in advanced materials and manufacturing?
- How to protect intellectual property rights to ensure that there are economic returns to Australia from in complex emerging areas such as bio-materials?

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8. OPPORTUNITIES FOR DEFENCE

Based on the complete EDTAS campaign of events and input from key subject matter experts, this section identifies the emerging areas in materials and manufacturing that potentially offer the greatest opportunities to Defence.

In considering how to respond to these opportunities, the 'exploitation stance' of the department needs to be assessed. Should Defence look to become an early adopter and developer of technology, or should it respond to developments on an opportunistic basis and be a buyer of the technology from other countries?

Funding through the Next Generation Technologies Fund represents one mechanism by which emerging technologies can be funded.

Defence uses the Force Design Cycle to deliver evidence-based capability investment and force structure options. As part of this, the Defence Capability Assessment Program identifies priorities and addresses gaps and opportunities for the planned force. Technology opportunities outlined in EDTAS feed into this cycle and permit novel and potentially game-changing technologies to enter the Force Design Cycle.

8.1. Case studies

This section details two case studies that demonstrate the emerging and novel uses of advanced materials and manufacturing within Australia, and outline future applications for Defence and national security.

8.1.1. Transformative energetics research

Across the next two to three Defence acquisition cycles, it is expected that advances in energetic materials, coupled with the cutting edge processing and manufacturing technologies necessary to fully exploit their benefits, will see the introduction into service of new classes of future weapons offering revolutionary gains in performance and operational flexibility.

Key technologies of relevance in this regard are: nano-scale energetics; structurally reactive materials; the processing technology of resonant acoustic mixing, and; the additive manufacturing of energetic materials. A sub-set of these technologies are anticipated to significantly lower the cost of entry for the munitions manufacturing industry base which, in the Australian context, would allow for the diversification of the supply of advanced munitions and provide security of warstock as a consequence.

Nano-energetics

Nano-particles typically have unique physical, chemical, biological and toxicological properties that often differ markedly from larger forms of the same material (see Section 3.1). Similarly, nano-scale energetic particles share a number of these material property differences that, when compared with more traditional micron-sized energetic material particles, give rise to munitions that offer enhanced energy output with reduced sensitivity. For a given volume of energetic material this enables enhanced effect on a target. Alternatively, the use of nano-energetics can enable the same energy output as a conventional explosive to be achieved with a significantly reduced warhead size, thus resulting in lighter weapons or the creation of additional space for other weapon components. The prospect of energetic materials that are less sensitive to unintended external stimuli, as may be offered through the incorporation of nano-scale energetics, may also enable the use of explosive ordnance in previously inaccessible extreme operational environments.

Structurally reactive materials

Structurally reactive materials (SRM) comprise a granular mixture of metal and metal oxides that form the warhead case in which an explosive charge is contained. Upon detonation of the explosive, the SRM case fragments and these reactive fragments then ignite and combust, thus significantly augmenting the blast effect of the explosive.

The choice of elements used in the metal alloy, and the manufacturing process used to produce the case, are critical as the material needs to have bulk solid properties comparable to steel in terms of density and strength such that it can withstand the operational environment, but also have micro-grain structures that allow the rapid ignition and combustion of the case material upon fragmentation. Because the fragments are being consumed as they move away from the point of detonation, and as the fragment size can be controlled via the quantity and type of high explosive contained in the warhead case, they pose less of a collateral damage risk than traditional steel warhead cases. As such, warheads fabricated out of SRM are well suited for operational scenarios in contested urban environments.

As the SRM case represents an insensitive energy source that supplements the energy of the explosive, munitions employing this technology afford: more flexibility in terms of the partitioning of warhead weight for precision and range with enhanced effect on target and; increased durability of the munition and, therefore, breadth of operational scenarios over which it can be employed.

Resonant acoustic mixing

Resonant acoustic mixing (RAM) is a novel processing technique that uses low frequency, high intensity acoustic energy to generate mixing phenomena that create uniform and rapid mixing of highly viscous slurries, liquids and powders. When compared with conventional energetic material processing technologies, the mixing ability of RAM enables the incorporation of a higher proportion of high energy-density solids, including hard to process materials such as nano-energetics, into the polymeric resins that constitute the remainder of the resultant energetic material. This confers additional energy into the system and a more uniform end-product.

