NOVEL MATERIALS AND ADDITIVE MANUFACTURING

Special Report
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Novel Materials are essential for the progress of science and technology, and their continued research and development is vital to meeting current and future challenges facing NATO nations. Additive Manufacturing (3D printing) facilitates more rapid integration of new technologies and the incorporation of new, smarter materials into existing products. Investing in these technologies therefore constitutes a necessary part of strengthening Allies’ resilience to future economic and security shocks.

This report explains why they are relevant for economic competitiveness and national security. The Rapporteur argues that the benefits of Novel Materials and Additive Manufacturing are numerous and wide-ranging, and that the opportunities offered by both technologies are particularly relevant in the context of the changing global security environment. For example, Additive Manufacturing promises to combine the affordability of mass or industrial-scale production with the customisation options of one-off production. Technological leaps in other areas, such as in artificial intelligence, will allow for faster, more efficient, and more affordable production methods. In addition, the potential for Novel Materials and Additive Manufacturing to transform the quality and availability of essential equipment for armed forces is significant. The benefits of incorporating Novel Materials into military planning and procurement are substantial and numerous. For example, they promise that future defence systems will be lighter, stronger, and more powerful and more energy-efficient than those currently used by militaries.

One of the main drivers for the advancement of novel materials and additive manufacturing within the Alliance is the Science and Technology Organization (STO), which plays a pivotal role in promoting research on these disruptive technologies. Allied collaboration through the STO not only limits duplication of effort, but also enables Allies and partner countries to focus their efforts on developing technologies that will be critical to future military capabilities.

However, the implementation of Novel Materials and Additive Manufacturing into defence faces a number of hurdles and will require time, testing and investment. While technological progress in Novel Materials and Additive Manufacturing is primarily driven by the private sector and research institutes, national governments play a key role in promoting more widespread use of these technologies, in particular regarding defence procurement. The report concludes by emphasising that Allies should evaluate if and how cooperation in the areas of Novel Materials and Additive Manufacturing can further be developed.
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I- INTRODUCTION

1. The energy crisis is far from over and many NATO nations have only begun to develop long-term solutions to the systemic challenges that over-dependence on authoritarian actors and under-investment in advanced, sustainable technologies has caused. At the same time, Russia’s brutal and unprovoked war against Ukraine has reminded Allies of the problems their armed forces are facing, notably in the areas of logistics and procurement.

2. These two issues represent challenges for the Alliance that will likely persist well after peace is restored in Europe. In today’s globalised world, economics, security and technology are increasingly intertwined and dependent on one another, making the resilience of our societies and economies and independence from adversarial and malign actors more important than ever before.

3. As the Euro-Atlantic community/region seeks to move away from fossil fuels and develop solutions for sustainable energy security, many have not yet fully come to terms with the fact that Allies depend on China for scarce critical raw materials and rare earth elements (REEs), which poses additional challenges to security and stability. As demand for these materials increases, disruptions in the market for these commodities could potentially lead to economic and security instability in the next decade. This would increase the risk of tensions with China and others (DiEuliis et al., 2022). If it becomes impossible to procure these resources via secure supply chains, finding alternative solutions, particularly creating substitute materials, will become a top priority for Allies.

4. Investing in Novel Materials (NM) and Additive Manufacturing (AM) technology constitutes a necessary part of strengthening Allies’ resilience to future economic and security shocks by limiting dependence on supply chains controlled by outside actors that seek to undermine or disrupt Euro-Atlantic stability.

5. The impact of NM is already far-reaching. Not only are they used to create new materials with unique properties that exceed those of existing materials, but also their advanced features such as semiconducting can be applied to existing objects to increase functionality. NM are also likely to be instrumental for the development of sustainable energy resources. In addition, experts predict that further NM development will have a revolutionary effect on the battery industry, transportation, LED technology, healthcare, warfare, communications and much more. Therefore, NM will likely be essential for addressing several large-scale societal and economic challenges, including with regard to green transition policies and global economic, geopolitical and security developments.

6. Due to the ever-growing need to increase the availability and usage of new and advanced materials, AM must be used to exploit NM’s full benefits, enabling increase applications for these unique materials and broadening the scale at which their properties are applied to new and existing technologies.
II- STATE OF PLAY

A. WHAT ARE NOVEL MATERIALS AND WHY ARE THEY IMPORTANT?

7. NM, sometimes called advanced materials, are artificial materials with uniquely advanced properties that are manufactured using nanotechnology or synthetic biology (STO, 2020). The materials are typically produced using nanotechnology, i.e., by manipulating the atomic structure of a material for industrial use, or synthetic biology, which involves re-engineering natural substances to equip them with new abilities (National Human Genome Research Institute, 2019). Lab-based manipulations of these materials can include special coatings that enable, for example: extreme heat resistance; impact-resistant surfaces; stealth properties; energy storage; superconductivity; the creation of advanced sensors; and decontamination and filtration (STO, 2020).

