ADDITIVE MANUFACTURING: THE FUTURE FOR SAFEGUARDS

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Abstract

Additive manufacturing is described as a transformative technology that will allow objects with complex topologies and 21st Century materials to be produced locally. The impact on safeguards by the availability is s not yet clear as the technology just beginning to impact industry. Exactly what the technology will be able to produce in the near-future of relevance to nuclear safeguards is unclear, especially if it allows States to solve manufacturing challenges posed by technology controls.

This paper addresses four key points: given how the additive manufacturing is developing, what it will be possible to produce with this technology by 2025; whether additive manufacturing provides developing nuclear States with access to new capabilities; how technology controls may be undermined by allowing States either to outsource production or produce traditionally manufactured items using additive techniques, and; the policy responses that are available and appropriate to meet this challenge.

1. INTRODUCTION

This paper should disabuse the reader that additive manufacturing (AM) will allow a proliferator to build anything, anywhere, anytime, at the push of a button. Additive manufacturing is challenging, even for the most capable users. It does not remove tacit knowledge from manufacturing but demands that any operator master new skills. Using this technology to make metal parts requires multiple teams of expert engineers for raw materials production, part design, machine commissioning, printing, postprocessing and validation.

If additive manufacturing, more commonly known as 3D printing, is so difficult we may ask why it is being discussed at all. Recent studies by Christopher [1], Volpe [2] and Fey [3], have all sought to understand what role additive manufacturing may play in proliferation. Technological assessments by Kelley and Brockman [4], Shaw et al. [5], and Christopher [6] conclude that additive manufacturing cannot act as a substitute for 'traditional' or conventional manufacturing along proliferation pathways of enrichment reprocessing, and weaponisation. These authors agree that, based on the current state of the technology, additive manufacturing has a very limited role in proliferation at present but does have relevance to production of specific nuclear-related items.

There are many questions about the The future of the technology. Will new processes be invented to overcome existing problems? What could the nexus of artificial intelligence with digital manufacturing, that is both subtractive and additive computer-controlled processes, allow us to make? Will entirely new classes of materials be possible? These questions are asked, if not completely answered in the following sections.

1.1. The basics of additive manufacturing

The technologies known as additive manufacturing all follow the same design principle. A material is built up layer by layer, using a computer-controlled machine, as instructed by a digital design file. Michelangeo's David was produced by a subtractive manufacturing process, where it was revealed by the arist from within the block of marble. Additive manufacturing is the creation of an object built up from smaller formless objects. In AM, as each layer is built up, the raw material is attached to nearby material aside and below. The technique used to stick the material together – directed heat, UV light, or glue – is what defines each AM technology. The raw material may be a powder, wire or resin, made from metal, ceramic or plastic.

The most relevant technique for safeguards uses a laser or electron beam to melt metal power. In this technique, a thin layer of power is spread across a build chamber and the laser is directed to melt only the areas of powder that will compose the part. As the layers build up the part is 'submerged' in a sea of powder. This technique goes by various names, of which the most common is Powder Bed Fusion (PBF). After printing the part is not finished. A team of engineers with specialised equipment remove the part from the build plate, cut support structures and the surface is smoothed and polished. High-precision milling may be required to bring the part to required dimensional tolerances. From a proliferation perspective, postprocessing may require use of the very tools AM was supposed to be able to bypass. Design, building and postprocessing of metal parts using PBF is extremely complex topics and the relevance to proliferation is discussed in much greater detail by Christopher [6].

The second most relevant technique to consider, dubbed Directed Energy Deposition (DED), uses wire or powder deposited directly with the laser or electron beam melting the powder as it is applied. DED is generally faster than PBF but produces coarser features which require additional high-precision milling.

There are a few other techniques of relevance. Binder jetting uses powder, but unlike PBF the powder is stuck together using a glue. The glued powder is then melted in a furnace. This is used for producing tooling parts with tungsten. Fused Deposition Modelling (FDM) is the hobbyist's technique of choice that typically works with plastic melted plastic wire. However, it is a highly flexible process that can be used with any material that can be melted. As such, it has been used to print high explosives [7]. Finally, stereolithography, where UV light is used to cure a resin, has been used to print fully fluorinated polymers [8].

2. ADDITIVE MANUFACTURING IN 2025

Predicting the future development of any technology is challenging. To do so, in this paper, we extrapolate from existing trends. This includes the interaction of AM with other emerging technologies, such as artificial intelligence and blockchain.

Today's state of the art is the baseline for tomorrow's developments. This is best represented by Siemens' turbine blade – a PBF metal part with a complex internal topography. This part has been tested under extreme operating conditions of rotational speeds greater than 13,000 rpm and above temperatures of 1250 ºC [9]. This shows that today it is possible to produce high-precision metal parts with complex internal geometries designed to operate in demanding environments.

