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Review of Structural Additive Manufacturing for Defence Applications

Current State of the Art

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Abstract

Additive Manufacturing (AM) techniques are seeing increasing use for the fabrication and repair of commercial engineered components, and could offer significant advantages over traditional manufacturing methods for defence use. However, the field of AM is broad, and it can be difficult for the non-expert to separate the hype from reality. Parts used for defence applications are often critical and operate in demanding environments, and so knowledge of AM capabilities is necessary in order to choose the best option. This Scientific Report summarizes the current state of the art of commercially available AM techniques, focusing on their applicability and usage in defence structural applications. Particular attention is paid to the variety of material feedstocks available and the resulting mechanical properties, anisotropy, residual stresses, and fatigue and fracture performance of each technique. The relative pros and cons of each technique from a defence standpoint are also addressed. This report thus offers useful guidance to the novice and expert alike when considering AM for defence structural components.

Significance to defence and security

AM represents an opportunity to defence agencies to reduce manufacturing/repair costs and lead times for structural components. However, knowing when and how to effectively use AM requires an understanding of the characteristics and nuances of the techniques that make up this field. Each AM technique exhibits unique strengths and weaknesses, and it is unlikely that any one technique will be optimal, or even preferable to traditional manufacturing, for all possible applications. Relying only on superficial information, such as marketing materials, may not provide enough detail and may lead to an under appreciation for the drawbacks to certain systems. To help guide AM development and use for defence applications this report consolidates extensive information about each technique and highlights any knowledge gaps or shortcomings. This report therefore offers useful direction to help promote effective decision making in the near-term when researching, contracting and conducting AM for structural applications.

Résumé

Les techniques de fabrication additive (FA) sont de plus en plus utilisées pour fabriquer et réparer les composants techniques commerciaux et pourraient offrir des avantages considérables pour la défense par rapport aux méthodes traditionnelles de fabrication. Toutefois, comme les pièces utilisées dans les applications de défense sont souvent cruciales et employées dans des milieux exigeants, il est essentiel de connaître les capacités des différentes techniques de FA pour choisir les meilleures options possible. Le domaine de la FA étant vaste, il peut être difficile pour le profane de distinguer le mythe de la réalité. Dans cette perspective, le présent rapport résume les techniques de pointe en matière de FA actuellement offertes sur le marché et s'attarde sur leur applicabilité, ainsi que leur usage dans des applications structurelles de défense. On prête une attention particulière à la grande variété des matières premières qui peuvent être utilisées, à leurs propriétés mécaniques et anisotropiques, aux contraintes résiduelles, ainsi qu'à la résistance à la fatigue et à la rupture associée à chaque technique. Les avantages et les inconvénients de chaque technique du point de vue de la défense sont également abordés. Le présent rapport renferme donc des indications utiles autant pour les profanes que pour les experts lorsqu'on envisage l'utilisation de la FA pour les composants structuraux de défense.

Importance pour la défense et la sécurité

La FA offre la possibilité aux organismes du domaine de la défense de réduire leurs coûts de fabrication et de réparation, ainsi que les délais de production des composants structuraux. Cependant, pour savoir quand et comment utiliser efficacement les techniques de FA, il faut en connaître les caractéristiques et les nuances. Chaque technique de FA a ses forces et ses faiblesses et il est peu probable qu'une seule d'entre elles puisse être optimale, voire préférable aux techniques traditionnelles pour l'ensemble des applications possibles. On ne peut compter uniquement sur l'information générale, notamment les documents publicitaires, pour obtenir suffisamment de détails, au risque de sous-estimer les inconvénients de certains systèmes. Pour orienter l'élaboration et l'utilisation des techniques de FA à des fins de défense, le présent rapport fournit une mine de renseignements sur chacune des techniques et met en évidence les lacunes et les faiblesses sur le plan des connaissances. Le rapport offre ainsi des orientations utiles pour favoriser la prise de décisions à court terme efficaces, notamment en ce qui concerne la recherche, la passation de marchés et l'utilisation des techniques de FA dans les applications structurales.

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1 Introduction and scope

The terms *Additive Manufacturing* (AM) and *3D printing* can invoke a range of responses. Some view this group of technologies as truly disruptive, rendering obsolete traditional manufacturing and representing a "third industrial revolution" [1], while others remain skeptical of AM's promises [2]. However, while it is true that the marketing of these technologies often minimizes their limitations and drawbacks, their potential capabilities and advantages are too attractive to be ignored. Given the recent growth of AM for industrial purposes, it is very worthwhile to understand the current state of AM technologies and their suitability for defence applications.

AM refers to a range of techniques that are used to progressively fabricate parts through material build-up, usually involving layer by layer growth, based on a 3D computer model. From a defence standpoint, AM techniques are attractive as they could greatly advance fabrication and supply chain efficiencies, and also increase design freedom. Some examples of these potential benefits include:

- reduced material waste, and thus overall material costs;
- ability to fabricate hollow, lightweight structures;
- on-demand production, obviating part warehousing;
- potential for fabricating on-site, or even in-theatre, rather than at a dedicated factory;
- cost-effective fabrication of small production runs and "one-offs;"
- potential for repair of damaged components;
- potential to locally tailor material properties within a part; and
- reduced equipment footprint and necessary skilled labour compared to traditional fabrication.

Not all of the AM techniques offer these advantages to the same degree, though, and each comes with its own set of disadvantages. Any specific AM technique is thus not a panacea, and so proper exploitation of AM requires an understanding of the available options and nuances.

This Scientific Report is intended to provide enough up-to-date information for even the novice to decide which, if any, AM techniques to pursue for a specific defence structural application. There are many review articles in the literature that delve deeper into the mechanisms of operation, research activities and/or commercial uses of the different AM techniques, and so this information will largely not be reproduced. Instead, the focus here is on the capabilities of current commercially-available systems and materials, their advantages and disadvantages from a defence perspective, and any proven defence applications of each technique. Particular attention is paid to aspects that may facilitate or hinder their immediate use for defence parts. These include: the range of available feedstock materials; the typical resulting mechanical properties; whether or not other features (i.e., anisotropy, fatigue and fracture properties, residual stresses, etc.) of finished parts are well characterized and acceptable; the degree of post-processing/machining necessary; the amenability of the technique to part repair; and, the existence of qualification standards or other guidance documents to expedite acceptance of a part for service.

This discussion is limited to only certain defence applications and materials. While AM has potential for many uses, such as fabrication of functional materials, electronics, sensors, drugs, food, etc., not all have seen significant commercial/industrial development. Meanwhile, fabrication of structural parts represents both the best developed AM application and the most likely immediate defence use of AM, and so is the focus of this report. Since defence structural components typically use metals or polymers these are considered in greatest depth, although ceramics and composites are also discussed when applicable.

It should be noted that lists of equipment and material feedstocks included in this report are not to be taken as exhaustive, unless otherwise stated. In most cases it is pointless to catalogue all of the up-to-date commercially available options, as this information is summarized elsewhere. For more information on equipment specifications, ranges of available materials and advertised mechanical properties the reader is directed to the online database offered by Senvol LLC (www.senvol.com). This very useful, current database allows for easy comparison between different systems and materials, and provides an understanding of what can be achieved when using a given feedstock and technique. Note that the database summarizes advertised specifications, and so the actual performance when using a specific system/material may vary from that quoted.

2 AM of non-metallics

The fabrication of non-metallic materials, such as polymers, ceramics and certain composites, tend to use similar AM techniques. However, polymers represent, by far, the biggest class of non-metallic materials used in AM, and so are emphasized in this section.

The following subsections describe the distinct AM techniques as defined by ASTM International [3]. Each subsection begins with a brief description and history of the technique, and presents some of the various industry terms and acronyms by which it is referred. Next, the types of materials that can be used with the technique are discussed, and a sense of the typical mechanical properties compared to traditional manufacturing methods is provided. Any information on other features of parts (i.e., anisotropy, fatigue and fracture properties, residual stresses, etc.) is also included, when available in the literature. Finally, the pros and cons of using the technique for defence purposes are summarized, and published usage for defence applications is given. For ease of comparison between the AM techniques, with respect to advantages and disadvantages from a defence perspective, a summary table is provided in Section 2.8.

2.1 Material extrusion

Material extrusion techniques comprise some of the most widely used AM methods at present. Technologies within this class include Fused Deposition Modelling (FDM; trademarked by Stratasys, Inc.), Fused Filament Modelling (FFF) and Melt Extrusion Manufacturing (MEM). Despite the differences in name, these techniques are all essentially the same. These processes typically use filaments of solid material that are fed into a heated nozzle using a pinch roller. The heat causes the filament to melt, and the solid filament entering the nozzle acts as a piston to extrude the molten material. The nozzle is moved relative to the build platform in the X-Y and Z directions, to build up a part line by line, layer by layer. Because thermal gradients affect the cooling and solidification of the molten polymer they can lead to variations in mechanical and dimensional properties. Thus, systems often employ a heated build stage or temperature-controlled enclosure to try and stabilize the gradients. The components of a typical material extrusion system are shown in Figure 1.

Traditionally, material extrusion techniques have used amorphous thermoplastic filaments, such as Acrylonitrile Butadiene Styrene (ABS), Polylactic Acid (PLA), polyimide, polyamide, polycarbonate, polyphenylsulphone, etc. These filaments are usually 1.5–3 mm in diameter [4], and when deposited result in layers on the order of hundreds of microns thick. Recently, filaments consisting of thermoplastic embedded with ceramic particles, carbon fibre strands, and even wood fibres have become available. These are used not only for improved strength or aesthetic reasons, but they also enable the fabrication of, for example, ceramic parts via extrusion. This approach requires further post-processing to burn out the thermoplastic binder and to sinter the ceramic particles after the build (see Section 3.1 for more information).

The strength of extruded AM parts is limited by the strength of the bond between adjacent tracks of deposit. These bonds generally are not as strong as those of the bulk material, making extruded AM parts typically weaker than those made from traditional processes like injection moulding [5]. The exact strength of the bonds is dependent on the extrusion parameters (i.e., filament feed rate, nozzle temperature, deposition speed, ambient temperature, etc.). Furthermore, because of the directionality of deposition and the thermal gradients involved, the mechanical properties of a part commonly vary with orientation. Predicting the mechanical properties is therefore not a trivial task.