8. NM can surpass traditional materials in remarkable ways due to their unique properties such as substantially greater durability, elasticity and strength. Some NM can also respond to environmental changes without automation (Callaghan, 2012). For example, certain types of alloys – a mixture of multiple metals – called shape-memory or smart alloys can remember their shape, allowing them to change form when responding to changes in their environment (for example, being exposed to extreme temperatures) and revert back to their original state. Such materials have direct applications in the medical and aerospace industries, among others.

9. The development of NM can lead, and in some areas already has led, to the design of completely new products such as medical implants and pocket-sized computers (Callaghan, 2012). However, advances in the development and application of NM are not just about creating new materials, they are also about making things that are already used smaller, smarter and cheaper (Belcher, 2014). NM not only pave the way for new technologies, but they also enhance the performance of the components and systems within existing products, allowing for more compact designs, greater efficiency (including fuel efficiency) and increased durability (European Commission, 2021).

10. Novel Materials have had an impact in a number of areas, including semiconducting and developing sustainable energy sources. In the future, experts predict that NM will be hugely transformative for creating high-efficiency batteries, manufacturing emission-free and fuel-efficient transportation (including in space), LED technology and more. Technological advances in the development of these materials will therefore be crucial for the implementation of green transition policies, among other things. More generally, “progress in materials science and in the engineering application of new materials is essential to the pursuit of solutions to societal grand challenges” (Rogers and Desimone, 2016).

11. In 2020, the European Commission included advanced materials and advanced manufacturing in its report on technologies that are “a priority for European industrial policy and that enable process, product and service innovation throughout the economy and hence foster industrial modernisation” (Izsak et al., 2020). NM and AM are defined as technology domains that are expected to “substantially alter the business and social environment”, and the related areas of nanotechnology and industrial biotechnology are also key focuses of
the report (Izsak et al., 2020). The report notes that these key enabling technologies (KETs) will ensure the competitiveness of essential industries by contributing to technological leaps in the production of electric cars, satellites, medical devices and other advanced consumer goods (Callaghan, 2012).

12. Similarly, the European Commission’s Horizon Europe Strategic Plan (2021–2024), highlights the growing importance of KETs including advanced materials and manufacturing in industries such as healthcare, transportation, space exploration, energy infrastructure, battery-making, as well as carbon capture, utilisation and storage (CCUS). The plan, which acts as a “compass” for EU policy, also notes the role that NM and AM will play in policies related to carbon neutrality, green transition and digitalisation, asserting that sustainable-by-design advanced materials and technologies will facilitate decarbonisation in “all major emitting industrial sectors” (European Commission, 2021).

13. Moreover, NM and AM are high on the agenda of NATO: they are among the nine priority technology areas the Alliance has identified as having a major impact on security and future military capability development. Thus, AM and NM feature prominently on NATO’s Emerging and Disruptive Technologies Implementation Roadmap. Materials research is a strategically important field for the future because materials are a prerequisite for all technological progress. Newly developed materials are the basis for innovations in many areas of application. As a basic and cross-sectional technology, materials research sets the pace for the further development of important fields of technology, such as artificial intelligence or quantum technologies. The NATO Science and Technology Organisation (STO) is focusing considerable work and effort to advance research in NM and AM.

**B. CURRENT RESEARCH AND PROMISING NOVEL MATERIALS**

14. While experts widely cite Novel Materials’ ability to improve current products and generate new technology, many specific applications and ideas for the use of NM remain in the testing phase. At the same time, however, there has been slow but steady progress in implementing NM in practical, real-world contexts.

15. One area in which NM have already had a significant impact is the healthcare industry. A common application of NM in medicine is the use of nanomaterials for drug delivery systems, since nanotechnology allows a smaller dose of medicine to be applied to a specific area inside the body. Hence, nanomaterials have been used to improve the diagnosis of cancer and increase the effectiveness/reduce side effects of radiotherapy (Théard-Jallu and Carrio, 2022). Similarly, carbon nanotubes (CNTs) have been used for vaccine delivery systems and in Parkinson’s disease treatment (Kecel-Gunduz et al., 2020). While nanomedicine is already an established and growing field, like with many other NM applications, some potential benefits remain un-tested or unavailable on a large scale.

16. The development of NM has advanced significantly in recent years. An example of the advantages that NM have over “traditional” materials is graphene. Applications for graphene, which was discovered in 2004, are growing rapidly as it is the strongest known material in proportion to its thickness and is an extraordinary conductor of heat and electricity (Siegel, 2021). In addition to creating extremely durable yet thin and flexible surfaces, it can also enhance power-generating capabilities and be used in water filtration systems (Schwandt,
2022). There is already a multimillion-dollar industry surrounding this material and the use of and applications for graphene are expected to grow exponentially in coming years (Siegel, 2021). The areas in which graphene is expected to or has already begun revolutionising industry include: energy storage (batteries and supercapacitors); touchscreens; transistors; computer chips; energy generation; DNA sequencing; water filters; and antennae (Bernardo, 2019).

