sipri

SIPRI Background Paper
November 2017

3D PRINTING AND MISSILE TECHNOLOGY CONTROLS

KOLJA BROCKMANN AND SIBYLLE BAUER*

SUMMARY

● Additive manufacturing (AM), also referred to as '3D printing', is a rapidly developing technology. AM enables the production of objects of virtually any shape by depositing and bonding together successive layers of material. AM machines are increasingly capable of producing a variety of items for aerospace and missile applications which are subject to dual-use export controls. The increasing capabilities of AM machines in combination with their reliance on intangible transfers of technology (ITT) have raised concerns in the multilateral export control regimes. Specifically, AM may impact the effective implementation of export controls and pose proliferation risks.

This SIPRI Background Paper takes stock of the current state of the art of the technology by explaining its basic features and by highlighting the level of maturity and spread of AM applications in the aerospace sector. Building on this review, it discusses the specific challenges that AM poses to export controls by examining existing controls and proposals for new controls on transfers of AM machines, feedstock materials and digital build files. Drawing on this analysis, the paper proposes potential ways forward for the MTCR and the other multilateral export control regimes, for national export control authorities and for companies involved in AM.

I. Introduction

The Missile Technology Control Regime (MTCR) is one of the four major multilateral export control regimes.[1] It seeks to prevent the proliferation of missiles and other unmanned aerial vehicles (UAVs) and delivery systems, especially those capable of delivering nuclear, biological and chemical weapons.[2] Through the regime, states establish agreed standards, share information and maintain control lists for dual-use and arms export controls. These control lists define which goods and technologies should be subject to national licensing requirements and export controls. The public statement from the 2016 plenary meeting of the MTCR in South Korea officially acknowledged that '3D printing technology poses a major challenge to international export control efforts' and announced that the topic will be on the agenda of future MTCR meetings.[3] This follows several years of discussions in both the MTCR and the other multilateral export control regimes on if and how to implement controls on the export and use of 3D printers and additive manufacturing technology in national export control systems.

Additive manufacturing (AM), or '3D printing', describes manufacturing processes in which layers of material are deposited and bonded together by a machine, to form an object of nearly any shape. The most widely known AM machines use plastic polymers in a process similar to the functioning of a common inkjet printer, thus often referred to as '3D printing'. However, AM includes a much greater variety of manufacturing processes, of which the AM of metals and alloys presents the most significant proliferation challenge. This is particularly so because AM machines are capable of producing a wide range of items that are subject to dual-use and arms export controls. Items that have been produced to date range from basic forms of small arms

[1] The other multilateral export control regimes are the Australia Group (AG), the Nuclear Suppliers Group (NSG) and the Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-use Goods and Technologies (Wassenaar Arrangement, WA).

[2] For further details see the MTCR website.

[3] Missile Technology Control Regime, 'Public Statement from the plenary meeting of the Missile Technology Control Regime (MTCR), Busan, 21st October 2016', Public statement, 21 Oct. 2016.

* An earlier version of this paper was made available to the delegations of the MTCR Partners participating in the Dublin Plenary in October 2017, as part of the 'Compendium of Research Articles' compiled by the Permanent Point of Contact of the MTCR to mark the occasion of the 30th anniversary of the regime.

to rocket engines.[4] Concerns have also been raised about the potential use in nuclear weapon programmes, to produce centrifuges for uranium enrichment, but opinions in the academic discussion diverge significantly on the assessment of the proliferation threat this poses.[5] The potential impact of AM in the field of missile technology and production, however, has received particular attention, highlighted by the coverage of a string of successful deployments of 3D-printed items both in civilian and military rocket applications.

AM presents a profound challenge to the effective implementation of export controls

AM presents a profound challenge to the effective implementation of export controls, since these have traditionally been largely based on controlling the physical movement of goods across national borders. Controls on intangible items have also been covered by export controls, mainly through restrictions on the transfer of technology, but their implementation, oversight and enforcement have proven much more difficult. Controls on tangible goods, such as AM machines, lasers used by AM machines, special metallic powders and machines that produce special metallic powders, remain a cornerstone of the application of export controls to AM. However, AM enables an intangible transfer of technology, such as an email or another digital file transfer, to deliver a significant amount of the information required for the automatic production of an object, thus helping overcome the knowledge barrier to producing a controlled item.[6] While the finishing processes still require considerable knowledge, for example, to make an additively manufactured object suitable to use under high mechanical stress or in very high temperatures, AM could increase the possibility that an actor seeking to circumvent existing export controls exploits the difficulties with controlling intangible transfers of technology (ITT).

As an increasing number of companies working in the defence and aerospace sector are embracing this technology, it is worth reviewing how national and international control institutions apply controls to it and how these controls could be improved. The scope of national controls on the transfer of arms and dual-use goods are usually adopted from the guidelines and control lists drawn up by the MTCR and the other multilateral export control regimes. Currently, the controls on technology mean that transfers of the build files used to produce 3D-printed objects could require a licence if the items they describe are themselves subject to control and they provide a knowledge transfer beyond the pure geometry of the object, for example, the technology for specific processes and finishing procedures that make the item more heat-resistant. However, in practice, this is interpreted and implemented differently across member states. Moreover, complete 3D printers and AM machines—as well as the associated specialized software

[4] Walther, G., 'Printing insecurity? The security implications of 3D-printing of weapons', *Science and Engineering Ethics*, vol. 21, no. 6 (Dec. 2015), pp. 1435–45; and Aerojet Rocketdyne, 'Aerojet Rocketdyne successfully tests engine made entirely with additive manufacturing', 23 June 2014.