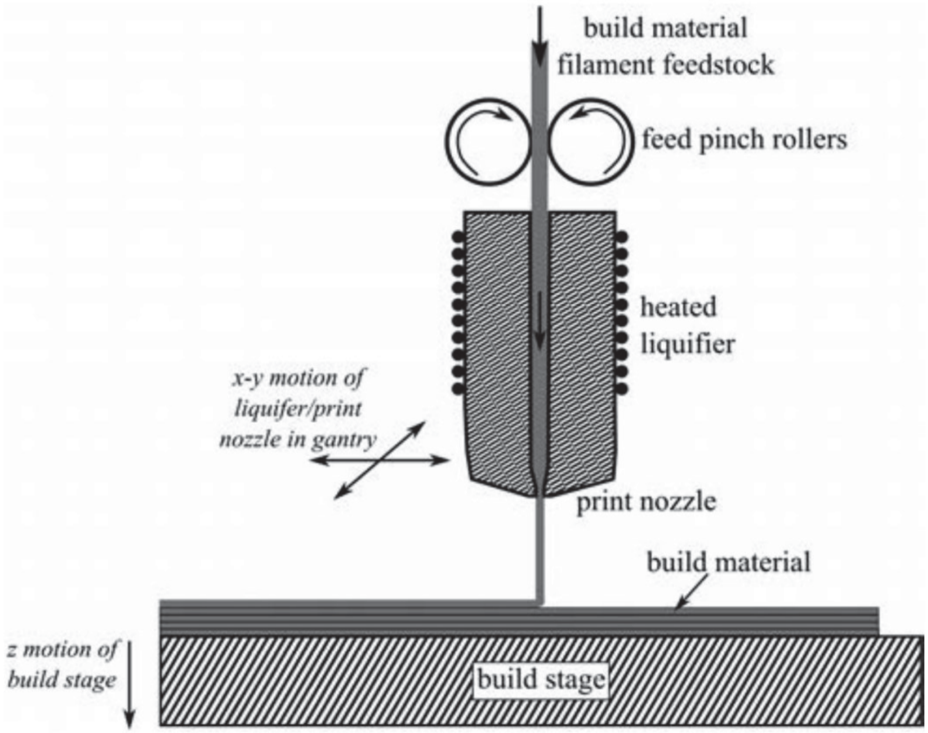

Figure 1: *Schematic of material extrusion system [4].*

With all the caveats stated in the previous paragraph, it is still useful to provide a sense of the mechanical properties of extruded AM parts. When parts are tested with the applied stress in the X-Y plane (see Figure 1) they tend to be strongest. In this orientation, parts made from ABS have exhibited Ultimate Tensile Strengths (UTSs) of ~19–35 MPa [5–7]. By comparison, injection moulded ABS can exhibit strengths of 45 MPa and higher [8]. Similarly, a direct comparison of injection moulded ABS to extrusion AM parts have suggested the former is ~37% stronger than the latter [7]. Parts built and tested with the applied stress in the Z direction tend to be even weaker. Strength in the Z direction has been shown to be as low as 52% of the X-Y plane strength [6]. From this data it is clear that the performance of extruded AM parts can vary greatly depending on the particulars of the build process and on part orientation.

There are several pros and cons to using extrusion AM in defence applications. On the pro side, extrusion AM systems are relatively simple, inexpensive and have been well developed commercially. They take filaments as feedstock, which are less reactive, easier to work with, more compact and pose less health and safety risks than powders. There is also a relatively large range of feedstocks to choose from for material extrusion. On the negative side, extruded parts tend to have visible ridges corresponding to each of the layers and parts are often built with support structures that need to be removed. This post-processing is commonly done by hand, making the whole fabrication process more labour-intensive. Furthermore, the space required for post-processing can be much larger than that of the printing, and can involve hazardous solvents. The strength of extruded parts is modest, and anisotropy can be particularly significant. Moisture absorption by either the feedstock or by the molten polymer during the build can lead to processing issues, such as blocked nozzles, distortion or voids/blistering of the part, as this moisture vaporizes and expands in the heated nozzle [4]. This can necessitate the use of desiccants for feedstock storage and/or controlled atmospheres during the build, depending on the material used. Finally, the use of a moving nozzle and molten deposit make this process susceptible to external motion/vibration. Thus printing parts in an unstable environment can be problematic and lead to unpredictable results.

From a defence perspective, the pros are considered to outweigh the cons, and so material extrusion has seen considerable interest and exploration. Although extruded AM parts are generally limited to strengths in the tens of megapascals, this can be sufficient for certain production parts. The U.S. Army's Rapid Equipping Force deployed extrusion AM equipment (Fortus 250mc; Stratasys, Inc.) to Afghanistan in 2012 as part of their Expeditionary Labs. These labs were intended to enable the on-site fabrication of replacement parts and/or new parts as designed by the soldiers [9]. Extrusion AM is also the most widely used AM technology within the U.S. Navy [10]. They have used this technology in domestic facilities for the fabrication of custom tools, functional prototypes, concept models and some end-use parts [11]. In 2012, a DARPA technology evaluation project was conducted wherein surgical instruments were printed via FDM in a mock field hospital. The temperatures involved in the FDM resulted in sterile instruments directly from the printer (uPrint Plus SE; Stratasys, Inc.), which were then used for a simulated surgical procedure [12]. In 2013, this same model of printer was tested aboard the USNS Choctaw County [13]. The system was used to print sample ABS parts both pierside and underway, and these parts were tested for dimensional accuracy and mechanical properties. Part warping and internal defects were noted for the samples printed underway. The system was further trialed in 2014 aboard the USS Essex where crewmembers were trained and able to use the system for printing spare parts and surgical instruments [13]. None of the printed parts were cleared for actual use, however. The exercise was merely meant to further explore the operational issues associated with use of AM equipment onboard. The Norwegian Armed Forces also chose extrusion AM systems as the only kind used in an experimental mobile manufacturing lab [14], and the technology is used by the Armed Forces of the Netherlands for fabricating replacement parts from ABS [15]. While metal systems would have been very useful, they were considered too problematic for use in the field. There are many more examples of extrusion AM being trialed or even being used for non-critical defence components, but it is unnecessary to summarize all those uses here. Suffice to say that extrusion AM has so far been the most popular choice for AM of polymeric parts for defence applications.

2.2 Vat photopolymerization

The first commercially available AM system of any type was based on vat photopolymerization and entered the market in 1987 [16]. The SLA-1 was produced by 3D Systems and relied on Stereolithography (SLA). Since then, other vat photopolymerization techniques have been commercialized, such as solid ground curing, liquid thermal polymerization, beam interference solidification, holographic interference solidification and digital light synthesis (trademarked by Carbon, Inc.) [17]. These techniques use photosensitive monomer resin as a feedstock. The resin is held in a vat and a build plate is either submerged in the vat or inverted and in contact with the upper surface of the resin. A light source (often a laser) is used to induce polymerization of the monomer in the desired locations in the particular area. The build plate is then moved to allow resin to flow to the next layer and to expose the new layer to the light source. Sometimes a recoater blade is used to create an even layer of resin. The light source is then reapplied corresponding to the cross-section of the new layer, and the photopolymerization causes layers to bond together. This is repeated until the part is complete. A schematic for a vat photopolymerization system is shown in Figure 2.

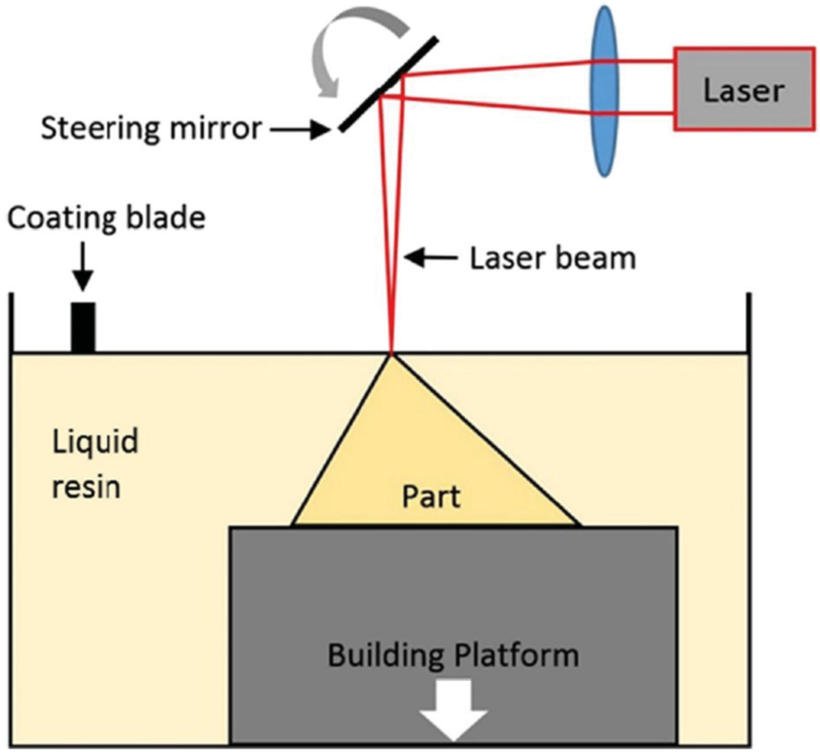

Figure 2: *Schematic of vat photopolymerization system [18]. This schematic shows the "right-side-up" configuration. In the "upside-down" or inverted configuration the part is drawn up from the vat as it is built and the light source is projected through the transparent bottom of the vat.*

Post-processing for vat photopolymerized parts is almost always required, involving more steps beyond simple support removal and surface finishing. This is because the build process does not fully cure all of the resin comprising the part. Post-processing involves washing the part in a solvent to remove any uncured resin, and then subjecting the part to a post-cure treatment consisting of elevated temperature and/or further light exposure. The upside of post-curing is that it tends to result in improved adhesion between the layers of the part and thus improved mechanical properties.

One of the defining characteristics of vat photopolymerization is the level of detail and precision that can be achieved. Because the resins are initially cured using focused radiation very small areas can be solidified and surface quality is excellent. Typical feature resolution and layer thickness is 25–100 µm; when layer thickness is below 50 µm the individual ridges between layers will likely not be visible to the naked eye [19]. The materials available are somewhat restricted, as they must photopolymerize relatively quickly and meet certain viscosity requirements (generally low viscosity, but not too low). There may also be certain requirements in optical transmissivity/absorptivity in order to be suitable for specific systems. Based on these restrictions, the most commonly used materials are epoxides and acrylates [19, 20].

Vat photopolymerization can also be used to manufacture ceramics in addition to polymers [21]. Slurries are currently on the market containing a range of ceramic particles in suspension in a photocurable resin. Once cured the material can be left as a composite or the polymer can be burned out and the resulting material sintered to form a solid ceramic component.

The strength of photopolymerized parts is somewhat hindered by the fact that low viscosity, fast curing resins are necessary. Nonetheless, mechanical properties are generally favourable compared to those associated with extrusion AM [20]. A range of ultimate strengths are possible, usually quoted by the manufacturers as < 100 MPa, as are elastic moduli. Anisotropy is also not an inherent feature of vat photopolymerization so long as a post-cure is performed; typically variation in properties between the X-Y and Z build directions is well within 10% [22, 23], and can even be so low as to be statistically insignificant [24]. It should be noted, however, that the mechanical properties of common photopolymers do tend to degrade over time [25], and so this degradation should be taken into account when deciding to place a part in service. Because of concerns about long-term durability, vat photopolymerization is used less frequently for the fabrication of production parts than material extrusion.

The pros of using vat photopolymerization in defence applications are related to the level of detail and surface finish achievable. Parts produced via this technique also have good mechanical properties and uncharacteristically low anisotropy for AM. Unfortunately, there are many drawbacks to this technology for defence use. The equipment is somewhat expensive, particularly compared to material extrusion. Post-processing adds further time and labour and generally involves solvents that need to be managed. Once all of the build and post-process equipment is accounted for, this technology can also take up a relatively large footprint. Both the equipment optics and the liquid resin are sensitive to external motion/vibration, meaning this technique generally requires a very stable operating environment. Finally, the long-term stability and durability of photopolymerized parts is a concern, making this technique not commonly used for production components.

Despite the drawbacks, vat photopolymerization is still seeing some defence use, with the equipment tending to be housed in domestic facilities rather than being deployed. SLA was in use by the U.S. Army as early as 1996 for the fabrication of prototype components for guided missiles [26]. The ability to fabricate new prototypes sped up the design and testing process. The most common uses today for this technology are the fabrication of prototypes, surgical models and custom surgical guides [10], and model ships and other components for experimental testing [11].