17. As with many other NM, the body of research on graphene is growing quickly, with scientists regularly finding innovative ways to make and use the material. In 2020, a Rice University lab made graphene from waste materials such as food and plastic (Williams (a) 2020). In 2022, the same lab produced graphene using an often-discarded by-product of crude oil production (Williams (b), 2022). As early as 2020, physicists at the University of Arkansas harvested energy from graphene, which creates a limitless clean power source when incorporated into a chip or circuit (University of Arkansas, 2020).

18. Graphene represents one of many NM that could fundamentally alter the energy, defence and infrastructure fields. Other new NM may even surpass graphene’s unique capabilities. Among them is graphyne, which was created in a lab in 2010 (Li et al., 2010). Graphyne is similar to graphene but is believed to have even more powerful and flexible semiconducting properties. Research on and experimentation with graphyne has only just begun, but multiple breakthroughs occurred in 2022 (Patel, 2022), which will enable wider experimentation regarding graphyne’s applications in the real world (Wogan, 2022). (See Table 1 for additional examples of such materials.)

<table>
<thead>
<tr>
<th>Novel Material</th>
<th>Properties</th>
<th>Potential Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphene</td>
<td>Thermal/electrical conductivity, mechanical resistance</td>
<td>Optoelectronics, ballistic protection, coatings, camouflage, water filters, biomedical devices, sensors, batteries</td>
</tr>
<tr>
<td>Graphyne</td>
<td>Potentially stronger than graphene, possibly better semiconducting capabilities</td>
<td>Batteries, including lithium batteries</td>
</tr>
<tr>
<td>Superconducting Metal Oxides (e.g., Copper Oxide)</td>
<td>Superconductivity</td>
<td>High-efficiency semiconductors</td>
</tr>
<tr>
<td>Nitride Semiconductors</td>
<td>Semiconducting capabilities</td>
<td>LED technology, sensors, lasers, photonics</td>
</tr>
<tr>
<td>Phosphorene</td>
<td>Semiconducting, high carrier mobility, high optical and UV absorption</td>
<td>Optoelectronics</td>
</tr>
<tr>
<td>Nanomaterials (e.g., Carbon Nanotubes)</td>
<td>Mechanical properties with quantum effects</td>
<td>Delivery systems for medicine and medical treatments</td>
</tr>
</tbody>
</table>

19. Researchers are quick to point out the transformative potential of NM as well as the challenges of producing them at a large enough scale to generate widespread impact. As one expert noted in 2019: “We want to harness nature’s process to better protect people. Biodesign exists today, but it doesn’t exist at the scale and to the quality of defence standards” (Defense Daily, 2019). This obstacle represents a key barrier to unleashing the transformative potential of NM across industries.

C. NOVEL MATERIALS AND ADDITIVE MANUFACTURING

20. Novel Materials’ full potential cannot be utilised without Additive Manufacturing (AM). AM, which typically refers to 3D printing, is the process of building physical 3D objects from a digital model or computer-aided design (CAD) (Linke, 2017; Falconi, 2023). This process, which is usually completed layer-by-layer, is essential for enabling NM to have a wider impact. AM produces faster solutions by facilitating more rapid integration of new technologies and incorporating new, smarter materials into existing products (Belcher, 2014).

21. AM (or 3D) printing has existed for decades. However, the production method has only taken off in recent years. This is in part due to lessons learned about the process as a result of the Covid-19 pandemic and related rapid-response efforts (Raytheon Technologies, 2022), as well as an increasing demand for manufacturing methods that are less volatile to global markets.

22. Today, 3D printing is rapidly becoming larger scale and more affordable, causing some to refer to recent and expected progress made in AM as the fourth Industrial Revolution (McKinsey & Company, 2022). New solutions for mass manufacturing through high-volume
printing are emerging, for example through making existing printers more efficient by improving software used for printing (Kamps, 2023), implementing new methods that enable continuous instead of layer-by-layer manufacturing and using new materials for manufacturing (Janusziewicz et al., 2016; Monroe, 2023). Each factor on its own has the potential to expand the availability and potential of AM, especially by lowering the cost of production and the speed and volume at which it can be completed.

23. One company in the US has reportedly achieved a 300% increase in productivity of 3D printing and lowered the cost-per-part by 30% (Kamps, 2023). The ability of manufacturers to significantly increase production without raising labour requirements or capital investment will no doubt have a notable impact on AM. Rather than being used primarily for creating prototypes and spare parts, AM could become a solution for mass manufacturing and more producers will likely turn to AM as it becomes faster and more cost-effective compared to traditional methods (Princ, 2023).

24. Rapid developments are also taking place in the construction industry. In 2022, researchers at Spain’s Institute for Advanced Architecture of Catalonia developed a large-scale AM process to create TOVA clay houses, which are equipped with walls that have intricate insulation pockets, a feature that can only be created through AM (Eldridge, 2023). In the US, a company called ICON creates large-scale sustainable and affordable housing and recently won an award from NASA to explore 3D printing technology opportunities in space (Zisk, 2022).