[5] See Kroenig, M. and Volpe, T., '3-D printing the bomb? The nuclear non-proliferation challenge', *Washington Quarterly*, vol. 38, no. 3 (Fall 2015), pp. 7–19; Kelley, R., 'Is three-dimensional (3D) printing a nuclear proliferation tool?', Non-proliferation Paper no. 54, EU Non-Proliferation Consortium, Feb. 2017; and Nelson, A., 'The truth about 3-D printing and non-proliferation', War on the Rocks, 14 Dec. 2015.

[6] Christopher, G., '3D printing: A challenge to nuclear export controls', *Strategic Trade Review*, vol. 1, no. 1 (Autumn 2015), p. 18.

they use—have not been added to any of the control lists. In this environment, the discussions that have been initiated within the MTCR represent an invaluable opportunity for states, industry and civil society to engage in a focused dialogue about how this rapidly developing technology can be effectively addressed in the different export control regimes. However, realizing this potential effectively will require a more nuanced understanding of to what extent AM poses a challenge to export controls, especially for missile technology.

Section II outlines the current state of the art in AM technology. It describes the basic features of the technology, its maturity and spread, specific applications in missiles and its potential impact on missile technology proliferation. Section III examines the specific challenges that AM poses to export controls. It analyses the main challenges posed by the technology and discusses existing controls, proposals for new controls and specific challenges for controls on transfers of AM machines, the material they use and digital build files. Finally, Section IV considers potential ways forward for the MTCR and the other multilateral export control regimes, for national export control authorities and for companies involved in AM.

II. State of the art in additive manufacturing

Additive manufacturing technology and the current state of the art

AM is an umbrella term for generative manufacturing techniques that use a manufacturing device that deposits a material layer by layer and fuses the layers together using binders or techniques such as sintering, laser beam melting (LBM) or electron beam melting (EBM). AM technology originated in the 1980s, when it was mainly developed for rapid prototyping purposes.[7] The applications of the technology have since expanded and started to include the direct manufacturing of products for different markets. Production using AM involves hardly any loss of material or production of waste, as opposed to traditional 'subtractive manufacturing' processes that rely on cutting away excess from a larger block of material. In addition, AM promises to produce more complex parts and do so faster, and these parts can be lighter and consist of fewer individual components, compared to parts produced using subtractive manufacturing processes. The technology can significantly reduce the expert knowledge required to produce dual-use parts, as an increasing amount can be coded into digital build files.[8] As such, AM is widely characterized as 'disruptive technology', with the potential to revolutionize the manufacturing industry by transforming the existing modes of production, sales and transfers of goods and technologies in many industrial sectors.[9] Whether the technology will deliver on these promises,

[7] Fey, M., *3D Printing and International Security: Risks and Challenges of an Emerging Technology*, PRIF Report no. 144 (Peace Research Institute Frankfurt: Frankfurt, 2017), p. 8.

[8] Stewart, I. J., *Examining Intangible Controls—Part 2: Case Studies*, Project Alpha, Centre for Science and Security Studies (King's College London: London, June 2016), p. 21.

[9] Brimley, S., FitzGerald, B. and Sayler, S., *Game Changers: Disruptive Technology and US Defense Strategy*, Disruptive Defense Papers (Center for a New American Security: Washington, DC, Sep. 2013); Horowitz, M. C., 'Coming next in military tech', *Bulletin of the Atomic Scientist*, vol. 70, no. 1 (Jan. 2014), pp. 54–62.

and whether changes will occur in a revolutionary way—rather than a less disruptive evolutionary one—is still to be determined.

AM manufacturing devices, often referred to as '3D printers', range from mobile desktop devices that cost as little as $150, to industrial grade, metal AM machines that can cost several million US dollars. The main differences between AM machines are in the materials used and the techniques employed to deposit and bond them together. The feedstock materials used vary from tissue, polymers, metals and alloys to so-called superalloys such as Inconel, which is highly corrosion-resistant, as is required in some key parts of a missile.[10] AM technology is developing to enable the more effective use of maraging steels, ceramics and other advanced materials such as carbon fibre. However, there are remaining challenges before AM can produce objects with the same quality, characteristics and precision as traditional manufacturing processes already achieve. At the present stage of the technology, the speed of production, the speed quality relationship and the reliability of individual pieces still limit productivity. While AM has demonstrated its capabilities for rapid prototyping, applications for large scale industrial manufacturing of pieces with high performance standards still suffer from small defects that are inherent to any 'printed' piece. These are neither easy to predict or detect, and their potential for material fatigue is still being investigated.

The different AM techniques vary from the basic application of liquid binders onto thin layers of powder or other forms of material in 'binder jetting', to the heat liquefying of thermoplastic filaments in 'extrusion processes', to EBM and LBM techniques (mainly used in metal AM) that use powder beds or spray thin layers of metal powder, which are then melted or sintered in the precise locations encoded in a build file.[11] Finally, depending on the design and maximum build size, AM machines vary in their specific technical requirements. For example, some require an inert atmosphere within the build chamber, while others require certain high-powered lasers moving on multiple axes.