2.3 Material jetting

Although the term *3D printing* can refer to any of the AM processes, within the AM industry it often refers specifically to material jetting and/or binder jetting (see Section 2.4), as these techniques are conceptually similar to traditional 2D printing. The first commercial material jetting system became available in 1994 [16]. The ModelMaker, by Solidscape, Inc., used an inkjet print head to deposit wax materials. The resulting parts could be used as prototypes or, more commonly, for creating metal objects via investment casting.

Today's material jetting systems have improved upon the capabilities of the ModelMaker. Current print heads utilize Drop on Demand (DoD) technology, wherein heat and/or a piezoelectric actuator is used to eject individual droplets of material from each nozzle. Hundreds of nozzles can be incorporated into the print head, and systems are capable of depositing multiple materials in each layer [19]. Material jetting often uses photopolymers which are cured after deposition, giving increased strength to the growing part. Meanwhile, support material is used to fill the voids in each layer and to provide a substrate for the subsequent layer. This support material, which can be water soluble, is removed after printing to yield the final part geometry. A schematic for a popular material jetting system (PolyJet; Stratasys, Inc.) is shown in Figure 3.

Material jetting results in very good surface finish, high dimensional tolerance and high detail. Layer dimensions below 20 µm are possible with this technology [20], and so visually smooth surfaces are possible without further surface finishing. Post-processing involves removal of the support material, and this is done either by hand or through the application of heat or water/solvent depending on the support material. Generally parts made via material jetting do not require a post-curing process. One of the selling features of material jetting is the ability to deposit multiple materials in the same part. This multi-material capability means that the final part can have variable chemistry, colour, mechanical properties, etc. at different locations.

Materials suitable for jetting must have low viscosity at the print head temperature, and have adequate strength and thermal stability once deposited. Photopolymeric materials must also cure rapidly. Similar to vat photopolymerization, acrylates are common for material jetting, although epoxides are not commonly used [19]. While the exact formulations of each material are proprietary, there are available a range of materials with different strengths (generally ≤ 70 MPa) and rigidities. However, anisotropy is an issue with parts made by material jetting. Elastic modulus, elongation at fracture and ultimate strength can all be affected by build orientation [27], varying by as much as 30% [28]. Aside from the anisotropy, the mechanical performance of parts formed by material jetting can be viewed as similar to vat photopolymerization. While it is possible to create mechanically adequate parts, questions about durability and long-term stability make material jetting much less frequently used for production parts than material extrusion.

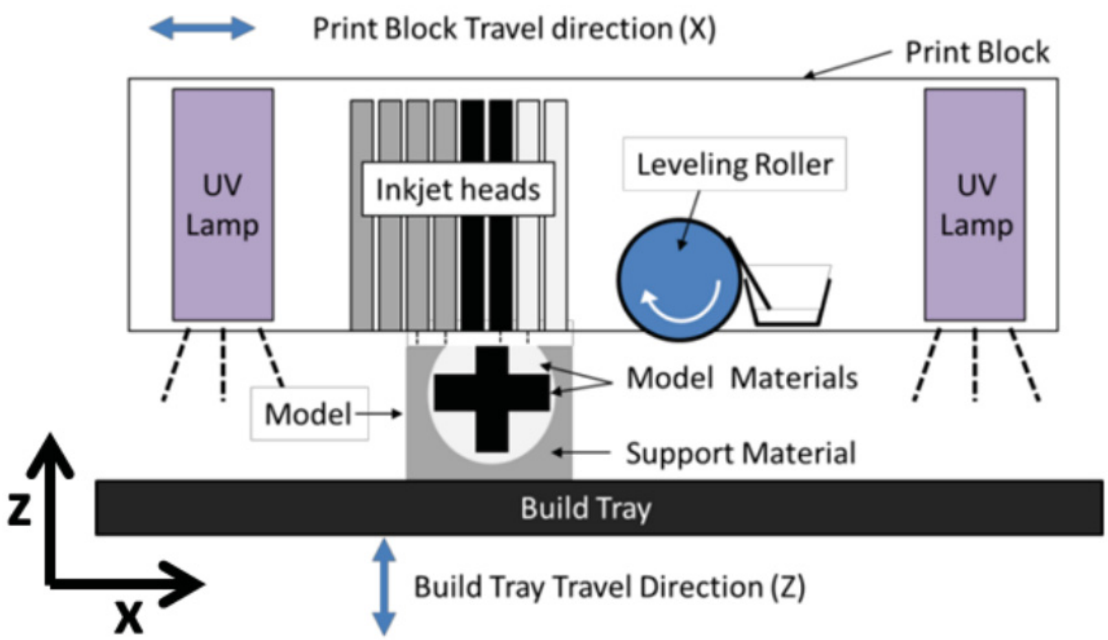

Figure 3: *Schematic of PolyJet process [27].*

Almost all of the materials used with material jetting systems are polymers/waxes. However, recently a new system was announced that is intended to print other materials, including ceramics [29]. This system, developed by XJet Ltd., deposits nanoparticles suspended in a volatile liquid. After deposition the liquid is rapidly evaporated causing the solid particles to remain in place. The particles are then sintered to consolidate the final part. The XJet system and its ceramic feedstock have only been announced at this time, and thus independent results have yet to be published. See Section 3.3 for more information on the XJet process.

Material jetting has several features that are attractive from a defence standpoint. It is relatively fast, and results in high precision and fine detail/surface finish. The process is also capable of printing a wide variety of materials with different properties, and these materials can be combined within a single part. This makes the technology very useful for prototyping. Furthermore, the process is potentially scalable, so that larger objects could be built without prohibitively long build times. Support removal and post-processing can require less labour than, for example, material extrusion. Finally, the feedstock material, being a liquid, has fewer handling and health and safety requirements than powder feedstocks. As for drawbacks, the print heads have finite lifespans after which they must be replaced. The process also requires support material to be deposited beneath all overhangs. This increases material costs and the amount of "wasted" material for a build. Mechanical properties of parts made by material jetting are variable depending on part orientation, and so parts often exhibit notable anisotropy. Long-term durability and stability of such parts is also a concern, and commonly these parts are not considered rugged enough for structural use. The ability to successfully build parts in an unstable environment via material jetting has not yet been tested.

Material jetting is not frequently discussed as an AM technology for defence purposes. Defence agencies, such as the U.S. Navy [10], are using material jetting systems, but there is a lack of published information regarding applications and case studies. It is likely that these systems are being used for prototyping, printing of surgical models and possibly the printing of positive models for investment casting of metals.

2.4 Binder jetting

Binder jetting is very similar to material jetting, as it also uses inkjet print heads. However, instead of jetting the final part material the print head deposits a polymeric binder onto a powder bed. Commercialization of this technology actually slightly predates material jetting, as the first binder jetting system began selling in 1993 [16].

A schematic of a typical binder jetting system is shown in Figure 4. A layer of powder is initially deposited on a build platform capable of vertical motion. A recoater is used for depositing and/or smoothing the powder to ensure a uniform layer thickness. Next, a print head with multiple nozzles traverses the powder layer, depositing a liquid binder material in areas that are intended to comprise the final part. This binder causes the local particles to stick together, either through solvent welding or physical adhesion [20]. Once the binder has been applied to the layer the build platform is dropped and a new layer of powder is deposited and smoothed. This cycle is repeated, resulting in the final geometry consisting of bonded powder.

After printing, the part is removed from the powder bed and the unbonded powder can be reclaimed, processed and reused for future builds. At this stage the part itself (which is often referred to as the *green body*) is relatively weakly bonded and contains significant porosity. To improve strength and density, the part is usually post-processed. This involves either infiltrating the interconnected pore structure with resin or sintering the particles together, depending on the powder material used [19].

In terms of resolution and accuracy, binder jetting tends to be somewhat better than material extrusion, but not as good as material jetting or vat photopolymerization. Layer thicknesses are usually around 100–150 μm and, since the technique uses a powder that is not melted, finished surfaces tend to be relatively coarse.

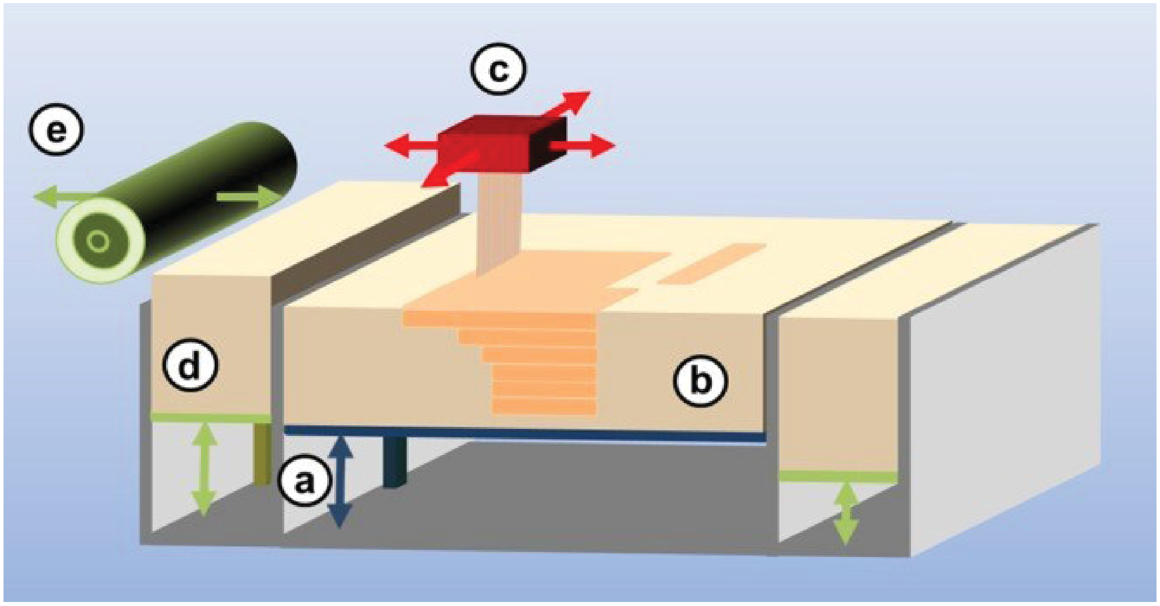

Figure 4: *Schematic of binder jetting system [19]; showing a) build platform with vertical motion; b) powder bed; c) inkjet print head depositing binder; d) powder feedstock; and e) recoater.*

In theory, binder jetting is amenable to virtually all types of materials, provided, of course, that they can be procured as powders. Since the process is conducted at low temperatures it is suitable for use with a wide range of polymers, including cellulose, carbohydrates and other biopolymers [19]. The main restrictions are related to the binder compatibility to both the powder and to the inkjet process. For jetting, the binder must meet similar viscosity requirements to material jetting feedstocks and must not have a tendency to clog the print nozzles. Alternatively, the binder can be contained within the powder bed and then merely activated by the jetting of a solvent [19]. This circumvents any nozzle clogging issues.

In reality, there are a limited variety of commercially available powder/binder combinations for binder jetting systems. The only widely available structural polymer is Polymethyl Methacrylate (PMMA). More commonly available are ceramics, such as gypsum, tungsten carbide, iron oxide and various silicates. These materials are typically used for visual prototyping or for the direct fabrication of casting moulds, as an alternative to traditional mould preparation for sand casting. Soda lime glass is also available, although it results in a porous, opaque and fragile solid after sintering.