25. In addition, significant advances in AM technology are now enabling the manufacture of semiconductors. AM has already been used to develop chips that are bendable and have a microcontroller with built-in memory. 3D printing technology can be used to print directly onto a variety of substrates, including plastics and ceramics (Smith, 2021). This capability allows highly complex and customised components to be produced in low volumes. This can be particularly beneficial in situations where traditional manufacturing methods are impractical or too costly.

26. One of the more recent developments in this area is the use of 3D nanoprinting with semiconductor quantum dots. This approach expands the potential applications of 3D printed semiconductors by enabling the creation of extremely small and intricate structures. However, it’s important to note that there are limitations to what can currently be achieved with 3D printing technology. For example, the complexity of most integrated circuits currently exceeds the resolution of most 3D printers (Cohen, 2019). Therefore, while AM offers promising possibilities for the construction of semiconductors, it is still an evolving field with ongoing research and development efforts.

D. Global Leaders in Additive Manufacturing

27. According to a recent study on the current and future potential for 3D printing in 12 countries, the United States, the United Kingdom and Germany have the highest overall “index score” and the “greatest expectations for implementing additive manufacturing and capitalising on its opportunities” (UltiMaker, 2021). The index score measures: market awareness; adoption and install base (the number of printers already in use); 3D printing
growth indicators; perceived future impact and optimism; technology infrastructure; and ease of adoption (UltiMaker, 2021). The study also revealed that although only 35% percent have adopted 3D printing technology, 65% of respondents believe that AM will revolutionise their industry and almost 40% percent say that AM will bring significant operational efficiencies and cost savings to their businesses over the coming year, which indicates how quickly perceptions and adoptions of this technology are progressing (UltiMaker, 2021).

28. The majority of the largest companies of printers and AM related services are headquartered in NATO member countries – for example, in the US, Belgium, UK, Netherlands, France and Spain (Reiff, 2023). Some notable companies also operate from NATO partners such as Israel, Ireland and Sweden (Schwaar, 2022). Additional studies indicate that, globally, the top suppliers of AM are the US, China, Japan, UK and India (Govini, 2022). This overlaps in part with the top suppliers of NM, which are the US, China, South Korea, UK and Japan (Govini, 2022; see also figure 1).

29. Only one company that is typically included in the top 10 largest AM manufacturers is located in China: however, this could change in the near future. China has been steadily investing in AM and increasing its market share in recent years (Freund et al., 2022), in part due to its 2025 plan to make advanced manufacturing a key focus of the Chinese economy (McBride and Chatzky, 2019).

30. As a result, China’s AM industry is quickly expanding, reaching a volume of more than USD 2 billion in 2018 (Berger and Beba, 2021).

31. Shifts in the global balance of who dominates in the 3D printing space may fluctuate over time. However, the clear trend of AM’s expanding influence is predicted to remain consistent, with AM becoming an even more wide-reaching tool in the years to come. Some experts predict that the value of parts produced by the 3D printing industry will reach over USD 50 billion by 2030 (Molitch-Hou, 2022; see also figure 2).

III- THE TRANSFORMATIVE POTENTIAL OF NOVEL MATERIALS AND ADDITIVE MANUFACTURING

A. ECONOMIC AND SOCIETAL IMPLICATIONS

32. The advantages of NM and AM are not only numerous and wide-ranging, but the benefits of these materials and methods have already been proven in multiple industries. NM are already used and/or being tested for use in the following industries: electronics; aerospace; automotive; healthcare; water purification; energy storage; solar energy; and communications (STO, 2020). AM has already revolutionised the hearing aid industry and is regularly used to make aircraft parts and prosthetics. However, even though additive methods are already strongly preferred in some industries, AM has yet to transition from prototype making to mass production in others (Marx (a), 2022). As this transition continues, it is important to understand the advantages of AM.
33. AM promises to combine the affordability of mass or industrial-scale production with the customisation options of one-off production. Technological leaps in other areas, such as in artificial intelligence, will allow for faster, more efficient and more affordable AM production (Marx (b), 2020).

34. AM’s potential to reshape industries need not be limited to the world’s most advanced economies, either. 3D printing offers opportunities for less advanced economies that seek to be globally competitive. Countries that lack the necessary infrastructure to transport goods to and from factories could create a local printing plant by investing in AM technology. While upfront costs may be steep, an additional advantage of AM is that one 3D printer can be used to make numerous different goods, which would contribute to a wide range of locally produced goods and create less dependence on imports (D’Aveni, 2019).

B. SECURITY AND DEFENCE IMPLICATIONS

35. Advances in materials and manufacturing are also predicted to have a profound effect on security and defence in the coming decades (Burnett et al., 2018). The potential for NM to transform the quality and availability of essential equipment for battle, for example, could soon be a reality. These possibilities are of particular importance in the context of two key shifts in the global security environment.