An AM device produces an object based on a digital build file, usually made using computer-aided design (CAD) software. Build files reproduce the geometry of an object as a sequence of two-dimensional slices and may contain additional information on the build process, which an AM machine can reproduce layer by layer. Scanning the exact dimensions of an object offers an alternative to obtaining the original design files, at least with regard to the pure geometry. However, such scans may require additional reverse engineering efforts for them to produce an object of the same quality and properties, as opposed to just a copy of the desired shape.[12]

The level of maturity of AM technology varies considerably across different techniques and applications, and none of them has reached the mainstream yet. Gartner's famous 'hype cycle' uses five phases to describe the level of expectation that is projected onto an emerging technology

[10] Christopher (note 6), pp.19–20.

[11] This is not an exhaustive account of the techniques used in AM; for a more comprehensive overview see Committee on Education, Research and Technology Assessment, 'Technikfolgenabschätzung (TA): Additive Fertigungsverfahren (3-D-Druck) [Technology assessment (TA): Additive manufacturing (3D printing)]', Bundestag Drucksache [Report] 18/13455, 29 Aug. 2017, pp. 69–89.

[12] Fey (note 7), p. 3.

during its development and estimates the years until it reaches the mainstream. Of the many AM applications and techniques, in 2017, it only places ‘3D Printing for Prototyping’ and ‘3D Printing of Hearing Devices’ in the fifth and final ‘Plateau of Productivity’ phase, thus firmly expected to enter the mainstream shortly. The analysts at Gartner assess powder bed techniques to be close to the second ‘Peak of Inflated Expectations’ phase, while ‘3D Printing in Manufacturing Operations’ and ‘3D Printing for Aerospace and Defense’ may well have entered the third ‘Trough of Disillusionment’ phase, but are expected to enter the mainstream in five to ten years.[13]

Beyond this, it is worth considering additional indicators that highlight the capabilities that AM already provides and the potential that many governments, scientists and investors see in the technology. The following are all indicative of the extent to which the technology is being embraced: investment by multinational companies in pioneering firms, as well as in research and development; industry cooperation with universities and state actors; incorporation of the technology into production facilities by main firms in the industry; and demand created by major customers, such as large retailers, militaries and the manufacturing industry.

Several large multinational companies are strategically investing in or acquiring companies pioneering in promising sectors of AM technology, such as metal AM. The most significant move to date has been by the United States multinational General Electric Company (GE), which acquired the German company Concept Laser GmbH and the Swedish company Arcam AB in November 2016—both pioneers and leaders in metal AM—to form the core of a new aviation unit.[14] The German company Siemens AG has also strategically invested in AM by acquiring the British company Materials Solutions Ltd and opening new AM facilities in Sweden.[15] Multiple branches of the US military have adopted a variety of 3D-printing and AM processes in their own research and development efforts, even using them in forward deployment in conflict zones and for repair and replacement part production at sea.[16] Since 2014, the US Army has been cooperating in the development of AM applications for missile technology in an ‘Integrated Product Team’ with the Marshall Space Flight Center of the National Aeronautics and Space Administration (NASA) and the University of Alabama in Huntsville.[17] This is just one of many examples of cooperation between the military, civilian industry and academia to further develop AM technology. Major aerospace companies like Boeing and Airbus are using an increasing number of additively manufactured parts in their new aeroplanes. While the vast majority of these are plastic parts without high mechanical stress requirements, Boeing has partnered with Norsk Titanium and now uses additively manufactured, Federal Aviation Administration-approved, structural

Large multinational companies are strategically investing in companies pioneering in AM

[13] Park, R., ‘Hype, hype cycles and applying reason’, Disruptive Magazine, 28 July 2017.

[14] General Electric, ‘GE agrees to purchase controlling shares of Arcam AB’, Press Release.

[15] Michaels, D., ‘Europe leads as industrial 3-D printing takes shape’, *Wall Street Journal*, 5 May 2017.

[16] Hallex, M., ‘Digital manufacturing and missile proliferation’, *Public Interest Report*, vol. 66, no. 2 (Federation of American Scientists: Washington, DC, Spring 2013).

[17] Keith, R., US Army Aviation and Missile Research, Development, and Engineering Center (AMRDEC), ‘Army, NASA, university collaboration promotes additive manufacturing’, 22 May 2014.

titanium components in its 787 Dreamliner.[18] In addition, Norsk Titanium is opening a state-subsidized, 'industrial-scale metal additive manufacturing plant' in Plattsburgh, New York, to service demand for titanium parts by the wider aerospace industry.[19]

At this point, the demand structures for AM devices still vary significantly across the different types of AM technologies, and in domestic and international markets. There is considerable demand at consumer level and among major companies, but few small and medium-sized businesses are acquiring 3D printers and AM machines.[20] For those who do not wish to purchase an AM machine themselves, a growing number of service providers offer AM on demand, or customers can design and 'print' objects in a so-called makerspace.[21] These service providers increasingly offer metal AM services, even using maraging steel and Inconel, as well as finishes such as heat treatment, turning and machining, for example, for customers in motor sport.[22] As the technology matures, it is clearly an area worth monitoring because service providers may expand their capabilities and product range, especially with regard to materials, build size, finishes and post-build treatment.