Since powder particles are merely bonded together during binder jetting resulting green bodies tend to be brittle and with very low tensile strengths. The UTS of PMMA is advertised as < 5 MPa with elongation at failure typically below 1% [30]. Strength can be improved by infiltrating the porous part with epoxy, but only up to ~25 MPa. Other studies have also indicated that anisotropy can be relatively high [31]. Thus, the majority of non-metallic binder jetting parts are not considered strong or durable enough for functional use.

There is one exception to the preceding discussion about binder jetting materials and performance. In 2016, HP Inc. began sales of its Jet Fusion printers. These printers introduce some slight modifications to binder jetting, which are intended to increase printing speeds and reduce costs. These printers are advertised as capable of layer thicknesses as low as 70 µm [32]. Currently, the only materials available for these printers are polyamides, although it is intended that other materials will be available in the future. HP also intends for their next systems to be capable of full colour printing [33]. Parts made from the currently available polyamides are specified by HP as having tensile strength of 48 MPa and elongation at fracture of 15–20% [34], which is roughly comparable to parts made by material extrusion [35]. Although there is a lack of published independent test results to validate these claims, it is fair to assume that the Jet Fusion process will see increasing interest going forward.

The advantages of binder jetting are similar to those of material jetting. Printing speeds are relatively fast, and, being a low temperature process, it is theoretically amenable to a wide variety of materials. And while the powder material cannot be varied within a part, the binder material can. This can enable full colour printing, which is very useful when fabricating visual prototypes. One unique feature of binder jetting is that it is highly scalable. Print heads can easily (and relatively inexpensively) be made larger and contain more nozzles, which means that equipment can be tailored to very large builds without the process being prohibitively slow. The process also does not require dedicated and sacrificial support structures as the unbonded powder feedstock supports any overhangs in the final part. This unbonded powder can be reclaimed, to a large extent, after the build and can be used for future parts. The drawbacks to binder jetting relate mainly to the resulting physical properties. With the possible exception of HP's new system, non-metallic binder jetting parts tend to have quite low strength and ductility, and a coarse surface finish. While mechanical properties can be improved by resin infiltration or sintering, these processes add to the time and cost of part fabrication and there is still a limit to the strength that can be gained. Post-processing, in general, can also be a concern with binder jetting. Unbonded powder must be removed from parts, usually by blowing with compressed air, which is labour-intensive. The use of powder feedstocks presents health and safety concerns (i.e., inhalation and flammability/explosivity) that are not typical of solid or liquid feedstocks. The use of a powder bed makes this process likely susceptible to external motions/vibrations and so printing in an unstable environment would be questionable.

Binder jetting is seeing some exploration for defence purposes [10], but, like material jetting, there is little published information regarding specific uses and case studies. Published uses for binder jetting for defence purposes include the rapid fabrication of casting moulds [36, 37], which is described in more detail in Section 4.1. One example of direct fabrication with binder jetting is the use by Walter Reed National Military Medical Center for the fabrication of custom surgical guides [11]. The technique is used to print full colour models of patient anatomy, allowing for better surgical planning and ultimately reducing the time for surgery and healing. This type of application, requiring the quick, full-colour production of essentially prototypes, likely represents the typical defence usage of binder jetting. Additionally, it is probable that any experimentation into the printing of biopolymers, foods and drugs would also include binder jetting, although these topics are outside the scope of this report.

2.5 Powder bed fusion

As its name suggests, Powder Bed Fusion (PBF) relies on a bed of powdered feedstock, similar to binder jetting. However, rather than relying on chemical or physical adhesion, a focused heat source is used to fuse the particles together, through melting or sintering. The first PBF system was released in 1992 and used a laser to sinter the feedstock [16]. PBF processes for polymers are referred to by a number of names, including laser sintering, Selective Laser Sintering (SLS) and Selective Heat Sintering (SHS). Although the heat source can vary among these processes, the general features are the same. The schematic of Figure 5 shows the laser sintering process as an example of all PBF processes.

The powder feedstock is deposited on the build plate using a hopper. A recoater traverses the powder bed to ensure the surface is uniform and the layer height is consistent before the heat source is applied to the regions comprising the final part. After fusion of the layer has finished, the build plate drops down, more powder is applied and the process is repeated until the part is complete. During the build process the build chamber is sealed and the atmosphere controlled. Generally, the build plate/chamber is also heated to bring the feedstock temperature closer to the fusion temperature, reducing the amount of energy required to fuse the powder and mitigating thermal distortion.

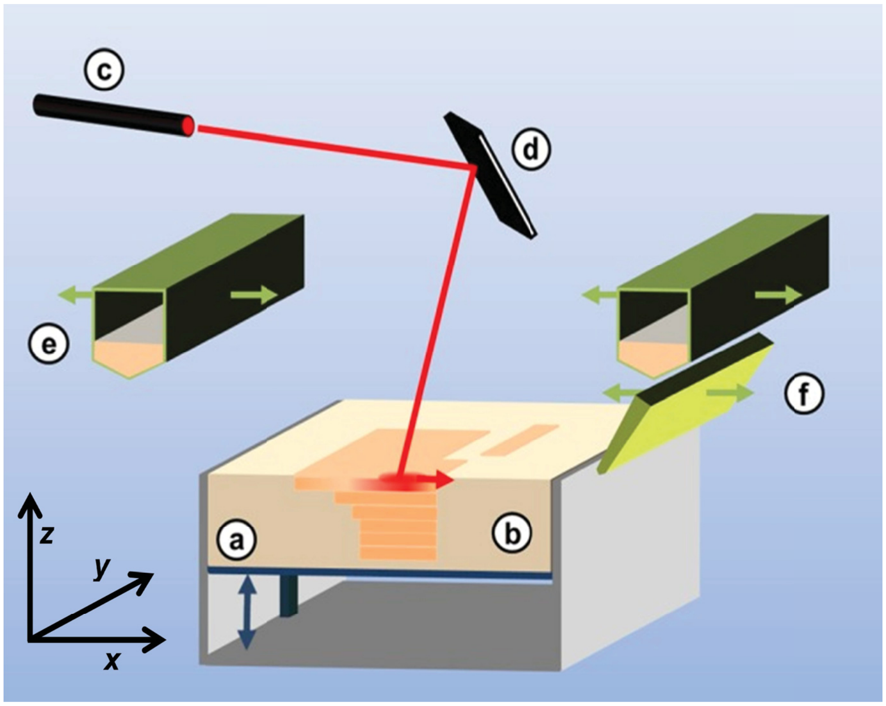

Figure 5: *Schematic of laser sintering process [19]; showing a) build platform with vertical motion; b) powder bed; c) laser; d) laser optics; e) powder feedstock; and f) recoater.*

The surface finish and resolution of PBF parts is generally related to the particle size of the feedstock powder [19]. Typically layer thicknesses are on the order of 100 µm, meaning that the layered structure of finished parts is visually evident. PBF is theoretically applicable to a wide range of thermoplastic polymers, but the vast majority of commercially available PBF polymers are polyamides [20]. For this material tensile strengths ≥ 50 MPa and elongations > 10% are achievable, which are similar to the properties of injection moulded parts [38]. PBF parts are thus often considered to have adequate strength and durability for structural use [19]. Other polymers that are available for PBF include ABS, polystyrene, polycarbonate, polypropylene and Polyether Ether Ketone (PEEK). As well, there is a range of polymer-matrix composite powders available.

PBF has been investigated for use with ceramic powders, with a variety of different approaches [39]. However, commercially available ceramics for PBF are very limited, with only silicates (i.e., sands) represented. These materials consist of resin-coated particles which are fused together to make sand casting moulds. They result in parts that are weak and brittle, and so not intended for structural parts.

Despite resulting in robust solid polymers, there are several features of PBF that tend to cause detrimental characteristics in as-printed parts. Because the feedstock used is a powder, there is a notable amount of void space within the powder bed. And since there is insignificant bulk material flow during processing this void space necessarily results in porosity in the finished product [19]. Post-processing, either through isostatic pressing, resin infiltration or bulk sintering, is required if reduction in porosity is desired.

Another issue with PBF is variability in the physical/mechanical properties of the resulting parts, either between those produced using different machines or even within the build environment of a single machine. Optimized parameters can vary from machine to machine, even when the same model of equipment is used [40]. Within a single machine, significant temperature variations have been noted in the powder bed, particularly at the corners/edges of the build plate versus the centre. The consequences of this variation in bed temperature depend largely on the material being used, with some materials being more sensitive to variations than others [41].

Even within individual parts mechanical properties resulting from PBF tend to vary. This anisotropy is a function of the layer structure of parts and of transient heat input variations occurring at laser start/stop locations [42]. The degree of anisotropy is statistically significant, although typically not as severe as results from material extrusion. Studies of SLS of polyamides have compared tensile samples built with the gauge length in the X-Y plane to those with the gauge length in the Z-axis (see Figure 5). Strength in the Z-direction has been shown to be roughly 15% lower than strength in X-Y direction [42, 43]. Elastic modulus and elongation to failure also vary based on build direction, but usually less than tensile strength. Ultimately the variability of PBF parts means that in order for production parts to have consistent properties they should be made on the same machine, in the same orientation, and at the same location within the build envelope.

For defence applications, PBF of non-metallics is attractive as it results in parts with relatively high strength and ductility. During the build, parts do not require support structures since the powder bed supports overhangs. The lack of support structures means that many parts can be packed onto the build plate, with only slight increase in build time, and means that post-processing to remove supports is unnecessary. On the other hand, PBF has several notable drawbacks. Mechanical property variations are very common, both within a single build volume and from machine to machine. The technique necessarily results in porosity, and so post-processing is required for improving density. Parts often require long cooling times before removing from chamber to mitigate distortion. The feedstock is powder, with all its health and safety issues. Despite the lack of dedicated support structures, not all feedstock can be reused since heating and/or partial sintering of powders tends to result in permanent changes in the polymer properties, such as its molecular weight [41]. PBF equipment is also relatively expensive, as are the powder feedstocks, and, because the systems use a focused heat source, energy consumption tends to be high for the building of a single part. The build envelope requires environmental stability in terms of ambient temperatures, motion/vibration and purging of the chamber with inert gas, which reduces the scalability of the process and typically imposes a practical limit on build size.

Although machine and feedstock costs are relatively high for PBF systems, this technology can be surprisingly cost-effective for relatively small production runs. Traditional injection moulding, although having a fraction of the equipment costs and as low as 3% of the material costs [44], requires the fabrication of expensive moulds. Mould costs thus dominate for small production runs. It has been estimated that, even when 5000 parts are required, SLS can reduce total costs by more than 80% compared to injection moulding [44], simply by not requiring a mould. In that particular analysis, injection moulding only became cost effective when more than 80,000 parts were required. Similarly, comparing SLS to the other AM techniques capable of producing functional parts (i.e., material extrusion and vat photopolymerization) shows that it tends to be the most cost-effective for production runs in the thousands of parts [45].

For these reasons, PBF has seen significant use by defence agencies. For example, the U.S. Naval Undersea Warfare Center Keyport has used SLS since 2002, and during the subsequent 12 year period they printed over 35,000 parts [10]. SLS has been explored for the replacement of non-flight critical aircraft parts, such as the under leading-edge root extension forward fairing fitting on the AV-8B Harrier II [46]. One of the most prominent uses of SLS is on the Boeing F/A-18E/F Super Hornet [47]. Each jet carries approximately 100 SLS parts in the air-cooling duct system. The Norwegian Armed Forces also have developed SLS capabilities in their production facilities for the rapid fabrication of new or replacement parts [14]. In general, defence uses for polymer PBF parts include custom tooling, test and production fixtures, and end-use parts [11].