36. First, the lack of critical raw materials, including Rare Earth Elements (REEs), available globally and to Allies poses a security challenge. NATO Secretary General Jens Stoltenberg has consistently emphasised that current dependence on China for critical raw materials has serious consequences for Allied security (NATO (a), 2022).

37. Second, the return of full-scale war in Europe has highlighted the importance of sufficient weapon stockpiles, reliable supply chains and robust logistics for successful combat operations (Chávez et al., 2023; Financial Times, 2023; Hugos et al., 2022). Manufacturing techniques such as agile or AM are integral to enabling NM’s transformative potential. The development of equipment that utilises NM, combined with advanced manufacturing techniques would, among other benefits, make the rapid production of spare parts for weapons and vehicles possible on or near the battlefield (Burnett et al., 2018). The use of 3D printing techniques would also reduce dependence on vulnerable stockpiles in the kinetic warfare context, since parts would be easier to make and transport near military bases. These examples represent only some of the ways in which NM and AM can alter the security landscape.

C. RECENT DEVELOPMENTS AND FUTURE APPLICATIONS

38. The numerous advantages of NM and AM have obviously been noted in the defence sector as well. Recent research on critical technology expenditures shows that the US government steadily increased investments in NM or “Advanced Materials” from 2017-2021, especially for Metals, Polymers, Rare Earths and Composites (Govini, 2022). Spending on AM was also substantial, especially for digital engineering and industrial printing, but less significant than NM during the same period.
39. While the potential future impact of NM in security and defence is likely to be even more revolutionary than AM, the timeline for adopting NM-related technologies in this space will take longer. AM, on the other hand, is already having a notable impact in this sector.

40. The aerospace industry was an early adopter of 3D printing methods, due to the superior strength/weight ratio of materials possible through AM, overall lighter-weight components, highly customisable and accurate designs, quick production and decreased manpower requirements. The nexus between AM and defence is also evolving quickly. For example, aerospace experts predict that astronauts will soon be able to print equipment in space (Marx (b), 2020).

41. The US Navy has also realised the advantages of 3D printing not only for one-off needs and spare parts, but of integrating AM into long-term procurement processes. US military officials regularly note persistent challenges in their national industrial base affecting the submarine, aircraft carrier, and surface ship production. These are partly due to a decreasing number of manufacturers and suppliers and recent needs to increase production (Eckstein, 2023). Using traditional methods, a delay in receiving a single component, as was recently the case with a part needed for the USS Enterprise, risks setting deadlines back months and increasing expected costs significantly. AM could shorten production time for some parts by an average of 80% (Eckstein, 2023). As the benefits of AM in the military realm are already apparent, scaling up production is the main challenge for utilising its full benefits, and multiple projects are currently underway to do just that. For example, the US Navy recently launched a project for printing key metals at volume for use on submarines (Eckstein, 2023).

42. Implementing NM into defence poses additional hurdles and will require time, testing and investment. However, the benefits of incorporating NM into military planning and procurement are substantial and numerous. Some experts believe that research and investment should be channelled toward those NM applications that are most likely to create technological solutions in the near-to-medium term, such as optoelectronics (STO, 2020). In general, it can be expected that future defence systems will be lighter weight, stronger, more powerful while also and more energy-efficient than what is currently used by the military. The table below illustrates some of the key NM-enabled defence solutions known to-date, including for the near-, medium- and long-term (STO, 2020).

<table>
<thead>
<tr>
<th>Defence Applications for Novel Materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reduced equipment burden due to implementation of lighter weight materials</td>
</tr>
<tr>
<td>• Covert wearable devices, made possible through lightweight, flexible electronics that can be woven into fabrics</td>
</tr>
<tr>
<td>• Faster communications and improved computation</td>
</tr>
<tr>
<td>• Extended physical range of operating platforms used for communications, range-finding, and thermal imaging</td>
</tr>
<tr>
<td>• Improved signals detection</td>
</tr>
<tr>
<td>• Protection against and/or better detection of bio-chemical attack and explosive vapours</td>
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REPORT – 033 STC 23 E rev. 1 fin
• Lightweight high-impact resistant materials for body armour and digital systems worn by soldiers
• Reduced radar reflections from platforms in the land, sea, and air domains, through radar-absorbing coatings
• Improvements in energy storage capabilities
• Coatings for wearable fabrics that include weather-resistant and chemical protection capabilities, and/or coatings that enable monitoring using smart/intelligent textiles
• Coatings for vehicles that reduce reflection and radiation of electromagnetic waves

Table 2 – NATO Science and Technology Organization

43. Many of the applications above have not yet been tested publicly in the military domain. Some, however, such as energy storage in ultra-capacitors and batteries using graphene-based storage, have led to products that have already been certified for usage in space (STO, 2020).