RAM is also a contactless mixing technique, so unlike traditional processing technologies where mixing blades and impellers are employed, there are no moving parts in contact with the energetic material. This promotes enhanced processing safety and also enables the mixing of energetic materials in-situ in the form of the end-application in question. This increases efficiency, obviates traditional material transfer challenges that can often introduce unwanted porosity into the end article and also reduces waste.

Additive manufacturing of energetic materials

The additive manufacture of energetic materials is an area of rapidly growing interest in a global sense across the energetic material community, with the utility of additive manufacture being assessed across all classes of energetic materials from propellants, both gun and rocket, to explosives and pyrotechnics.

The rapid growth of research investment in this area stems from the magnitude of the performance gains that stand to be unlocked through the use of additive manufacture technology to create geometries and multi-component structures that are not possible with traditional manufacturing techniques, thereby enabling greater tailorability over the nature of the energetic materials energy release.

In gun systems, this allows the design of propelling charges affording improved control over the propellant gas generation rate across the interior ballistics cycle, such that gun hardware performance limits can be fully exploited. For a given energy content this affords: enhanced muzzle velocity; enhanced range; improved shot to shot reproducibility; improved precision and improved barrel life. Improved control of propellant ignition and subsequent gas generation can also reduce peak acceleration loads on the projectile which may enable the effective deployment of sensitive electronic components in gun-launched systems.

For high explosive applications, control of the internal geometric structure of the energetic material may open the door to tuneable charge initiation offering improved detonation performance coupled with reduced vulnerability to initiation via unintended stimuli. Future weapon concepts requiring 'dial-a-yield' warheads or conformal warheads could also be enabled through such technology.

This same design philosophy can also be extended to: solid rocket propellant development where greater control over achievable thrust-time profiles affording performance gains and increased operational flexibility could be achieved; and increased tailorability over spectral output in pyrotechnic applications.

In addition to the performance benefits that stand to be gained via the use of multi-component structures with tailored geometries, additive manufacture stands to allow more agile and geographically agnostic energetic material production, potentially extending to the ability to be able to print energetic materials on-demand in theatre.

Concluding remarks

The aforementioned technologies stand to yield significant gains, and in some cases step changes, in performance in their own right. However, by dovetailing these technologies together, synergistic benefits can be unlocked that open the door to previously unrealisable, disruptive energetic materials systems and effects across all classes of energetic materials.

The prospect of on-demand production and small batch sizes offered by the processing and manufacturing technologies described herein will also drive cost, logistics, environmental and efficiency savings across the munition life cycle. For Australia, the ability to locally manufacture a wider range of advanced munitions, with relatively low infrastructure cost, offers significant strategic and competitive advantage for the future.

8.1.2. Supplying the RAAF with additive manufacturing

In conjunction with the RMIT University and industry partners, DST has developed a laser based additive repair technology for remediating aircraft components damaged by corrosion, wear and fatigue cracking.

The repair process involves fusing powdered metal particles to a component's surface with the heat of a high-energy laser beam. In many cases, the process can provide a more cost-effective way of keeping aircraft in the air than replacing the unanticipated damaged part and, in some cases, the repaired part can have properties superior to those of its original state.

The technology has already been applied to repair the rudder anti-rotation bracket on the F/A-18 Hornet aircraft, with the repaired component having been certified for flight. It has also been applied on a steel landing gear component of the C-130J Hercules military transport aircraft, which typically shows signs of corrosion after years in service. For the C-130J repair, stainless steel powder was used to give the component greater corrosion resistance.

DST is working with both national and international partners to explore the possibility of using additive technology for both repair and manufacturing at forward military operating bases to reduce deployed footprint. The work is currently focused on a new approach to certification by monitoring in real time the performance properties of components made by additive manufacturing techniques. This work is of particular importance for enabling applications of the technology in the aerospace domain where components have to be certified as airworthy.