3D-printing technology is spreading rapidly around the world, especially the more low-tier technologies such as polymer 3D printing. The USA and China are major producers and markets for polymer printers. Although believed to be an imported or copied version, even North Korea has displayed a 3D printer at a trade fair, which is illustrative of how far interest in the technology has spread.[23] However, for the time being, capacity in the cutting-edge end of the market remains concentrated in Western states that are also members of the main export control regimes. Suppliers from the USA dominate in polymer 3D-printing applications for private and small business applications. The main competitors in the field of metal AM technology are concentrated in Europe, especially in Germany, Sweden and the United Kingdom, and in the USA.[24]

Applications for missile technology

AM is inherently a dual-use technology, as it allows the production of objects for both civilian and military applications, for example, for guided missiles and civilian spacecraft. It promises to reduce lead times due to its ability to rapidly produce prototypes, facilitating testing and design processes, which remains its greatest impact on military and civilian technological development to date. Regarding the threat of missile proliferation, the possibility

[18] Norsk Titanium, 'Norsk Titanium to deliver the world's first FAA-approved, 3D-printed, structural titanium components to Boeing', [n.d.].

[19] Norsk Titanium, 'Norsk Titanium to build world's first industrial-scale aerospace additive manufacturing plant in New York', [n.d.].

[20] Committee on Education, Research and Technology Assessment (note 11), p. 135.

[21] Shaw, R., '3D printing: Bringing missile production to a neighborhood near you', NTI Analysis, Nuclear Threat Initiative, 22 Feb. 2017. For an example of a basic printing-on-demand service provider see the Shapeways website.

[22] Christopher, G., '3D printing: Implications for non-proliferation', eds F. Sevini and A. De Luca, *JRC Technical Report: ESARDA 37th Annual Meeting Proceedings*, Report EUR 27342 (Publications Office of the European Union: Luxembourg, 2015), pp. 640–42. For an example of a metal AM service provider see the 3D Alchemy website.

[23] Fey (note 7), p. 29.

[24] Michaels (note 15).

of AM deskilling and making advanced manufacturing processes available to a wider range of actors is of particular concern, as it may undermine existing export controls and it presents new problems for future control efforts. While experimental applications of AM have spread to many fields and industries, applications in the aerospace industry have already made significant achievements.

One of the key advantages that AM offers in the realm of avionic products, such as missiles, is the ability to produce complicated shapes and hollow but stable parts, thus allowing a weight reduction and component performance that may not be reached using traditional manufacturing techniques.[25] In 2013, NASA successfully tested an additively manufactured engine injector for a rocket that generated 20 000 pounds of thrust, while significantly reducing the number of necessary components.[26] AM offers particular advantages in these types of components that require voids in bulk pieces for cooling channels, such as in engine nozzles or combustion chambers.[27] In 2014, the US company Aerojet Rocketdyne built and successfully tested an entire engine for a liquid oxygen rocket using only additively manufactured elements.[28] In 2015, the defence company Raytheon proclaimed that 'The day is coming when missiles can be printed', after it had manufactured a guided missile with 80 per cent of the parts made using AM.[29] Further potential applications of AM in missiles may be to 'print' energetic materials, such as explosives or solid rocket propellants, to optimize their microstructure and the bonding to missile casings.[30] As recently as July 2017, NASA successfully tested the first additively manufactured bimetallic rocket engine igniter using both a copper alloy and Inconel, promising significant reductions in cost and production time.[31]

Current applications in high-tech missile production have not yet reached the 'at the push of a button' scenario

However, there are still a number of hurdles in the development of the technology and the current applications in high-tech missile production have not yet reached the 'at the push of a button' scenario that many envision or fear. The European missile manufacturer MBDA, collectively owned by Airbus, BAE Systems and Leonardo, for example, has already integrated AM devices into one of its missile production plants.[32] However, as Leonardo revealed in a press release in 2016, the 3D printers only form part of the design and production process and are still far from replacing the majority, let alone all, of the manufacturing machines in the plant.[33] In addition, the parts currently produced using AM devices still require finishing procedures, such as

[25] Committee on Education, Research and Technology Assessment (note 11), pp. 39–40.

[26] NASA, 'NASA tests limits of 3-D printing with powerful rocket engine check', Press Release 13-260, 27 Aug. 2013.

[27] Committee on Education, Research and Technology Assessment (note 11), p. 45.

[28] Aerojet Rocketdyne (note 4).

[29] Raytheon, 'To print a missile: Raytheon research points to 3-D printing for tomorrow's technology', News feature, 19 Mar. 2015.

[30] Hutterer, E., Los Alamos National Laboratory, 'Explosiv3Design: 3D-printing technology is booming and could revolutionize the design of high explosives', *1663* (Mar. 2016).

[31] NASA, 'NASA tests first 3-D printed rocket engine part made with two different alloys', News release, 18 Sep. 2017.

[32] Leonardo, 'Missiles produced with 3D technology', Focus, 15 Jan. 2016.