44. Future progress in this area will depend substantially on private entities, and some Allies have already begun to cooperate with industry regarding NM applications in defence. For example, in 2019, the US Army Research Laboratory signed an agreement with Lockheed Martin to initiate cooperation on bioproduction of new materials, which involves manipulating existing natural materials for a range of defence-related capabilities, especially related to optical technology and coatings (Husseini, 2019). Optical technology is crucial for defence- and security-related endeavours, particularly for communications such as signal transmissions. These communication-facilitating connections, or “optical interconnects”, facilitate faster data transmission and data processing, which are key in a warfare context since a large amount of data is acquired and exchanged on the digital battlefield (Howard, 2011). The technology that is normally used in these contexts requires communicating systems to be within a certain distance, or else data transmission and processing capacity decreases (Howard, 2011). Optical technology, however, enables high-volume data sharing, even between systems far apart (Howard, 2011).

D. CASE STUDY: GRAPHENE - USES IN SECURITY AND DEFENCE

45. The most widely researched NM today is graphene, whose discoverers won the 2010 Nobel Prize. Graphene has an exceptional strength-to-weight ratio and tensile strength as well as high elasticity, enabling it to absorb shocks without becoming permanently deformed (Asri et al., 2022; Schwandt, 2022). It can also distribute and store kinetic energy, therefore it can absorb energy in a way that lessens damage from impact such as gunfire (Schwandt, 2022). Graphene also has unique conductive properties: it conducts electricity and can conduct heat better than copper even though it is lighter (Schwandt, 2022).

46. In 2017, the European Defence Agency (EDA) initiated a project, together with the Spanish-based company Tecnalia Research and Innovation, the Technical University of Cartagena and Cambridge Nanomaterial Technology Ltd, based in Cambridge, UK. The study, completed in 2019, provides a comprehensive overview of potential uses for
graphene in the defence context and assesses how long it will take for graphene to be adopted in the defence industry market based on the potential application area (EDA, 2019).

47. According to the report, applications closest to market adoption are supercapacitor electrodes, which enable graphene to be used for batteries and energy storage (within four years, as of March 2019); multifunction coatings (within three to five years, as of March 2019); and lightweight ballistic protection materials (three to five years, as of March 2019) (Schwandt, 2022; EDA, 2019). Regarding multifunctional coatings, the EDA notes that further cost-benefit analyses are needed, and technical enhancement must be further demonstrated (EDA, 2019). However, the Agency notes that multifunctional coatings are widely used in non-defence sectors: therefore, the defence sector would be able to follow these developments and acquire technologies from civilian entities, rather than investing in these capabilities upfront (EDA, 2019).

48. For lightweight ballistic protection materials, the EDA assesses that this application is close to market, but further cost/benefit analyses are needed and additional technical enhancement regarding graphene’s use must be demonstrated (EDA, 2019). Defence applications for drones, high thermal dissipation materials, radar signature reduction coatings, flexible lightweight batteries, low-light working devices, membranes for water and air filtration and chemical/biological/radiological/nuclear sensors are expected to reach the market later. The study cites various obstacles to market adoption, from high upfront investment requirements to packaging issues. However, it also notes that graphene has a proven ability to improve capabilities dramatically across multiple applications, confirming the transformative potential of NM for defence (EDA, 2019).

E. ADDITIVE MANUFACTURING IN THE ALLIANCE AND PARTNER COUNTRIES

49. A key aspect of bringing NM-based solutions to the defence sector will rely on AM solutions for fast, cost-effective production. Not only can AM be used to improve production cost and efficiency, but increasing the utilisation of AM will also solve logistics challenges (Falconi, 2023). Addressing the latter is an even more pressing issue as the recent disruptions to supply chains due to the Covid-19 pandemic and particularly Russia’s war against Ukraine have demonstrated. AM can provide a secure way to obtain necessary items on demand, particularly on land and at sea (Falconi, 2023). 3D printing spare parts for repair within or near the battlespace would reduce the need to maintain vulnerable stockpiles near the front line, accelerate repair times and lessen transportation burdens (which would also decrease the environmental impact of logistics activities) (Eldridge, 2023).

50. New AM techniques and methods are being constantly developed, especially by Alliance and some partner countries. For example, the Spanish company BCN3D recently created a new process for 3D printing, which allows new types of material to be used in production, recovers unused material as it builds and allows multiple types of material to be incorporated into a product simultaneously (Eldridge, 2023). Sandvik, a company based in Sweden, has recently created the first-ever diamond products with AM, which can be used for industrial tool manufacturing (Eldridge, 2023).

51. Canada and the UK have also made recent progress in AM with regard to defence applications. In 2022, Canada’s Department of National Defence granted a 20-month
contract extension to Nova Graphene to develop 3D-printed ballistic armour (Press Advantage, 2022). In the same year, the UK Royal Air Force confirmed that it is working with BAE Systems to develop 3D-printed unmanned combat aircraft, including twin jet Pizookie drones (VoxelMatters, 2022).