Meanwhile, analysts see that the ability to easily repair parts on deployed assets will simplify the logistics of operations and further increase the speed at which they can return to service. In future, maintenance staff operating overseas could upload a computer-aided design file and print the part when required. This would reduce the supply chain timeline and nullify the need for large warehouses full of spare parts, resulting in increased warfighting readiness at a reduced cost.

Through its ability to print complex geometry, additive manufacturing also offers the prospect of manufacturing parts of similar strength but significantly reduced weight compared to those made conventionally. In addition, the technique may result in less wastage of materials, which is of importance particularly for components made of expensive materials like titanium.

8.2. Emerging opportunities

While the previous section looked at existing programs with great potential for Defence this section examines at new R&D opportunities to emerge from EDTAS.

8.2.1. Feedstock for additive manufacturing

Many speakers at EDTAS spoke of the ability of additive manufacturing to create complex parts with a very high level of precision and control, resulting in the reduction of material usage, weight, assembly, and maintenance. In a Defence environment, where products are likely to be used for safety-critical applications and in harsh environmental surroundings, it is critical that all parts are deemed safe. Certification schemes for additive manufacturing are in their infancy but emerging. For instance Lloyd's Register additive manufacturing Product Scheme [39] allows manufacturers to demonstrate that their parts meet existing manufacturing methods and standards.

Additive manufacturing has limited potential for the production of aluminium alloys because aluminium is comparatively easy to machine and the costs of aluminium parts made in traditional ways are comparatively low.

Titanium and titanium alloys, however, are prime candidates for additive manufacturing because of their broad industrial application in high performance parts, their high machining costs and long lead times in conventional processing Because of these factors, the additive manufacture of titanium parts offers substantial cost advantages. The UK government has recognised the importance of additive manufacture of titanium and has funded development of a process that allows the titanium powder used in additive manufacturing to be produced in a much cheaper and more abundant way [40].

Australia has the biggest deposits of ilmenite and rutile – titanium's base minerals – in the world [41]. Extraction and refinement of the material produces titanium dioxide, but currently this isn't processed into metallic form. Australia could consider an enabling initiative of the UK type to produce titanium feedstock for additive manufacturing.

8.2.2. Metamaterials research and development

Metamaterials is a relatively young scientific field with a number of important application areas for the military including radio-frequency (RF) metamaterial antennas; RF signature reduction; thermal and infrared signature control; metamaterials for imaging and sensing applications; active, switching, nonlinear metamaterials; and acoustic metamaterials.

There also appears to be a good fit for metamaterials with the megatrends that are driving the defence and aerospace sectors as a whole. The rise of drones, the need for light-weight materials and components and the increasing need for improved military communications are all areas where metamaterials can help move products forward.

For example metamaterials have the potential to broaden the use of radar by making it compact and inexpensive enough to be more widely used in antimissile systems, ocean surveillance systems, and aircraft anti-collision systems. Metamaterials also contribute to enhanced military communications through an improvement in the performance of antennas. Finally the trend towards drones is supported by the use of metamaterials to build lighter and more compact systems for aircraft.

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ACKNOWLEDGEMENTS

We wish to acknowledge the support of Noetic Group and Melbourne University in bringing the Advanced Materials and Manufacturing EDTAS to completion. Dr Graham Schaffer from Melbourne University provided excellent thought leadership for the theme, as well as his linkages to experts from across Australia and internationally. We also extend our thanks to all of the speakers who added to the intellectual rigour and challenged the delegates to think about how these technologies will develop over the next twenty years. Particular thanks go to our keynote speakers, Dr Dong Yang Wu (Chief Aerospace Division, DST), Dr Ian Dagley (Chief Partnerships and Engagement Division, DST), Professor Adi Patterson (ANSTO), Mrs Laura Jones (Dstl UK), Professor Göran Roos (Business SA), and Assoc Prof Justin Dirrenberger (CNAM France).

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ANNEX A: EDTAS PROCESS

The EDTAS Concept

Each symposium in the EDTAS series is focused on a specific theme to broadly determine the effects of emerging and potentially disruptive technologies for Defence. The EDTAS series considers an expansive science and technology topic that will likely have a major impact – transformational or disruptive – for the Defence or national security domains.