[33] Leonardo (note 32).

high-precision machining or galvanic processes, in order to meet tolerance, quality and durability standards.[34]

A 2017 study by the Peace Research Institute Frankfurt (PRIF) argued that hybrid applications, which exploit the strength of both AM and subtractive or finishing techniques, present a more likely future role of AM than the possibility of it replacing the majority of today's manufacturing technology.[35] An August 2017 report from the German Parliamentary Committee for Education, Research and Technology Assessment also concluded that hybrid applications would be prevalent and contribute to the maturation and steady enhancement of the technology in the next five to ten years.[36] Interest in revolutionary and transformative business models that seek to unlock the disruptive potential of the technology remains much more sparse. However, hybrid applications—and AM-centred production approaches even more so—pose significant challenges to traditional export control approaches, as they decrease the reliance on tangible exports of controlled products and increase the emphasis on ITT in the form of production data and build files.

III. Export controls and additive manufacturing

The challenge of additive manufacturing for export controls

An actor that seeks to obtain missiles or other UAVs and delivery systems—whether a state, a terrorist group or any other non-state actor—requires the knowledge to assemble, maintain and operate them, as well as the various required parts, or the technology and materials to produce them. In most cases, this capability is not obtained through purely indigenous development efforts, but through a combination of technology acquisition, off-the-shelf item procurement, indigenous manufacturing, and/or modification. Traditionally, export controls have sought to limit access to the required materials, production equipment, software, technologies and specific parts, by imposing licensing requirements on the export of relevant dual-use items and through a variety of enforcement measures, including customs checks, as well as through record-keeping requirements. Moreover, export controls are not necessarily aimed at parts as such, but more at their military application—in particular weapons of mass destruction (WMD)—which requires additional know-how.

The MTCR control list defines which goods and technologies are subject to export controls because they are relevant to the proliferation of missiles and UAVs. In addition, some relevant items and materials either overlap or are independently covered by other control lists, primarily by the control lists of the Wassenaar Arrangement (WA). In these cases, coverage often depends on a state's membership in the regimes, the translation of the lists into national regulations and their implementation. Catch-all provisions can also apply if an item is not listed but either the exporter or the competent authority of the state from which the item would be exported knows that it may be used in connection with nuclear, biological or chemical weapons, or their delivery

[34] Leonardo (note 32).
[35] Fey (note 7), p. 9.
[36] Committee on Education, Research and Technology Assessment (note 11).

systems. *Inter alia* in the European Union (EU), a similar catch-all provision applies for items that may be used in connection with military end use in an embargoed destination, but not generically for conventional military end use. These controls allow governments to strike a balance between security-driven control requirements and economically driven trade-facilitation imperatives, meaning that they avoid unnecessarily complicating legitimate, non-sensitive trade through increased transaction costs.

AM poses a number of challenges to the traditional list-based approach of the multilateral export controls regimes, such as the MTCR, and the corresponding national trade control measures. Physical checks of goods and verification of appropriate licences are typically applied when exiting the exporting country, on entry into the importing country and—less frequently—in transit. However, these levels of control may become significantly less effective if companies and other actors with high-performance printers at their disposal can use the potential that AM offers to decentralize production and replace transfers of goods and the transportation phases in a product's supply chain with a simple data transfer. An analysis by PricewaterhouseCoopers' strategy consulting group in 2015 suggested that a wide adoption of AM by industry might put up to '41 percent of the air cargo business and 37 percent of the ocean container business' at risk of becoming obsolete.[37] While this is not limited to, or necessarily representative of, transfers of controlled goods, it nonetheless illustrates the potential impact on the reliance on physical transfers of goods. A supply chain expert, Martin Palmer, stated in 2015 that the mainstreaming of 3D printing and AM will potentially remove several supply chain operations, such as the tangible export, transit and import of physical objects other than AM materials and machines.[38] These elements of global supply chains have thus far provided successive levels on which national export controls and internal company compliance measures have been applied. Palmer argues that, among other things, the control of export and import licenses, end-user screening and customs controls in transit and on import may become less viable tools if AM enables actors to move the production of controlled items directly to the customer.[39] In terms of the movement of materials, traceability also becomes harder, as the higher efficiency of AM machines decreases both the amount of material required and the level of waste produced.

AM offers to decentralize production and replace transfers of goods with a simple data transfer

AM technology is expected to spread further, and a variety of state and non-state actors could gain easier access to more advanced AM capabilities. With regard to the resulting proliferation risks, these capabilities have to be considered in terms of the state of the art in AM (see above) and the fact that the primary use, at least in the short to medium term, will most likely be in hybrid applications. Discussions on the control of AM technology and the challenges it presents have been taking place within the MTCR, and

[37] Duiven, F., Schmahl, A. and Tipping, A., PricewaterhouseCoopers, '2015 commercial transportation trends', *Strategy&*.

[38] Palmer, M., 'Ship a design, not a product! Is 3D printing a threat to export controls?', *WorldECR*, no. 43 (Sep. 2015), pp. 30–31.

[39] Palmer (note 38), pp. 30–31.

also the WA and the Nuclear Suppliers Group (NSG), since at least 2014.[40] Controls on AM could be enhanced in the following three areas: (*a*) controls on the export of AM machines; (*b*) controls on the materials used in the AM process; and (*c*) controls on the transfer of build files.