52. The US military has also realised the advantages of AM, especially its ability to provide quick production and repair solutions without being hindered by unpredictable supply chains. In 2019, the US Marines utilised 3D printing to create a bunker out of quick-dry concrete to conceal rocket launchers in less than 36 hours (Albon, 2022). The US Army Corps of Engineers also recently advanced 3D printing capabilities by creating a printer that could generate shrapnel-resistant structures that would allow isolated forces to make fortifications quickly to defend their positions (Falconi, 2023). The US Air Force has integrated AM into both small batch production and distributed manufacturing (Falconi, 2023). The US Navy recently created a submersible vehicle using AM, which reduced production costs per vehicle by 90% and cut overall production time from three to five months to four weeks (Falconi, 2023). Additionally, the US military has developed the world’s largest metal 3D printer (Falconi, 2023).

53. In addition to several services implementing 3D printing, there has also been a growing interest in the US in further research, investment and private sector cooperation in the area of AM. In January 2022, it was reported that the Naval Surface Warfare Center is investing in six AM prototypes to help protect military technologies from compromise and interference (Strout, 2022). In July 2022, the US Army Research Laboratory, in partnership with Raytheon Technologies, chose the company 3D Systems to initiate a research project focused on novel thermal applications (Langnau, 2021). In October 2022, the US Department of Defense announced that it will use AM to design and build hypersonic weapons and vehicle systems that can operate in extreme conditions (Albon, 2022). The US Army also launched the Jointless Hull Project, which “aims to use 3D printing to reduce production costs and manufacturing time for Army combat vehicles while minimizing weight and maximizing durability and reliability” (Falconi, 2023). By 2027, the US military’s 3D printing sector is expected to be worth USD 1.7 billion (Falconi, 2023).

IV- APPLICATIONS FOR NATO

54. While Russia’s brutal and unprovoked war against Ukraine has exacerbated supply chain challenges, Allies face a wide spectrum of threats that extend well beyond this conflict. Energy dependence, depleted defence industrial bases and supply, reliance on China for critical materials and asymmetric threats from emerging and disruptive technologies (EDTs) all represent ongoing challenges for Allies. Harnessing the potential that NM, through AM, promises will facilitate addressing these systemic problems. Moreover, these technologies will also be crucial to develop next-generation solutions for green transition goals.

55. In some Allied member states, the private sector and universities are already deeply involved in fostering solutions to broad societal, economic, health and security challenges through NM and AM. In others, the government and/or military are encouraging innovation in this field. Regardless of which entities are leading those efforts, national governments play a key role, in particular with regard to defence procurement. Defence companies must
receive incentives from Allied governments signaling that investing in, for example, graphene-based body armour, will lead to long-term contracts and profits. Those who are able to do so should work with industry to encourage this kind of advancement. Additionally, as AM becomes increasingly cheaper and larger-scale, Allies should strive to adopt this production method where possible and encourage further development of AM solutions where needed.

56. One of the main drivers of NM and AM advancements within the Alliance is the Science and Technology Organization (STO), which draws on the expertise of its vast scientific network comprising of over 6,000 researchers. The STO works with Allies to identify challenges for NATO and provide science-based solutions. The following table illustrates examples of how NM and AM can be utilised to respond to current challenges that the Alliance faces.

<table>
<thead>
<tr>
<th>Challenges for NATO</th>
<th>Solutions based on NM and AM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Dependence</td>
<td>• Energy generation and storage opportunities enabled by NM</td>
</tr>
<tr>
<td>Depleted Defence Industrial Base</td>
<td>• More durable equipment with NM and fast, agile production with AM</td>
</tr>
<tr>
<td>Dependence on Critical Raw Materials</td>
<td>• Lessened need with increased use of NM</td>
</tr>
<tr>
<td>Threats from EDTs</td>
<td>• AM as a positive EDT</td>
</tr>
</tbody>
</table>

57. Regarding Allies' depleted defence industrial bases, AM can have an immediate impact, much like examples mentioned in Section 2. The STO also highlighted three advantages of AM for defence procurement in its report *Science & Technology Trends 2020-2040: Exploring the S&T Edge*, published in March 2020. First, AM can support improved product development through shorter design cycles, increased cost/time effectiveness, and optimisation of design by avoiding traditional production design constraints (STO, 2020). Second, AM promotes improved maintenance and logistics by reducing stocks of on-hand spare parts since parts would be readily available instead of being transported across long distances (STO, 2020). Local or on-site manufacturing would also eliminate the need for hardware storage due to the implementation of printable designs (STO, 2020). Additionally, readily available spare parts would significantly extend the operational life of existing equipment (STO, 2020). Third, AM would bring a significant cost reduction and increased effectiveness, especially for new and costly equipment used primarily in the aerospace and maritime domains, since AM can repair intricate parts rapidly (STO, 2020).
58. Allies have already taken significant steps to invest in innovative thinking and solutions and further equip NATO for the future, for example with the NATO Innovation Fund and the Defence Innovation Accelerator for the North Atlantic (DIANA), both launched in 2022. The Alliance has also clearly identified an “urgent need to create momentum in the exploitation of new technology, and is aware of the opportunities EDTs also offer to countries and non-state actors that oppose Western values and international norms of behaviour and who have the wealth and motivation to exploit them” (Eldridge, 2023) To ensure that NATO is prepared for future adaptation, the transformative potential of NM and AM for defence should be seriously considered, including for solutions to near-, medium-, and long-term threats and challenges.