2.6 Directed energy deposition

While Directed Energy Deposition (DED) could potentially be used with non-metallic materials, commercial systems are currently all designed for the deposition of metals. For this reason DED is not further discussed in this section. See Section 3.6 for a description of the DED process for metal deposition.

2.7 Sheet lamination

The idea of consolidating sheets of material into a solid was first commercialized in 1991 [16]. This process, called Laminated Object Manufacturing (LOM), is shown in the schematic of Figure 6. The general features of LOM and other sheet lamination processes are similar. The sheet feedstock is introduced to the build platform, and may be pre-coated, or even pre-impregnated, with an adhesive/resin or may be uncoated. When adhesive is present a heated roller or press is used to activate and bond the sheet to the previous layer. If no adhesive is present on the feedstock, it is deposited selectively using an inkjet print head prior to rolling/pressing. Next, the contours are cut into the layer, either through the use of a laser or a knife. Sometimes the waste area surrounding the part is cut into smaller sections to facilitate removal. It is also possible to use another inkjet print head to deposit coloured ink on the perimeter of the part layer, enabling the creation of full colour objects. Once the layer has been cut the build platform drops down and more feedstock is rolled over top, and the process of layer adhesion and cutting is repeated until the part is finished.

Sheet lamination originally was commercialized with paper as a feedstock. This resulted in wood-like parts that retained the moisture-sensitivity of paper [19]. Since then, the technology has been explored using polymers [48], polymer matrix composites [49], ceramic matrix composites [49] and structural ceramics [50, 51]. A system (Solido SD300) was previously commercially available that used Polyvinyl Chloride (PVC) sheet as feedstock. Today, there are only a few commercial sheet lamination systems on the market. Paper lamination systems are currently available from Mcor Technologies Ltd. EnvisionTEC Inc. unveiled a system in 2016 (the SLCOM 1) capable of using various fibre-reinforced composite sheets, and Impossible Objects Inc. also makes composite sheet lamination machines.

Mechanical test data of parts made by sheet lamination are not widely available. None of EnvisionTEC, Impossible Objects or Mcor Technologies specifies mechanical properties for their currently available materials. However, paper parts made using older LOM systems have exhibited tensile strengths of 75 MPa [52], which is similar to typical parallel-to-grain strengths of green softwoods [53]. Ceramic parts, after sintering, have exhibited strength, hardness and fracture toughness similar to those of traditional pressed and sintered ceramics [50]. Polymer matrix composites also have demonstrated properties approaching those of the traditionally-processed analogous material [49].

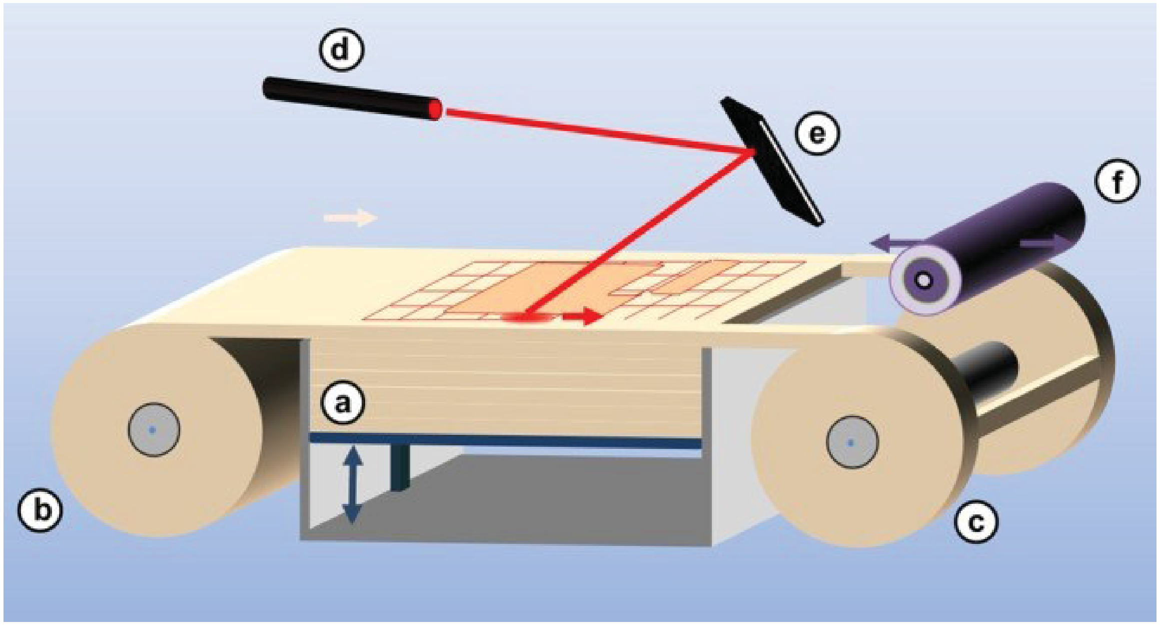

Figure 6: *Schematic of LOM [19]; showing a) build platform with vertical motion; b) sheet feedstock; c) collection of waste material; d) laser; e) laser optics; and f) roller.*

From a defence perspective there are a few advantages to sheet lamination. The technique uses sheet feedstock, which tends to be less expensive and have fewer health and safety issues than powder. Support structures are not required (since each layer is always supported by the layer below), and so time is not spent building or removing them during post-processing. When fabricating paper objects the technique is capable of full-colour printing, and paper systems tend to be small and can fit and be operated on a desktop. However, there are some significant drawbacks to sheet lamination. Finish and accuracy tend to be relatively low, and, although support structures are not needed, any material not incorporated into the final product typically cannot be reused. The technique thus can result in significant waste. Breaking the part out from this waste can also be time-consuming, although likely not as much as manual support removal when using other AM techniques. Paper systems suffer from random dimensional error related to moisture absorption and swelling of the sheet [54], and even finished paper parts often require sealing after fabrication to prevent warping. Other materials also typically require further processing to improve mechanical properties.

The U.S. military has looked at fabricating ceramic and polymer matrix composites via LOM for aerospace use [55, 56]. LOM has also been explored by the U.S. Navy for the fabrication of acoustic transducers [57]. No work has been published yet, but it is possible that the ability to fabricate fibre-reinforced composites will see exploration, for example for the fabrication of unmanned vehicle bodies.

2.8 Summary

Table 1 summarizes the advantages and disadvantages of each of the AM techniques for fabricating polymer parts. Only the advantages and disadvantages that are particularly notable compared to the other techniques are given, and so empty cells can be considered as indicating that the technique is neither the best nor the worst at exhibiting the specific characteristic. In formulating Table 1 each technique was considered in general, rather than focusing on specific systems in each category. As such, there is some subjectivity to the summary, since it is difficult to precisely average out the characteristics of many different systems within the same classification. For a more nuanced understanding of the advantages and disadvantages of whole categories or specific outliers within the categories, the reader is directed to the text in each of the preceding sections.

Table 1: *Summary of advantages and disadvantages of AM techniques for non-metallic part fabrication. Green check marks signify notable strengths and red exes particular weaknesses relative to the other techniques.*

		Material Extrusion	**Vat Photopolymerization**	**Material Jetting**	**Binder Jetting**	**Powder Bed Fusion**	**Sheet Lamination**
Process Characteristics	Low Equipment Costs	✓			✗	✗	
	High Build Rate				✓	✗	
	Fine Surface Finish		✓	✓			✗
	Capable of Locally Varying Material Composition			✓			
	Minimal Post-Processing		✗	✓	✗		
	Highly Scalable		✗		✓		
	Low Material Waste				✓		✗
Feedstock	Low Material Costs	✓		✗			✓
	Easy/Safe Handling and Storage				✗	✗	✓
	Wide Range Available	✓			✗		
Part Performance	Stable/Durable Long-Term Properties	✓	✗	✗		✓	
	Low Anisotropy	✗	✓				✗
	High Strength/Ductility				✗	✓	
	Ability to Locally Tailor Properties Within Part	✗		✓			✗

3 Direct AM of metallic materials

AM is most well known as a method of producing a part in a single step, without the need for moulds, jigs, tools, fixtures, etc. This approach, which can more specifically be referred to as *direct* AM, is discussed in this section. Here, direct AM refers to all instances where (more or less) the desired geometry is produced directly from a desired material.

The organization of this section follows that of Section 2, with each category of AM technique discussed in a separate subsection. Typically the mechanisms of each technique are not described, unless they vary significantly from the non-metallic case. The mechanism for each technique can therefore be found in the corresponding subsection of Section 2. A summary of the advantages and disadvantages of direct AM techniques for metals is included in Section 3.8.

3.1 Material extrusion

In the past few years several suppliers have begun to make available standard polymer filaments loaded with metal powders, enabling the fabrication of metal parts using standard material extrusion systems. When using these filaments the build process is essentially the same as for non-metallic parts (see Section 2.1). However, once extrusion is finished the part is heated in a furnace, first to burn off the polymeric component and then to sinter the remaining metallic particles.

Alloys available in filaments for traditional material extrusion systems commonly include stainless steel, copper and bronzes. The amount of metal powder contained in a filament can vary. For example, Ultrafuse 316LX (BASF SE) has ~80 wt. % [58], while Filamet (The Virtual Foundry LLC) is commonly quoted as having > 90% [59]. In theory higher metal content should yield better parts, provided the metal loading is not so high as to inhibit the flowability of the molten filament. There are other filaments with lower metal loading and these are typically aimed at the hobbyist who wishes to have the weight and/or appearance of metal in their printed objects, as low metal-content filaments are less likely to lead to dense, sound parts after sintering.

Because these filaments are relatively new, there is a lack of published data on the performance of as-sintered parts. BASF's internal testing suggests that sintered material can have a density up to 99% of the wrought alloy, with similar ultimate tensile strength [58]. Yield strength, however, can be significantly lower than that of the wrought alloy. At this time metal parts made with the BASF filament do not yet have properties that rival those of other metal AM techniques, such as PBF. It is also unclear how the properties of as-sintered parts vary with orientation, as material extrusion is known to lead to notable anisotropy in non-metallic materials.

Alternatively, there are two material extrusion systems recently available that are specifically designed for metal part fabrication. Both systems use fluid debinding, wherein the polymeric binder is dissolved away from the metal particles, rather than the thermal debinding required for aftermarket metal-loaded filaments. Desktop Metal, Inc. is taking reservations for what they call the "Studio System," while Markforged, Inc. started shipping their Metal X system in late 2017. Both systems offer similar build envelopes (300 x 200 x 200 mm for the Desktop Metal, 200 x 200 x 250 mm for the Metal X), and have similar total equipment costs despite slightly different features. The Desktop Metal system can be purchased with the debinding system and a sintering furnace for a total suggested retail price (SRP) of $120,000 USD [60], while the printer alone has an SRP of $49,900 USD. Unlike the Desktop Metal system, the Metal X system includes a built-in 3D scanner for dimensional quality assurance of the finished part, pushing the printer price to an SRP of $99,500 USD [61]. However, the Metal X system has a similar SRP of $124,480 USD when the debinding equipment and base sintering furnace are included. These equipment costs are worth noting as they are considerably lower than other metal AM systems, which typically run into the high hundreds of thousands, or even millions, of dollars.