Controls on the export of additive manufacturing machines

Currently, there are no explicit controls on AM devices or 3D printers in the MTCR control lists. To date, the WA is the only multilateral export control regime that has introduced control list items mentioning AM. A 2016 amendment to the WA's list of dual-use goods added 'directional-solidification or single-crystal additive manufacturing equipment' for the production of gas turbine engine blades, vanes and tip shrouds, and the associated software, to the control list (items 9B001 c. and 9D004 c.).[41] As such, this introduced controls on a specific AM technique for a narrow set of applications, to ensure the coverage of equivalent technologies for this specific purpose. While these are the only controls on complete AM machines, many of the proliferation-sensitive metal AM machines are mounted with high-powered lasers. Several categories of these lasers and their components are already covered by control lists, but the technical definitions are not yet specific to the lasers used in AM. As long as AM machines are used in hybrid applications—and are therefore incorporated into production plants with other types of devices that apply specific finishes that reveal more about their end use—gathering information about the likely end use or end user as part of the existing pre-licensing risk assessment process remains an essential tool in preventing the machines from being employed for illicit or undesirable purposes.

In February 2014, Australia presented a proposal to introduce specific controls on AM technology at a meeting of the MTCR.[42] This would introduce controls on 'machine tools for "additive manufacturing"' that are configured to process listed propellants, or listed metals, ceramics and alloys, in a controlled atmosphere environment and 'with greater than 98% theoretical density'.[43] In April 2016, France put forward a proposal to the NSG to control AM machines that have a controlled atmosphere, that have a build chamber with one dimension larger than 20 centimetres and that use LBM or EBM powder bed techniques. Both proposals were rejected. However, following a subsequent Australian proposal to the WA, the subject of AM was qualified as being of interest and to be revisited in subsequent meetings of the WA.[44]

Controlling AM machines may seem straightforward, but their capabilities do not make it easy to distinguish between machines that are proliferation-relevant and those that are not. The multilateral export control regimes and states implementing controls seek to strike a balance between creating

[40] Jennen, T., 'Aktuelles aus den Regimen/Güterlisten' [News from the regimes/control lists], Presentation, German Federal Office for Economic Affairs and Export Control, 8 Dec. 2016.

[41] Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies (Wassenaar Arrangement), 'List of Dual-Use Goods and Technologies and Munitions List', Feb. 2017.

[42] Finck, R., '3D printing', Presentation at the 20th Anniversary Practical Export Control Workshop of the Wassenaar Arrangement, 27–28 June 2016.

[43] Finck (note 42).

[44] Finck (note 42).

barriers to proliferation and limiting the negative side effects these controls can have on legal trade. Defining machines along the lines of the materials they use is problematic. Titanium, for example, is used both by AM machines to produce dental and other implants, and in the aerospace industry and possibly missiles. In general, AM machines are hardly distinguishable with regard to the type of objects they can produce, apart from the size, but they may be to some degree by their precision and the finishes that they can apply. As such, there is a natural overlap with many civilian uses that do not necessitate licensing requirements. For new controls on AM machines, the challenge is therefore to introduce an element of control over those high-performance machines that pose the greatest proliferation risk, without impeding too much on the further development and profitability of the technology, especially for civilian uses.

Dual-use licensing requirements on high-performance AM machines could define the AM machines that should be covered according to technical specifications, such as the lasers used, the ability to create certain atmospheric conditions in the build chamber, the size of the build chamber, and/or the number of axes on which the lasers or nozzles operate. However, such an approach would be more effective and user-friendly if it avoided introducing different metrics across the regimes and national control systems, as controls on subtractive Computer Numerical Controlled (CNC) machine tools suffer from this problem to some extent today. Initiating a dialogue between the regimes in this phase of the discussions may provide an opportunity to share experiences and possibly to develop a coordinated approach.

Controls on the materials used in the additive manufacturing process

AM machines can use an increasing variety of materials. Those AM machines that process metals, alloys or ceramics—widely viewed as being the most proliferation-sensitive—require these materials to be fed into the machine as a powder with certain characteristics, often specific to the binding or fusing technique employed in the machine. The WA's list of dual-use goods and technologies currently covers a wide range of special metals and alloys in category 1C, including in the form of powders.[45] However, the powders currently controlled are defined according to the specific chemical and physical properties necessary for the production processes that existed when they were devised, which are not the same properties necessary for use in AM. In addition, there is considerable variation between the control regimes in terms of which materials and powders are covered. For example, the MTCR and NSG control lists cover maraging steels of certain characteristics, but not specifically in powder form, while the WA does not control maraging steels at all. France proposed adding maraging steel powders to the WA control list in 2015. The proposal sought to introduce controls on metal alloy powders and alloyed materials of a certain particle size and composition with specific alloying elements, thus also covering powders for use in AM.[46] The proposal was not adopted.

[45] Wassenaar Arrangement (note 41).
[46] Finck (note 42).

Materials—even in powder form—are inherently dual-use and therefore hard to control without impeding on their legitimate use in civilian industry. This is especially the case as AM technology is increasingly embraced by different industry sectors, such as the aerospace industry. In high-performance metal printing, in particular, there are specific requirements for the materials to be in a specific powder form with a certain particle size, structure, chemical composition and controlled gas content, in order to achieve the desired material strength, durability, heat resistance and surface finish. These are distinguishable features that could be used as criteria for specific export controls on special metallic powders that are relevant to the production of parts for missiles and to a lesser extent UAVs.