**CHALLENGES**

59. Science, including defence-related science, is evolving rapidly. Experts predict that synthetic biology (one of the ways NM are created) alone will drive the next revolutionary wave of change. Synthetic biology already has a wide range of applications not only in medicine, but also the defence space. They can already be used both for defence and, unfortunately, for harm. The rapid evolution of NM, AM and related fields represents both an economic and defence opportunity as well as an enormous threat to global security. The increasing dissemination of AM technology and its accelerating development raises fears that this technology could be used and deployed by potential adversaries, including both state and non-state actors. These can use AM to create sophisticated weapons and components that are difficult to detect. Allies and partners need to be aware of these emerging security threats and develop policies and tools to address them. For example, Allies and partners could work together to develop or strengthen international regulations governing the use of 3D printing technology. This would allow for the monitoring of supply chains to prevent illicit access to AM technologies and materials, and the development of robust countermeasures to detect and neutralise 3D printed threats.

60. Similarly, particularly given synthetic biology’s rapid advancement, NM-related technological advances and use need a strong legal framework. The Alliance can serve as an essential platform for dialogue and standard-setting in this area. Recent work by NATO’s Data and Artificial Intelligence Review Board on developing a certification standard for the responsible use of Artificial Intelligence (AI) (NATO (b), 2023) could be used as an example of how to initiate this process. However, broader coordination within the international community beyond NATO would enable even more substantial progress with regard to safeguarding the usage of NM technology.

**V- CONCLUSIONS**

61. NM and AM are of strategic importance because materials are a prerequisite for all technological progress. Newly developed materials are the basis for innovations in many areas of application, ranging from medicine to microelectronics to battery research. As a basic and cross-sectional technology, materials research sets the pace for the further development of important fields of technology, such as artificial intelligence or quantum
technologies. Materials research and related NM and AM processes are also key for the development of future military capabilities.

62. NATO’s STO plays a pivotal role in promoting research on NM and AM. In addition to limiting duplication of effort, Allied cooperation in the STO’s framework also allows to focus Allies’ and partner countries’ efforts on the development of technologies which will be crucial for future military capabilities. In addition to the work already being done, Allies should evaluate if and how cooperation in the areas of NM and AM can be further developed. More generally, Allies should:

- Continue developing strategies for research, investment and application of NM and AM for defence and security purposes;
- Share best practices on the military usage of NM and AM;
- Utilise the STO to the maximum national benefit, including fostering coordination between STO and national subject matter experts (SMEs);
- Consolidate efforts and reduce any potential overlap between Allies’ efforts in developing and implementing NM and AM;
- Evaluate, and where possible strengthen, cooperation with like-minded partners and particularly the European Union, by sharing best practices and lessons learned with regard to developing and implementing NM and AM technologies across industries;
- Raise awareness of the potential risks associated with NM and AM in the hands of adversaries and the necessity for proactive measures to safeguard Allies’ national security interests;
- Continue to prioritise individual and collective resilience domestically and as an Alliance, including regarding securing supply chains for critical materials and technologies.
BIBLIOGRAPHY


Chávez, Steff, Heal, Alexandra, Bott, Ian, Joiner, Sam, Learner, Sam, de la Torre Arenas, Irene, and Samborska, Veronika, “How Arming Ukraine is Stretching the US Defence Industry”, Financial Times, 31 January 2023, https://ig.ft.com/us-defence-industry/


Financial Times, “Nato’s Weapons Stockpiles Need Urgent Replenishment”, 31 January 2023, [https://www.ft.com/content/55b7ba35-6beb-4775-a97b-4e34d8294438](https://www.ft.com/content/55b7ba35-6beb-4775-a97b-4e34d8294438)


Marx, Uwe (a), “3-D-Druck an der nächsten Schwelle”, Frankfurter Allgemeine, 16 November 2022, https://www.faz.net/aktuell/wirtschaft/unternehmen/additive-fertigung-3-d-druck-an-der-nachsten-schwelle-18460824.html


NATO (a), Keynote Speech by NATO Secretary General Jens Stoltenberg at the Berlin Security Conference, 1 December 2022, https://www.nato.int/cps/en/nato_qh/opinions_209188.htm?selectedLocale=en


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Siegel, Ethan, “These 5 Recent Advances Are Changing Everything We Thought We Knew about Electronics”, Big Think, 7 October 2021, https://bigthink.com/starts-with-a-bang/graphene-advances-electronics/