The alloys offered for these systems are currently limited. Desktop Metal offers stainless steel (17-4 PH and 316L), Inconel 625, steel (4140 and H13) and pure copper. It does not appear that mechanical properties for any of these feedstocks are currently available from Desktop Metal or from third parties. Meanwhile, Markforged only offers stainless steel (17-4 PH and 316L) as proven feedstocks, although aluminum (6061 and 7075), Inconel 625, tool steel (A-2 and D-2) and Ti6Al4V are currently advertised as in the "beta" stage. Markforged's preliminary data indicates that 17-4 PH stainless has a relative density of ≥96% after printing, debinding and sintering, and UTS of ~96% of that of wrought material [62]. However, yield strength is only ~83% that of wrought, and elongation only 4–6% compared to 16% for wrought. There also appears to be no independent verification of this performance, and there is no indication of degree of anisotropy or fatigue/fracture properties that can be expected.

Nonetheless, material extrusion is attractive for metal part fabrication for the same reasons as it is for non-metallics. Extrusion systems are inexpensive and have relatively simple operating mechanisms. Furthermore, containing the metal particles in a polymer filament overcomes some of the issues inherent to storing and working with powders, such as the dangers of inhalation and chemical reaction/combustion. This could reduce the need for support equipment for dust filtration and feedstock storage, perhaps making this technique more suitable for AM in the field. Finally, extrusion has the potential to fabricate totally sealed, hollow structures, although in practice the need for pathways for polymer burnout/dissolution may pose some limitations on build geometry. In general, other techniques require some means of removing loose material from within cavities and so can be more limited in terms of internal geometries. The drawbacks to metal extrusion AM include the need for post-build debinding and thermal processing and the potential for reduced mechanical performance. Parts need to undergo a burnout/dissolution treatment and then sintering in a furnace, and this requires extra equipment, space, time and energy. Furthermore, the removal of the polymer will tend to leave porosity in the final part. Reducing this porosity may require the use of further treatment such as Hot Isostatic Pressing (HIPping). Although the data is unavailable, it is possible that as-sintered metal extrusion parts will exhibit similar anisotropy to non-metallic parts made using the same process. This technique is also unlikely to be suitable for part repair because of the shrinkage that occurs during debinding/sintering. Finally, post-processing would likely be labour-intensive, as support structures often require manual removal.

Since material extrusion for metallic components is a relatively recent development there is a lack of published information regarding its use for defence applications. However, given the wide uptake of material extrusion by defence agencies for non-metallic parts, exploration for fabrication of metallic parts is very likely for the near future.

3.2 Vat photopolymerization

Vat photopolymerization, as described in Section 2.2, has been explored for use in fabricating metal parts. The basic principle has been understood for some time [63]. Essentially, the process would use a paste of metal particles in a photosensitive resin, and light application would cure the resin as in traditional vat photopolymerization. After the build, parts would then be subjected to debinding and sintering heat treatments.

Metal/resin pastes have been developed to some extent, for example using stainless steel powders at a solids loading of ~60 vol. % [64]. Titanium pastes are also in development [65]. However, as of today there are no pastes or dedicated equipment on the market for creating metal parts via vat photopolymerization, and it is unclear when the technology will be commercialized.

The pros and cons of using vat photopolymerization to make metal parts are theoretical at this point, since no workable commercial system exists. The hope is that the attractive features of traditional vat photopolymerization can be maintained while creating a metal part. These include the capability for fine detail, high surface finish and low anisotropy. Also, compared to other traditional metal AM techniques, vat photopolymerization would almost certainly involve cheaper equipment. And, just as for metal material extrusion, surrounding the metal particles in a paste has the added advantage of reducing the health and safety issues of working with powders. On the other hand, parts needing high density and decent mechanical properties would require debinding/sintering heat treatments, and perhaps further processing (i.e., HIPping) to reduce porosity. This adds to the labour, time, energy costs and footprint of the AM process. This technique is also unlikely to be useful for part repair, because of the shrinkage associated with debinding and sintering. Support material removal may also require notable labour.

3.3 Material jetting

There are two approaches to using material jetting to fabricate metal parts. The first, which is very similar to material jetting of non-metallics (see Section 2.3), involves melting the feedstock prior to jetting. The idea behind this approach dates back to the early 1970s [66], and was originally intended for depositing low-melting-point solder for electrical connections. By the 1990s the idea was expanded and began to be explored for the creation of structural parts. Today, the jetting of molten metal has still yet to be fully commercialized, although there are two experimental systems that have been produced. The first was the result of a joint venture between The University of Nottingham and Canon-Océ. Called Metaljet, it uses DoD technology to deposit drops of metal at up to 2000°C [67]. At this stage it appears that the system will be used for fundamental research and not for commercialization. The second system, the MK1 (Vader Systems LLC), is purported to be at technology readiness level (TRL) five, and a beta system has been released for purchase [68]. It currently uses aluminum wire as feedstock, although it is capable of depositing other molten metals at temperatures up to 900°C. The minimum droplet size is 300 μm, and so, even though the molten metal does flow somewhat after deposition, finished objects tend to have relatively coarse layers. Further information, such as how support structures are built, resulting mechanical properties, anisotropy, etc., is not available at this time.

The second approach to material jetting is to print a metal particle suspension at relatively low temperature. As mentioned in Section 2.3, XJet Ltd. is commercializing this approach in a technique referred to as nanoparticle jetting [69]. Here, metal nanoparticles dispersed in a volatile suspension are jetted onto a heated build platform. Once the drops are in place the solvent evaporates, leaving behind weakly consolidated metal particles. Sintering is then used to densify the particles and give strength to the final part. XJet claims that the support material, which is also deposited as a nanoparticle suspension, can be removed automatically and with very little labour. The exact support composition and removal mechanism have not been confirmed, but it appears that the material will be water/acid soluble or otherwise capable of burnout prior to sintering [70]. The first XJet system shipped in late 2017, and there is a lack of published data, either from XJet or third party, about the performance of parts created using this technique.

While the exact capabilities and limitations of commercial metal jetting systems are not yet widely known, it is still possible to comment on the potential pros and cons of this technique. There are indeed many attractive features. First, like material jetting of non-metallics, when optimized metal jetting should result in high precision and fine surface finish. Molten metal jetting could be used to deposit multiple alloys at precise locations within a part. The XJet process may also be capable of this, but the sets of compatible alloys may be restricted to those with similar sintering parameters. In either case, the use of wire or liquid suspension feedstock would pose less of a health and safety concern than metal powder, and wire feedstock has the added benefit of being relatively inexpensive. Support removal for the XJet process is also touted as requiring minimal labour. Molten metal jetting is likely capable of part repair as well as fabrication, and this may also be the case for nanoparticle jetting, as the use of nanoparticles should result in low shrinkage even though sintering is required. As for drawbacks, the nanoparticle suspensions used by the XJet system will likely be expensive compared to wires, sheets and possibly even traditional metal powders. Initial feedstock selection will also likely be limited. Support removal for molten metal jetting could require similar labour to that of material extrusion, while sintering of XJet parts also adds time, energy and equipment requirements. These technologies also lack an established marketplace with multiple competitors, meaning that equipment costs may be artificially high for the foreseeable future.

Considering metal jetting systems are either in the beta stage or have just recently shipped, it is unlikely that these technologies will see significant defence use in the near future. However, as the techniques mature and more data become available this approach may prove very attractive for the fabrication and/or repair of defence components.

3.3.1 Cold spray

Cold spray is a technique not inherently covered by any of the ASTM AM categories, but is nonetheless an intriguing AM approach. The technique, also known as cold gas dynamic spraying, already has a certain level of acceptance for defence purposes [71]. Since it has some process similarities to material jetting (and also to DED), the application of cold spray techniques to AM is discussed here.

Cold spray involves the acceleration of metallic powders to very high velocities using compressed gas [72]. A schematic of the process is shown in Figure 7. The gas is preheated and forced through a “DeLaval” converging-diverging nozzle, and as it exits the throat of the nozzle it expands, reducing in pressure and temperature and becoming accelerated to supersonic velocity. Metal particles with diameter ranging from 5–100 µm are injected into the gas stream either upstream or downstream of the nozzle throat. These particles are accelerated by the gas stream out of the nozzle, where they impact, deform and bond to a substrate. Because the temperatures involved are relatively low (i.e., < 100°C beyond the nozzle throat) compared to the melting points of metals the process is described as “cold.”

The bond formed between metal particles and substrate (and between particles and previously deposited material) does not involve melting of any material. Instead, the high velocity of the impacting particles causes them to splatter on the surface, inducing a solid-state bond. For a given powder there is a critical velocity required for adequate deformation of the particles to allow intimate contact with the substrate. Harder materials therefore require higher spray velocities or the addition of a softer secondary material that can deform at the applied velocity.

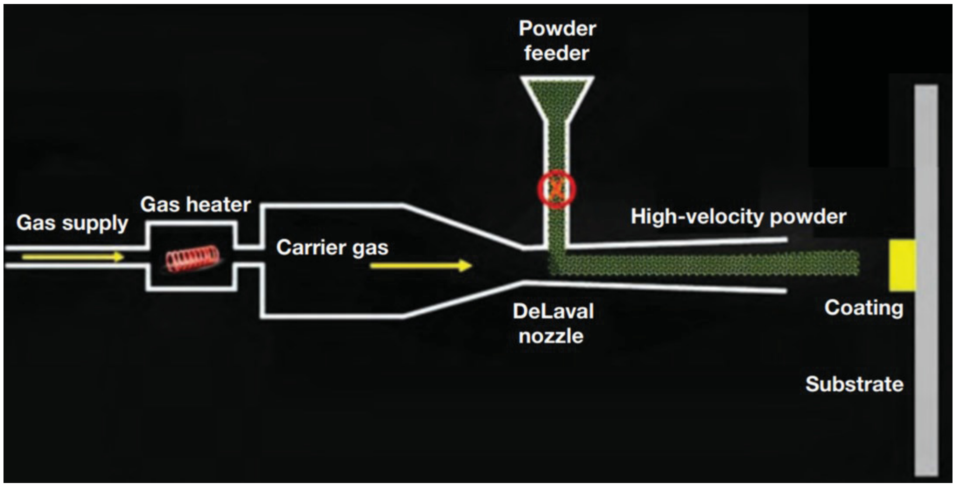

Figure 7: *Schematic example of cold spray process [73].*

Traditionally, cold spray has been used to deposit material in applications that are particularly sensitive to high temperatures [73]. These include dimensional restoration of bearing surfaces, deposition of metal onto non-metallics or the deposition of corrosion protective coatings on heat-sensitive surfaces. However, by combining cold spray with a positioning system (either capable of moving the substrate or the cold spray apparatus) this technique can be used to fabricate three dimensional shapes.

Presently, there are no commercially available, dedicated cold spray AM systems. Instead, the technique has been explored at the Research and Development (R&D) level for use with alloys including those of titanium [74, 75], aluminum [76], zinc [77], nickel [78] and others. Additionally, cold spray for the traditional application of coatings has proven amenable to deposition of a wider range of alloys, including copper and stainless steel [72, 79]. However, it should be noted that the results of cold spraying different alloys can vary significantly, as certain alloys are more suitable for the process than others. Soft alloys, like copper, are ideal for deposition, while higher strength materials, including the iron-based alloys, are more difficult to deposit.

One other aspect of the technique that limits its attractiveness for AM is its accuracy/resolution. The width of a single cold spray pass is typically between 2–12 mm [71, 72]. This means that the process is not particularly accurate (relative to other AM techniques), and so parts fabricated via cold spray would almost certainly require post-process machining to meet dimensional requirements. This could limit the capabilities of cold spray AM, for example in the fabrication of parts with hollow internal structures.