Beyond this example, several broad trends can be identified in AM. The first is that it will come to be considered as an aspect of digital manufacturing, that is computer-controlled manufacturing with subtractive and additive machines. Recognising this, Siemens is implementing an integrated design process, where engineers will use the same software and systems for both additive and subtractive manufacturing [10].

The second is that by 2025 we should expect more consistency in laser-metal manufacturing. Despite high-profile successes from General Electric and Siemens, today it is difficult to produce the same part twice with in the same machine with the same material and design. Failure during printing and postprocessing is common. To overcome this, fundamental research is being conducted to model and understand why parts fail and how defects form [11].

Third, processes that use expensive materials will experiment with using additive manufacturing. Orbitak ATK has printed parts for hypersonic weapons, citing material waste as a motivating factor [12].

Finally, AM will not totally replace conventional manufacturing. Rather, complex components with many parts will be reduced to a smaller number of parts, with some being conventionally manufactured and some printed. AM will be used where it can add the most value: when material can be saved by redesigning a complex internal topography while consoldating several conventionally manufactured parts. This is demonstrated in General Electric's LEAP fuel nozzle [13].

2.1. New materials

We should expect that by 2025 more materials will be available for AM. It is already possible to print maraging steel 300 series, Inconel, titanium, aluminium 7xxx series [14], fully fluorinated polymers [8] and uranium-niobium [15]. In the nuclear industry, research is being conducted printing 316L stainless steel for use in reactors [16] and printing thorium oxide nuclear fuel [17].

By 2025, the range of materials will widen. Materials that are only currently under reseach, such as maraging steel 300 series and aluminium 7xxx series, will be used commercially in aerospace. There will be a shift from copying the chemical composition of wrought materials to using new compositions that are optimised for the rapid heating and cooling cycles inherent to the additive manufacturing process. This approach has recently been realised by Elementum's new A6061-RAM2, an altered composition from wrought of AlSiMg specifically designed for AM [18]. Heat from lasers vaporises volatile elements, altering the chemical composition and hence the material properties which is especially important for aluminium 7xxx.series. Entirely new materials, what were not otherwise possible may also emerge, such as functionally graded materials (FGMs). In FGMs, two or more materials are mixed in varying proportions across the breadth of material, with allows a part to be produced with material properties that change from one side of the object to the other.

2.2. Advances in hardware

Recent advances in hardware have added more lasers and larger build chambers allowing larger parts to be produced faster. Yet, the fundamental technology remains unaltered and there have been no paradigm shifts in how metal AM is done. Disruptive techniques, such as Vader systems metal droplets production and Diode Area Melting have not yet shown they are ready to overthrow dominant laser-metal powder techniques for high-quality parts. Area melting techniques do show promise however. Lawrence Livermore National Laboratory is developing a technique that would irradiate each layer of power simultaneously. If matured, this would dramatically increase the speed of printing metals [19].

Harmonised standards for additive manufacturing are still in development, with ASTM standards for PBF only published as recently as April 2018 [20]. By 2025 we would expect a consistent set of international standards to be adopted across the additive manufacturing industry. This should hasten industry-wide adoption of AM and accelerate development.

2.3. New graduates, new ideas

As the next generation of engineers graduates, they will provide new ideas and innovations. They will be native digital manufacturers that will think of additive manufacturing as an element in digital manufacturing. This is another factor that will accelerate AM adoption and development.

2.4. The interaction with other emerging technologies

Artificial intelligence may also begin to impact the design phase and construction phase of additive manufacturing by 2025. An early application of machine learning has been to detect flaws in powder distribution prior to melting which will reduce the number of failed prints [21].

This is just the beginning: artificial intelligence will eventually be deployed across the entire digital manufacturing process, from design to postprocessing. All digital designs undergo an engineering stress-test phase known as Finite Element Analysis (FEA) where computer modelling is used to test the performance of the currently designed part. Any digitally designed part can therefore progress through many design iterations before prototyping. Artificial intelligence should greatly improve this. In the build phase, as part failure becomes more well understood, process monitoring coupled with an adjustment in build parameters controlled by an artificial intelligence system may lead to more consistent parts production. A similar improvement would be expected in the postprocessing phase.

Distributed ledger technology, i.e. Blockchain, is being explored in protracted supply chains to validate design files and provide permissive links to build sensitive parts [22]. If this technology becomes widely adopted, sensitive designs could then only be produced in approved machines lowering proliferation risks.

3. ADDITIVE MANUFACTURING IN DEVELOPING NUCLEAR STATES

Additive manufacturing, as recent studies have shown, does not provide proliferators a way to manufacture enrichment or reprocessing technology, by using uncontrolled materials in an uncontrolled machine. However, it has been discussed as a means to retain domestic capabilities in the face of sanctions on conventional goods [23]. For nuclear manufacturing, AM is too risky relative to conventional manufacturing for most applications and large printed parts do not meet required tolerances. In particular, centrifuges printed with maraging steel 300 series would need to undergo flow forming - an advanced manufacturing process where the machine tools are under export controls [4]. This reduces the unique utility of AM to proliferators.