Each symposium brings together internationally recognised experts to understand and shape the long-term vision in a multi-disciplinary workshop environment. The series considers the convergence of technology, and hence it is important that the theme encapsulates more than a single technology field. In addition to understanding technical developments, EDTAS considers a range of social, ethical, legal, and economic perspectives.

EDTAS is represented as a campaign of activities and events, as depicted in Figure A1, which is split into two phases. Initially, scoping activities are undertaken to determine critical issues and opportunities. Technology and Defence subject matter experts are interviewed, and an insights paper is developed and distributed to shape the initial event. The interviews and Insights paper allows for event delegates to anticipate the event and results in a more in-depth examination of related topics.

The symposia are a mix of carefully ordered presentations and immersive workshops. Technology (immersive video, Twitter feed, real-time issue capture and survey) is used to promote widespread discussion and capture of issues. The immersive video is a critical element that allows delegates to quickly appreciate complex scenarios.

The first phase considers technology developments and potential capabilities that could be developed and the second symposium phase considers capability opportunities based on military needs, scenarios and doctrine. Phase 2 explores how technology could fill a capability gap or create a game-changing military paradigm.

DST partners with universities and industry to co-host these events and help shape strategic planning and national research priorities. To ensure a quality event, a number of elements have been established:

- Partnership agreements with universities and industry (including memorandums of understanding and contracting arrangements between entities)
- Securing suitable high-quality international keynote speakers, senior-level participants and the venue
- Designing the workshop components to maximise the EDTAS outcome.

Broadly, the themes for the EDTAS are aligned with the priority areas of the Next Generation Technologies Fund. EDTAS is led by DST's Joint and Operations Analysis Division with other divisions actively participating in event planning, hosting, analysis and reporting.

The sequencing of activities within an EDTAS campaign series is illustrated in Figure A1. Each EDTAS campaign series is tailored to reflect the differing states of maturity of the various technology areas. The campaign commences with an one-day activity involving experts from across DST and Defence to discuss and define desired objectives and outcomes. Following this, subject matter experts are interviewed across Defence, industry and university community in order to develop an Insights Paper which is used to shape the unclassified and classified symposia. The outcome of Phase 1 is a technology concepts roadmap and research challenges for an S&T theme. The outcome of Phase 2 is military concepts that are able to inform war-gaming and strategic insights.