Controls on the transfer of build files

The transfer of build files forms an important part of any AM process, as build files carry the specific information that the AM machine needs to execute the desired task. ITT, both in the form of transfers of data and knowledge, for example, through digital transfers, access to cloud computing and provision of technical assistance, has posed a profound challenge to export controls, especially since the digitalization of technology and automation have become increasingly important in relevant industries. As such, the challenges faced in the context of AM are representative of many goods and technologies across the regimes that rely on ITT. The MTCR defines 'technology' as 'specific information which is required for the "development", "production", or "use" of a product'. This includes both 'technical data' and 'technical assistance'.[47] The General Technology Note in the MTCR stipulates that 'transfers of "technology" directly associated with any goods controlled in the Annex' are also controlled, unless the specific provisions attached to the item state otherwise.[48] However, there are different interpretations and national practices as regards what information qualifies as being 'required' to develop or produce a controlled item. Some states apply a distinction between the transmission of information on the pure geometry of an object and the transmission of information that also includes knowledge on how to produce an object with the specific qualities and characteristics according to which it is controlled, while others interpret any transfer of build files to be subject to controls. No guidance has been produced by the MTCR or any of the other multilateral export control regimes that defines if and how these controls should be applied and enforced regarding AM.

Effective technology controls present a broader export control challenge

Both companies and states are struggling to implement and enforce controls on digital transfers. In order to enforce controls on ITT, national licensing authorities need to rely on partnerships with industry, the promotion and monitoring of effective internal compliance programmes (ICPs), and effective intelligence-gathering tools to identify violations. Companies need to figure out ways to ensure the security of their own build files, which is clearly in their own interest, and to control and keep records of exports. The vulnerability of systems and the possibility of purposeful distribution

[47] Missile Technology Control Regime, 'Equipment, Software and Technology Annex', May 2017.
[48] Missile Technology Control Regime (note 47).

also shine a light on the increasing importance of cybersecurity for AM. Different approaches are being explored to ensure the security of transfers and access to build files. The US Navy, for example, is exploring the use of 'blockchain technology' to secure the exchange of AM data between their units.[49]

Innovative approaches, such as the introduction of end-user screening standards through self-regulation or codes of conduct for printing-on-demand service providers, similar to those for gene synthesis service providers, offer one course of action to engage the issue. In the case of gene synthesis service providers, a number of consortia and industry associations introduced customer- and product-screening protocols that were shared and implemented as a measure of industry self-regulation in order to mitigate potential risks.[50] Service providers that offer printing-on-demand could similarly screen the items printed, if they use certain material or meet certain criteria, as well as apply basic customer screening. However, questions on quality control, liability and due-diligence requirements for printing-on-demand service providers are yet to be answered. What is clear is that if AM technology continues to spread as anticipated, the reliance on ITT will increase and these challenges will become more pressing.

If AM technology continues to spread, reliance on ITT and associated challenges will increase

IV. Additive manufacturing and the way forward for the export control regimes, national authorities and companies

It has been argued that the increasing accessibility and potential development of AM technology could have a lasting impact on proliferation dynamics. Since the resulting export control efforts will most likely need to be focused on AM machines, special powders and ITT, this may necessitate changes to current export control efforts, through both additional requirements and the reinforcement of ongoing efforts. The multilateral export control regimes, national export control authorities and companies involved in AM are clearly the main actors to take this issue forward, and they could do so in a number of ways, as outlined below.

The export control regimes

While no proposals have been approved to date, the 2016 MTCR plenary publically acknowledged the challenges that AM and 3D printing pose to export controls.[51] Discussions have taken place, and are likely to continue, in the NSG, MTCR and WA. The MTCR could address these challenges by adding items to the control list; by sharing national experience regarding classification, licensing and enforcement; by linking the discussions between

[49] McCarter, J., 'DON innovator embraces a new disruptive technology: Blockchain', US Department of the Navy, 22 June 2017.

[50] Marris, C., Jefferson, C. and Lentzos, F., 'Negotiating the dynamics of uncomfortable knowledge: The case of dual use and synthetic biology', *BioSocieties*, vol. 9, no. 4 (Nov. 2014), p. 404.

[51] Missile Technology Control Regime (note 3).

the different regimes; and by developing guidance material for governments and industry on how to apply existing controls—particularly on ITT—to AM.

While adding items to the MTCR control list may appear a straightforward course of action, it is in fact politically, and potentially commercially, sensitive. Items that may potentially be added to the MTCR control list could include AM machines with certain technical specifications; lasers with technical specifications for use in AM techniques or machines; and materials, specially composed and in specific powder form, for use in AM processes.

The proposals put forward in the respective regimes show significant similarity, but they also reveal different approaches and preferences regarding export controls by the member states. In fulfilling the role as a forum for information sharing and dialogue, an exchange within the export control regimes regarding national experience with AM and past experience with subtractive CNC machine tools could enable states to benefit from each other's lessons learnt on classification, licensing and enforcement. In light of the parallel discussions taking place, it is worth noting that the introduction of different metrics in the different regimes for technical specifications of the same item could lead to additional challenges for implementation by industry and national licensing authorities.