This is not the end of the story. Solving how to print with nuclear-related materials or hard-to-make items may make AM appear more attractive to proliferators. Beryllium, which is used in nuclear weapons as a neutron reflector, is a difficult material to work with, but it may be possible to printed if combined with aluminium [4]. Alone, beryllium is toxic and cannot be melted or cast so it is typically worked with in powder form. By mixing with aluminium, the powder may be melted and could become suitable for PBF. The neutron reflectivity is lowered but the core function of neutron reflection remains. Kelley and Brockman argue that beryllium printing represents a relatively high risk and should be monitored in the future. Other highly sensitive items may have a majority proportion of their parts printed in the future. Pressure gauges are are potential use case., The internal system of a pressure gauge, which is, may be a good application for AM. These are used in monitoring gas centrifuge cascades, have been acquired by proliferators in several notable cases [4].

Proliferators have shown in the past a willingness to pursue unusual paths to obtaining a nuclear weapon, as evidenced by the South African aerodynamic enrichment programme, the Iraqi use of calutrons and the experiments with laser isotope separation in Iran and other States. Therefore, we must proceed with caution when making assessments of how AM will be used.

3.1. New approaches to old problems

We should consider the possibility that AM could make obsolete enrichment techniques more attractive. In the absence of an engineering study all reporting in this area should be treated as wholly speculative. The micrometre accuracy required for gaseous diffusion barriers are not suitable to be produced by any of the additive manufacturing techniques described in this paper, although the conventional manufacturing technique of vapor deposition is an AM-like technology that uses a substrate. However, perhaps there as-yet unidentified opportunities in such as manufacturing aerodynamic nozzles or in laser isotope separation.

Additive manufacturing has been used to great effect in solving difficult engineering problems. At Oak Ridge National Laboratory, in a programme designed to reduce use of highly-enriched uranium in Mo-99 production, a process was developed to print enriched Mo-100 targets using laser-metal printing. This was designed to overcome problems with distortion of the targets after being placed in the accelerator [24]. For this technique to be efficient, new methods were invented to preserve as much of the Mo-100 enriched powder as possible. This is indicative of the attractiveness of AM in efficient use of small quantities of valuable or hard-to-produce material.

4. TECHNOLOGY CONTROLS

At present, export controls do not cover 3D printers, some of the raw materials or digital design files for relevant parts.[1] Controls among raw materials are based on coverage in the multilateral export control regimes for purposes other than for nuclear proliferation. Maraging steel power is the most notable omission from the regimes in this respect and are only covered under catchall controls.

4.1. Outsourced manufacturing

Facilities offering advanced manufacturing are readily available from E-commerce service providers. Export control compliance is not a featured in descriptions for consumer E-commerce, but is reserved for industry service providers. Facilities in regions with weak export controls could provide proliferators with an outsourced manufacturing centre that provides equipment, raw materials and expertise not available to the state.

5. POLICY RESPONSES

Additive manufacturing does not at present provide an alternative path for proliferators to manufacture nuclear export-controlled items. Therefore, controls on machines are unlikely to be implemented in the near

[1] Single Crystal-capable (SX) additive manufacturing machines are controlled under the Wassenaar Arrangement. No machines capable of this type of manufacturing, which is currently used in turbine blade manufacturing, have been announced publicly.

future. Recent proposal for controls in the Missile Technology Control Regime, Wassenaar Arrangement and Nuclear Supplier Group were not implemented [25].

There are gaps in current controls. Most raw materials are controlled under the non-nuclear regimes and this is especially true of metal powders. There are some significant exceptions. Controls for maraging steel powder, which is currently covered only by catch-all controls, remains a possibility to be controlled. The controls for vital AM machine components such as lasers and electron beams may also be considered for control. As new capabilities are realised machines that are capable of printing sensitive items should also be considered. This covers printing with beryllium alloys, actinides, high-explosives and other materials that have few dual-use functions.

Sensitive design files should be controlled. Permissive controls for printing sensitive designs, design validation and should be encouraged by application of distributed ledger technologies [26].

6. CONCLUSION

The additive manufacturing industry, as it matures, continues to pose challenges to those seeking to monitor proliferation. The risk at present is minimal, but it may not remain that way. Recent applications in printing enriched molybdenum and thorium dioxide show an appetite for experimenting with the use of new materials to solve engineering problems. The desire of States to insulate against the threat of sanctions exploiting a relatively lightly regulated technology may make additive manufacturing more attractive to developing nuclear States. Coupled with the rise of a global digital manufacturing service industry this will make controlling additive manufacturing a continuing challenge.

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