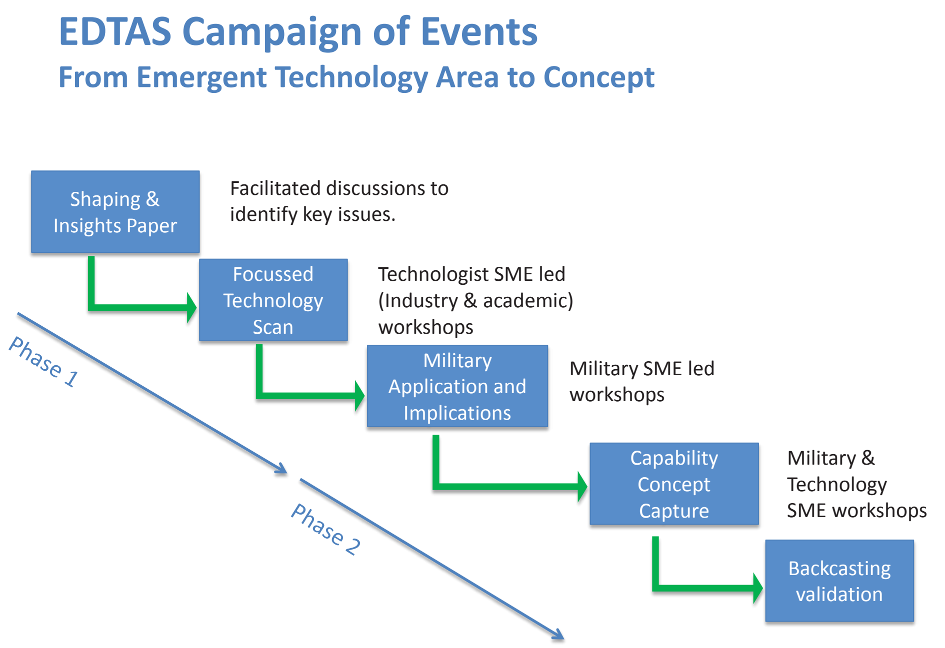

Figure A1. Campaign of events that constitute the EDTAS symposium series

ANNEX B: SYMPOSIUM AND WORKSHOP OUTLINE

Overview

The EDTAS for Advanced Materials and Manufacturing took place at the Cargo Hall in Melbourne on 28 and 29 November 2017. Across the two days, 80 delegates from Defence, industry and academia considered novel materials in 2040 and manufacturing and industry in 2040.

The format consisted of keynotes, panel speakers and supporting workshops across the 5 identified themes:

- Extreme environments
- Uninhabited vehicles
- Stealth
- Future sensors
- Power generation, distribution and storage.

To promote understanding and engagement with the themes, especially among the non-specialists in the room, scenarios for both materials (day 1) and manufacturing (day 2) were developed. The scenarios for day 2 were carried forward from the solutions presented by the syndicates on the first day, with each syndicate carrying its own ideas through. The scenarios used and the key group findings are shown in tables 1 and 2.

Table B1. Day 1 workshop themes and key findings

Theme	Scenario	Workshop findings
Extreme Environments	The current global economy is dependent on rapid and efficient travel. You have been appointed as a technical advisory team to develop the next generation of hypersonic vehicle. The considerations will be around the viability, manoeuvrability and development. The possibility of access to space is not to be discounted.	Thermal management the critical issue. Materials to consider/enable: • Ceramic matrix composites • Aerogel (heat management) • Carbon Matrix Composites/ Coatings: Spray on ablative to provide low resistance • Low-cost, reusable non-conductive material (similar to Apollo heat shields).
Uninhabited Vehicles	There is a requirement for Uninhabited Vehicles designed around a bio-mimicry principle. You have been tasked to examine this project, and suggest the materials to be used to develop them.	Need for multi-scale materials being optimised at micro and macro levels: • Hybrid manufacturing of multi-scale materials • Mechatronics, NDT optimisation processes require state of the art manufacturing tech
Stealth	You are a criminal syndicate, intending to steal a large shipment of precious metals. The storage area which is the best target is protected by highly sophisticated sensor grids. You need to consider what materials you can use to build an infiltration unit which would avoid detection.	• Use of adaptive meta-materials that affect function of the material • Interactive camouflage material — chameleon effect, with ability to be reactive/responsive to physical environment i.e. in front of walls/doors/metals.

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Theme	Scenario	Workshop findings
Future Sensors	The future vehicle will be designed with sensing as an organic capability, skinned rather than individual sensors. These sensors will be multi-spectral and fully integrated. You are to consider what materials would meet this requirement.	• What do we want to sense? • Interconnectivity and connectability are crucial • Low power, adaptable, organic, connectable, low environmental impact • Power solution needs to minimise consumption, and be recyclable • Self-aware materials • Sensing and actuation – materials as a system that can sense and regulate/ organise themselves – need a filter, connection, feedback – learning process – decision making = challenge.
Power generation, distribution and storage	Following a natural disaster in one of our pacific partners, it took four months to restore power using 2017 technology. What would systems of the future look like, and what material would they be made of to allow for easier generation, distribution and storage of energy?	Lithium-ion batteries have energy density limitations. Development of a solid nanocomposite electrolyte with an exceptionally high conductivity is required.

Table B2. Day 2 workshop themes and key findings

Theme	Scenarios	Workshop findings
Extreme Environments	Syndicate 1 — The proposed solution to the problem of hypersonic travel is an aerial vehicle with the key material being high temperature materials, structures, electronics and coating. Following this through, consider what the manufacturing system to develop the solution would look like.	Additive manufacturing for whole of production, using digital design and analysis tools in order to enable manufacture of high temperature capable (>1000 °C) ceramic and polymer matrix.
	Syndicate 6 — The proposed solution to the problem of hypersonic travel is an aerial vehicle with the key material being multi-use refurbishable materials. Following this through consider what the manufacturing system to develop the solution would look like.	Current state of the art is space shuttle. To develop refurbishable materials look at: • Future high entropy and max phase materials of interest. • SiC and Ti • Ceramics that are ductile.