Data on the bulk mechanical properties of cold spray deposits are limited in the literature, as the bond strength to the substrate is more typically studied. The information that is available indicates that, in general, deposits formed via cold spray are of high density and low porosity [72]. Because the particles undergo plastic deformation upon impact with the substrate, the strength of deposits tends to be high. In some cases the as-sprayed strength of deposits surpasses that of equivalent wrought material [80, 81], but this is not necessarily always the case [78, 82]. However, either owing to the plastic deformation or to linear defects between particle "splats," ductility of deposits in the as-sprayed state is commonly very low. Consequently, heat treatment is often required in order to improve ductility, which is usually accompanied by a reduction in tensile strength.

When a linear spray pattern is employed (i.e., the material is deposited by moving the spray nozzle back and forth over the substrate) significant tensile anisotropy can result. The difference in strength parallel to the substrate surface versus perpendicular has been measured as anywhere from 21% [78] to 45% [82]. Modification of the spraying pattern, however, shows promise for reducing the mechanical anisotropy and encouraging more uniform behaviour in each direction [83]. Post-process heat treatment also can be effective in reducing the anisotropy in tensile properties [78]. The current state of knowledge therefore suggests that mechanical anisotropy may or may not be an issue with cold spray AM, depending on process particulars.

Cold spray has several attractive features for defence applications. It is a relatively low temperature process, meaning that it results in no phase changes, low oxidization, low residual stress and distortion, and is amenable to dissimilar metal joining and joining of metals to polymers/ceramics. The technique is capable of relatively high deposition efficiency/rate, and is highly scalable, as it does not require a hermetic enclosure. Perhaps most importantly, military standards exist governing cold spray for coating and/or dimensional restoration [71]. The technique is capable of part manufacture and repair of 3D surfaces. On the other hand, cold sprayed materials typically have inherently low ductility, and so post-process heat treatment is often required. The technique is only a near-net forming method, which means that post-machining is necessary to achieve final geometry. There is a potential for limited material feedstocks (i.e., those with low hardness), however with further process development these limitations may be overcome. Although an enclosure is not necessary, some type of containment is usually used for health and safety reasons and to collect over-sprayed material for reuse. Finally, because spray patterns are relatively wide, it may be difficult or impossible to form certain structures, such as fine hollow lattices.

Cold spray has seen notable defence use for repair of damaged structures. The U.S. Army Research Laboratory (ARL) has developed a procedure for the repair of corrosion and mechanical damage to aluminum (alloy 7075) mast supports for army helicopters [84]. The technique has also been used for repairs to other aluminum and titanium components on the UH-60 helicopter and B-1 bomber, respectively, and, in collaboration with the Royal Australian Navy, ARL has also implemented cold spray repairs to magnesium components on the SH-60 helicopter [85]. All of these applications have been thoroughly qualified and the repaired aircraft have subsequently seen extensive use.

3.4 Binder jetting

Binder jetting of metal parts was first commercialized in the late 1990s [16]. The process is roughly the same as for non-metallic materials (see Section 2.4), the only difference being that metal parts can be heat treated after printing to burn off the binder and then to sinter the remaining metal particles. Alternatively, the part can be infiltrated with a different, lower melting point alloy to increase strength and/or toughness of the part.

There is a limited variety of metal alloys available that are specifically intended for binder jetting. ExOne Co., the biggest seller of metal binder jetting machines, offers stainless steels (Grades 420, 316, 316L, 17-4PH), Inconels (Grades 625 and 718), M4 tool steel, bronze-infiltrated iron, cobalt chrome and iron-chrome-aluminum [86]. Höganäs AB, another manufacturer of metal binder jetting machines, offers stainless steel (Grades 316L and 14-4PH) and titanium (Ti6Al4V) [87]. Third-party suppliers of binder jetting powders are limited to bronze-infiltrated stainless steel [88]. It can also be possible to use powders not specifically designed for binder jetting, although it would be up to the end-user to develop the processing parameters (i.e., binder chemistry, layer thickness, binder saturation, etc.) and heat treatment used for each powder. If this route is taken, then a variety of steel, stainless steel, aluminum, nickel, copper, cobalt and titanium alloys are available. As discussed in Section 2.4, HP Inc. intends to expand the capabilities of their Jet Fusion systems in 2018, including enabling metal printing [33]. The exact alloy(s) have not yet been announced, but it is likely that there will only be limited offerings to begin with.

In general, the strengths of sintered metal parts made by binder jetting can be expected to be lower than those of the corresponding wrought alloy. As an example, Table 2 shows the advertised properties of Inconel 625 produced using various AM techniques as compared to wrought, weld and cast metal. Binder jetting parts undergo significant thermal treatments and so this tends to result in a coarse microstructure with reduced strength [89]. HIPping increases part density to near full and improves the UTS and elongation, but still does not give strength levels as high as the wrought or welded material. Rather, the performance of the binder jetting material is more similar to that of cast metal.

Fatigue and fracture properties of binder jetting parts are lacking in the literature. However, it is likely that these properties are related to the extent and shape/distribution of porosity in the part, as is known to be the case for powder metallurgy [90]. In general, increased porosity tends to reduce fatigue performance and toughness, with surface porosity and non-spherical pores particularly detrimental. The porosity in a finished binder jetting part is a function of the green part density and the sintering response, which in turn are driven by the average particle size, particle size distribution and the binder jetting parameters [91–93]. The fatigue and fracture properties are therefore likely variable depending on the exact powder and process used.

With regards to part orientation, binder jetting tends to result in low anisotropy after either sintering or infiltration is performed [91, 94]. Since non-metallic binder jetting parts can have relatively high anisotropy [31], it appears that any differences in binder distribution can be overcome by heat treatment. Indeed, when developing a sintering schedule it is important to ensure that the resulting properties and shrinkage are consistent in each direction, since sinter response can vary with orientation [95].

In summary, metal binder jetting has several advantages. It is a relatively fast process for metal printing and the equipment is inexpensive. It is highly scalable, since a larger number of nozzles can be added to a print head without excessive increase in cost. Furthermore, the process does not use significant heat and so does not require a controlled atmosphere. This means that the process tends to result in low distortion and anisotropy of the as-printed part and is more amenable to fabricating large parts. Also, loose powder acts as a support structure for the growing part and is generally reclaimable and reusable, reducing material waste. On the other hand, metal parts fabricated using binder jetting require significant post-processing. Unbonded powder must be removed from the finished part (typically manually with blown compressed air) and parts undergo oven-curing, debinding, sintering and/or infiltration treatments. This post-processing adds considerably to the labour, time, equipment and energy costs of manufacturing, and the use of metal powders presents health and safety concerns. Mechanical properties of the sintered/HIPped part tend to be notably poorer than all but cast material, and the process is not suited to part repair.

There is a lack of information about the use of metal binder jetting for defence purposes. To date, the U.S. Navy has preferred to use PBF processes for the fabrication of small metal components [10], likely due to the improved mechanical properties and wider alloy selection available. And since binder jetting results in properties similar to cast metal, in most cases fabrication of larger metal components has instead used indirect AM techniques such as the production of casting moulds (see Section 4.1).

Table 2: *Advertised properties of Ni 625 (UNS N06625/N46625) fabricated using binder jetting and other laser-based AM techniques. Typical properties of wrought and weld metal are shown for comparison (all values at room temperature).*

Fabrication Process	Supplier	Material State	UTS (MPa)	Yield Strength (MPa)	Elongation (%)	Density (%)	Ref.
Binder Jetting	ExOne	Sintered	676	290	51	97%	[94]
		HIPped	717	290	57	~100%	
Powder Bed Fusion	3D Systems	As printed	1040	770	22	99.9%	[96]
		Stress relieved	1110	750	19		
	EOS	As printed	990	725	35	99.5%	[97]
		Stress relieved	1040	720	35		
	Renishaw	As printed	1055	767	34	99.8%	[98]
		Annealed	1020	633	39		
	SLM Solutions	As printed	961	707	33	-	[99]
Directed Energy Deposition	Optomec	As printed	938	584	38	-	[100]
Wrought plate	-	As rolled	827–1103	414–758	30–60	-	[101]
Weld metal	-	As welded	760	-	30	-	[102]
Cast metal	-	As cast	710	350	48	-	[103]

3.5 PBF

PBF processes (see Section 2.5) are the most widely used for metal AM [104]. The techniques go by various trade names, including Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), laserCUSING, Laser Metal Fusion (LMF) and Electron Beam Melting (EBM) [104]. As the names suggest, metal PBF systems can use lasers or electron beams as heat sources, and there are some key differences between laser PBF and EBM. Lasers are lower power and so tend to result in better surface finish, while electron beams lead to higher productivity. The layer thickness is also typically larger for EBM (50–200 µm) than for laser PBF (20–100 µm), reflecting the difference in power level [104]. EBM is conducted with a relatively hot build chamber (i.e., from 700–1000°C, versus ~100°C for laser PBF), which tends to reduce residual stresses in the as-built part [105]. Finally, laser systems use a sealed chamber purged with inert gas to prevent oxidation of the growing part, while in EBM the chamber operates at low vacuum (i.e., $< 10^{-2}$ Pa) as the presence of gases tends to deflect the electron beam [106].

There are notably more alloys available for laser PBF than for EBM. This may be because EBM has a greater number of process parameters, making it more difficult to optimize the parameters for each new powder [89], or may be because there are many more manufacturers of laser PBF systems (over a dozen) than EBM (just one) [107]. Today, EBM materials are limited to titanium (Grade 2 and Ti6Al4V), cobalt-chrome and Inconel 718 [108]. Meanwhile, powders for laser PBF include various alloys of aluminum, titanium, iron, nickel, cobalt and copper [89]. Just as for binder jetting, there are also powders available from third-parties, but these would require the end-user to optimize processing parameters.

Advertised mechanical properties of laser PBF parts often promise strength at the high end of what is achievable for wrought material. As an example, Table 2 shows the properties of Inconel 625 as advertised by four laser PBF companies compared to typical wrought, weld and cast metal properties. Of note in the table is the fact that stress-relieved laser PBF parts have higher UTS than as-built. This highlights the tendency for this technique to result in tensile residual stresses in the as-built part. Indeed, if not addressed the development of thermally-induced residual stresses can lead to distortion, cracking or detachment of the growing part from the build plate [109]. This means that in a typical build significantly more support material is required to constrain each part than is necessary for polymer PBF. In Table 2 it can be seen that the ductility of laser PBF parts can be very favourable compared to that of wrought material. However, this feature can be very alloy-specific. For example, ductility of as-built Ti6Al4V tends to be low [110], and so post-processing generally must be used to improve ductility to acceptable levels.

Since EBM uses a much hotter chamber, material cooling rates are lower than for laser PBF. Thus EBM materials (not shown in Table 2) tend to have lower strength than laser PBF, although still comparable with wrought material [99, 111]. And, as noted, residual stresses tend to be much lower than laser PBF. For this reason EBM parts often do not require the same support scaffolding as laser PBF, although sometimes it is necessary to include sacrificial structures to improve heat flow to the build plate.

EBM parts tend to exhibit microstructural anisotropy, including elongated grains in the Z-direction [112] and variation based on the height of the build [113]. The first feature is an indication of directional solidification, while the second is understood to be a function of the amount of time each layer spends at elevated temperature. Layers closer to the bottom of a part spend more time at elevated temperature than those at the top, leading to differences in microstructure. These variations have led to the strength in the Z-direction being notably different from that of the X or Y directions. For Inconel 718, the as-built UTS has been measured as roughly 10% higher in the Z-direction than X-Y [113–115]. Conversely, Ti6Al4V samples have been measured as ~10% stronger in the X-Y plane than in the Z-direction in one study [116], and of equivalent strength in each direction in another [117]. In all of these studies, yield strength and elongation at fracture have also been shown to vary widely depending on orientation, material and processing parameters. It has been proposed that some of these variations may be due to porosity differences rather than purely depending on microstructure [113, 118]. Regardless of the causes, the literature suggests that the anisotropy of EBM parts is not completely predictable and so it is important that any change in orientation be verified to ensure that a given part has the desired performance.