To be effective, controls on build file transfers need efficient resourcing for authorities and industry awareness

While controls on ITT do not lack a legal framework, national practices vary and show different interpretations of when a transfer of build files or similar construction data constitutes a transfer of technology that requires a licence. The MTCR, the other export control regimes and the EU, which implements the controls of all four regimes through the EU Dual-use Regulation, could therefore consider developing guidance material for national governments and industry on how to apply existing controls—particularly on ITT—to AM, in order to establish an agreed standard for their implementation.[52] Controlling the transfer of build files may be one of the most effective ways to implement AM controls, if properly implemented and enforced. This in turn not only requires an appropriate legal basis and institutional set-up, but also sufficient resourcing for licensing and enforcement authorities, including for company audits, as well as sufficient awareness by the relevant actors within industry.

National authorities

National export control authorities face a number of challenges in relation to AM controls. First, the traditional practice of imposing licensing requirements and carefully considering the end use or end user so far only covers a very small number of AM machines or their components. The capabilities of AM machines may not make them readily distinguishable or mean that they fall under the specially designed clause in existing export control regulations. Rather, catch-all provisions apply if the machines are used in relation to nuclear, biological or chemical weapons, or their delivery systems. Current and near future applications, especially in the high-end area, are most likely

[52] Council Regulation 428/2009 of 5 May 2009 setting up a Community regime for the control of exports, transfer, brokering and transit of dual-use items, *Official Journal of the European Union*, L134, 29 May 2009, as amended most recently through Commission Delegated Regulation (EU) 2015/2420 of 12 Oct. 2015, *Official Journal of the European Union*, L340, 24 Dec. 2015.

to be in the form of hybrid applications and therefore more distinguishable if the technical specifications of AM machines are considered in the context of other traditional machines also used in a production facility.

Thus, options that would strengthen AM controls include: (*a*) increased outreach and dialogue with industry on ITT controls, through both more and closer cooperation with companies (as data security and accountability for who ends up using their design files should be in their interest); and (*b*) other measures such as specialized company audit procedures, which involve reviews of digital security standards and record-keeping systems on ITT by digital file transfer.

Companies

Companies can be divided into three groupings: (*a*) those producing AM machines, (*b*) those using AM machines, and (*c*) those offering printing-on-demand services. As in other parts of the dual-use industry, companies' awareness of the potential misuse of their products and relevant legal control requirements, coupled with ICPs to enable compliance with company policy and legal requirements, are essential for functioning controls.[53] This in turn is only possible through partnership and cooperation between the private and public sectors, ideally also involving industry associations.

For companies producing AM machines, sharing best practices on effective customer screening could be a useful measure, while companies using AM machines could consider sharing best practices on record-keeping. For companies offering printing-on-demand services, traditional mechanisms of brokering or facilitation and technical assistance controls with regard to WMD end uses could be feasible. These would need to be applied in close cooperation with the country on whose territory the companies are operating. For certain types of conventional arms, some countries apply controls not only on export but also on production. These controls could also be invoked with regard to printing-on-demand services.

While not a new issue as such, the expanding market of printing-on-demand services clearly needs to be monitored in terms of the challenges it poses to the possibility of end-use or end-user controls, and methods of customer or product screening, similar to the ones developed for the gene synthesis industry, may need to be explored.

In conclusion, it can be said that AM technology, in its current stage of development, highlights and aggravates the challenge of ITT for export controls. While it does not pose an inherently new challenge, it makes the need to find appropriate solutions to the existing challenge more visible, and arguably more pressing. The potential relevance for missile proliferation depends on the further development of the technology beyond the experimental stage that numerous missile and rocket applications are currently in. Nonetheless, the technology clearly has the potential to affect industrial and technological developments and create considerable proliferation challenges as a consequence.

[53] Bauer, S. et al., *Challenges and Good Practices in the Implementation of the EU's Arms and Dual-use Export Controls: A Cross-sector Analysis* (SIPRI: Stockholm, July 2017).

STOCKHOLM INTERNATIONAL PEACE RESEARCH INSTITUTE
Signalistgatan 9
SE-169 72 Solna, Sweden
Telephone: +46 8 655 97 00
Email: sipri@sipri.org
Internet: www.sipri.org

SIPRI BACKGROUND PAPER

3D PRINTING AND MISSILE TECHNOLOGY CONTROLS

KOLJA BROCKMANN AND SIBYLLE BAUER

CONTENTS

ABOUT THE AUTHORS

Kolja Brockmann (Germany) is a Research Assistant in the Dual-use and Arms Trade Control Programme at the Stockholm International Peace Research Institute (SIPRI). He conducts research in the field of export control, focusing on internal compliance programmes and intangible transfers of technology, and maps cooperation and assistance activities relevant to the implementation of the Arms Trade Treaty in East and South East Asia. He has an MA in Non-Proliferation and International Security from King's College London.

Dr Sibylle Bauer (Germany) is the Director of Studies for Armament and Disarmament at the Stockholm International Peace Research Institute (SIPRI) and the Director of SIPRI's Dual-use and Arms Trade Control Programme. She has a long record of research, publication and capacity building on dual-use and arms export control issues. She has a PhD in Political Science jointly from the Free University of Brussels (ULB) and the Free University of Berlin. Before joining SIPRI in 2003, she was a Researcher at the ULB's Institute for European Studies.