Theme	Scenarios	Workshop findings
Uninhabited Vehicles	Syndicate 2 — Having designed an aerial vehicle, the key material of which is bio-mimetic, we need to consider the manufacturing and engineering systems which would allow us to bring this to fruition.	Bio-mimicry uses an evolutionary process; how to incorporate biology into tech sphere: • Synthetic spider web mentioned as example of this process of a synthetic evolutionary process. • Basic material and VAT allows control of forward modelling (synthetic biology). • Miniaturisation and nano-capabilities are focus points.
	Syndicate 7 — Having designed an aerial vehicle, the key material of which is infinite endurance and power, we need to consider the manufacturing and engineering systems which would allow us to bring this to fruition.	Attributes: Unlimited endurance; self-repair, persistence; Focusing on aerial uninhabited; Primary thing: long term energy supply. • Emerging and disruptive aspects: • Systems need to be scalable and deployable • Future is keeping platform affordable and scaling in new and innovative ways • Require ability to 3D print complex, controllable matrix • 3D bio-printing – completely new method. Needs new academic streams in universities studying more bioinspired engineering.

Theme	Scenarios	Workshop findings
Stealth	Syndicate 3 —You are a criminal syndicate, intending to steal a large shipment of precious metals. The storage area which is the best target is protected by highly sophisticated sensor grids. You have determined that an infiltration unit would be best constructed of adaptive intelligent metamaterials, given this finding what would the engineering system to enable this look like?	System has a number of constraints: • Safety mechanisms are less important if you are the 'bad guy'. • Financial constraints aren't to be considered when you are the bad guy – different in Defence. • Ethical considerations – difficult to define. Bad guy = possibly not. Defence there are several. • Environmental considerations – depends on what the constituent elements are – i.e. lead-based.
	Syndicate 8 - You are a criminal syndicate, intending to steal a large shipment of precious metals. The storage area which is the best target is protected by highly sophisticated sensor grids. You have determined that an infiltration unit would be best constructed of responsive polymers, given this finding what would the engineering system to enable this look like?	Design aspects: • We already have software that can do the complete design (structure, stresses, etc.) • Emerging: everything already exists, but it's not interconnected or harmonised; design that drives the process; autonomous design; • Artificial intelligence to play a big part in design; • Workforce: Create a trained workforce in a day!

Theme	Scenarios	Workshop findings
Future Sensors	Syndicate 4 - having designed a future vehicle with an organic sensing capability, based on a metamorphous organic life cycle materials skin rather than individual sensors your team has been invited to consider the manufacturing system which would enable this new technology.	Sensor as skin. Bio reactor manufacture - grown as a skin (absorb out of atmosphere and grow). Alternative: Graphene sub-strait with bio sensor implanted. Challenge – how to make it scalable & resilient? Needs: • Biotech industry in Australia • Development of AM hybrid machines with co-material deposition • Development of business model – duel Defence/other markets • Policy/ governance – who owns the IP? • What is the regulatory environment – what are the laws – hybrids, anti-GM, bio-ethics, etc.

Theme	Scenarios	Workshop findings
Power generation, distribution and storage	Syndicate 5 - following a natural disaster in one of our pacific partners, it took four months to restore power using 2017 technology. The R&D team has created a system based around solid state batteries to solve the problem. Your project team has been funded to consider the manufacturing system to support this.	Current manufacturing of batteries involves two separate processes, one for the negative side, one for the positive, which are brought together. Could look to using a layered approach by slowly adding layers on top of each other or could use a 'sandwich approach' where two layers are made separately and then put together – similar to the process of laminating. A really disruptive idea would be if the equipment used to manufacture the batteries could adapt to differing customer requirements. Currently very expensive specialist equipment is needed to manufacture specific batteries.

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