Likewise, in laser PBF, columnar grains in the Z-direction are common and anisotropy can be variable depending on the powder, system and processing parameters used. For example, laser PBF of Ti6Al4V has shown varying degrees of anisotropy, such as the strength in the Z-direction being 5–20% lower than in X-Y plane [119–121], or, conversely, up to 9% higher than in the X-Y plane [121]. Variations in ductility can also be drastic, for example with elongation at failure varying from 7.6% in the X-Y plane to only 1.7% in the Z-direction [122]. There is some evidence that the variability in ductility relates to the number of number of layers used to construct a sample, with a greater number of layers having reduced ductility [120]. Ultimately, like EBM, the relationship between part orientation and performance is complicated, and so it is important to test all production orientations before laser PBF parts can be deemed suitable for use.

Besides the orientation, the location of a part in the build chamber can also affect its microstructural and/or mechanical properties. As discussed in Section 2.5, properties of polymer PBF parts can vary depending on where that part is situated due to variations in the powder bed temperature distribution, particularly when parts built near the centre of the bed are compared to these built near the outer edge. However, for metal PBF this variability is generally relatively low compared to the anisotropy that can result from part orientation [123]. For example, during EBM the location on the build plate resulted only in a slight difference (≤ 2%) in tensile properties [117], while for SLM the location on the build plate has led to UTS variations of around 3% [124].

The fatigue and fracture performance of metal PBF parts can vary based on build orientation [116] and vertical location in the build chamber [125], too. In some situations these differences are likely related to residual stresses, as the variation can disappear after a stress-relieving heat treatment [119]. Fatigue and fracture properties are also greatly affected by the presence of fabrication defects and porosity, which can be distributed differently in each direction [110]. High cycle fatigue in wrought material is usually dominated by the crack-initiation phase, so the presence of crack-like defects/porosity in as-printed parts tends to reduce fatigue strength to well below that of wrought material [126]. In fact, when present in significant amounts these discontinuities have decreased fatigue strength by up to 75% [121].

Post-processing operations can be effective in improving mechanical performance, although at the cost of increased labour. HIPping is one technique commonly used, as it reduces porosity, which improves strength, ductility and fracture/fatigue performance [110]. The reduction in porosity can also reduce the variability in properties of EBM parts from sample to sample [113]. HIPping is also useful in improving ductility of laser PBF parts [127]. Besides HIPping, surface finishing operations such as machining leave a smoother surface than as-built and so also tend to improve fatigue performance [116].

PBF has become the dominant AM technique for fabricating metal parts because it has a few very important advantages. The main reason for its use is that it tends to result in relatively high strength, low porosity as-built parts, with decent surface finish and good dimensional accuracy. It is also capable of varying mechanical properties depending on the parameters used. Consequently, there is a vastly greater variety of feedstock materials and material suppliers than for any other metal AM technique; according to the Senvol database, 84% of all metal AM feedstocks available are used for PBF. Parts can be nested in the build envelope and unfused powder can be reused many times [128], making the process relatively material-efficient. The process is also theoretically capable of part repair, provided the surface requiring repair is flat. However, despite its popularity, there are significant drawbacks to metal PBF. The equipment is expensive, generally costing well into the hundreds of thousands of dollars, and the process is notably slow. The requirement for powdered feedstock also adds cost, as well as creating health and safety concerns (i.e., inhalation, flammability/explosivity). Although the powder can be reused, it must be separated from the as-built parts and typically requires processing between uses, for example through sieving. This adds time and labour and the health and safety issues must also be addressed during these powder processing operations. While as-built strength is often high, ductility and fatigue/fracture performance commonly requires post-processing (i.e., stress-relieving, HIPping, machining), which also adds expense to fabrication. Support structures must also be removed, particularly from laser PBF parts. These processes also require environmental stability, in terms of ambient temperatures, motion/vibration and controlled atmospheres. Finally, the build envelopes on current generation systems are relatively small (particularly for EBM) and the processes are not inherently very scalable (although larger-format laser PBF systems continue to be an area of development [129]).

PBF processes are the most widely used AM techniques for defence purposes [10]. Most often this involves polymers, but the technique is seeing increased use for metals. The U.S. Naval Research Laboratory recently purchased its first laser powder bed system, intending to use it for fabricating parts from stainless steel [130]. A flight-critical aircraft component (a titanium link and fitting assembly for the MV-22B Osprey engine nacelle) has even been demonstrated by Naval Air Systems Command [46, 131]. The Air Force Institute of Technology also purchased the same system for use with Inconel, titanium and aluminum [132]. The U.S. Army has used this technique for printing nearly all of the parts for a working prototype grenade launcher from aluminum [133]. The Norwegian Armed Forces have also used SLS for AM of supply parts made from stainless steel, Inconel, titanium and aluminum [14].

3.6 Directed energy deposition

DED systems have been commercially available since the late 1990s [16]. Many trade names are used to refer to specific variants of DED, including Laser Engineered Net Shaping (LENS), Laser Additive Manufacturing (LAM), Laser Metal Deposition (LMD), laser consolidation, laser cladding, Direct Metal Deposition (DMD), Direct Metal Tooling (DMT), directed light fabrication and Electron Beam Additive Manufacturing (EBAM). Just as for metal PBF, the particulars of each of these processes vary, for example in the heat source and feedstock used. However all are conceptually very similar; they all introduce a solid feedstock material directly into the path of a focused heat source to cause local melting and fusion of the feedstock to a substrate. Currently these techniques are only used commercially for the fabrication of metal parts.

As an example, the LENS process is shown in the schematic of Figure 8. This approach uses a powdered feedstock, delivered pneumatically through a coaxial nozzle into the path of a continuous-wave fibre laser beam. The laser creates a small molten pool in the substrate into which the powder is injected. The powder increases the size of the melt pool, forming a bead of material on the surface. The substrate and deposition head are moved relative to one another using a numerically-controlled positioning system to trace out the desired part, line by line, as the molten bead solidifies trailing the beam path. The build platform is hermetically sealed and back-filled with an inert gas to prevent significant oxidization of the growing part. Other DED systems function similarly to the LENS system, but the exact specifics can vary. For example, the deposition head (i.e., the combination of heat source and feedstock delivery system) and/or substrate can be capable of more than just three-axes of motion. This can allow for rotation of the growing part, allowing the build direction to be continuously varied. This can enable the deposition of material on curved surfaces and can greatly reduce the need for support structures.

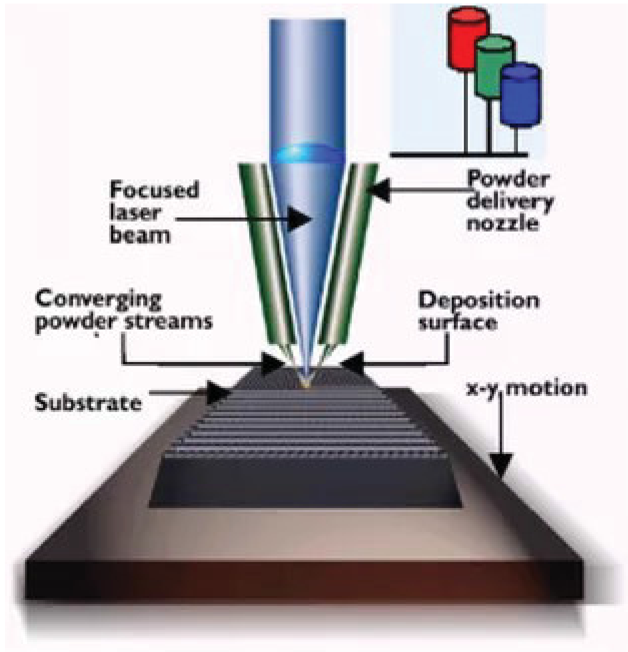

Figure 8: *Schematic of the LENS process [134].*

Table 3 lists some of the commercially available DED systems today. As shown, most use the same combination of powdered feedstock and continuous-wave laser as the LENS approach. The only non-laser commercially available system, EBAM from Sciaky, uses a wire feedstock and electron beam combination. There are also R&D systems that have not been widely commercialized, but that have seen limited industrial application. This includes laser consolidation as developed at the National Research Council – Integrated Manufacturing Technologies Institute. Fleet Maintenance Facility Cape Scott currently operates a laser consolidation system for niche part fabrication/repair.

Each DED system has its own capabilities and specifications, including build envelope size, geometric accuracy, resulting surface roughness, deposition rate, etc. These specifications are not included here, as they can be easily found on the Senvol database or from the vendor websites and specifications can be expected to continually evolve with the release of new systems. However, it is possible to generalize on the characteristics of each approach, based on the combination of heat source and feedstock material.

In general, the choice of feedstock influences deposition rate, dimensional accuracy and as-built surface roughness. Powder-based processes generally have low deposition rate, but relatively high accuracy compared to other DED approaches (although not as high accuracy as metal PBF) [135]. Deposition rates tend to be low because not all of the powder that is blown towards the substrate is melted and absorbed into the melt pool. Furthermore, the powder may continue to flow even when the laser is off, for example when moving to a new start position. As a consequence only a percentage of the powder that is supplied is actually incorporated into a part. The effects of powdered feedstock on surface roughness depend on how roughness is defined. Typically powder results in higher micro-scale surface roughness than wire, as the surfaces of as-built powder-DED parts contain partially melted or loosely adhered particles [136].

However, the boundaries between adjacent passes are not as prominent as when wire is used, so macro-scale roughness is relatively low.

Table 3: *Examples of DED systems. Those above the double line are currently commercially available while those below have seen limited industrial use.*

<table>
<tr><th>Process Trade name</th><th>Organization</th><th>Feedstock</th><th>Heat Source</th></tr>
<tr><td>Laser Engineered Net Shaping (LENS)</td><td>Optomec Inc.</td><td rowspan="6">Powder</td><td rowspan="6">Continuous-wave laser</td></tr>
<tr><td rowspan="2">Laser Metal Deposition (LMD)</td><td>BeAM Machines SAS</td></tr>
<tr><td>Trumpf GmbH</td></tr>
<tr><td>Direct Metal Tooling (DMT)</td><td>InssTek Inc.</td></tr>
<tr><td>Direct Metal Deposition (DMD)</td><td>DM3D Technology LLC</td></tr>
<tr><td>Laser Powder Fusion (LPF)</td><td>Huffman LLC</td></tr>
<tr><td>Electron Beam Additive Manufacturing (EBAM)</td><td>Sciaky Inc.</td><td>Wire</td><td>Electron beam</td></tr>
<tr><td>Laser Consolidation†</td><td>National Research Council – Integrated Manufacturing Technologies Institute</td><td>Powder</td><td>Pulsed laser</td></tr>
<tr><td>Wire + Arc Additive Manufacturing (WAAM)</td><td>Cranfield University</td><td rowspan="2">Wire</td><td rowspan="3">Plasma arc</td></tr>
<tr><td>Ion Fusion Formation (IFF)</td><td>Honeywell Aerospace</td></tr>
<tr><td>Plasma Transferred Arc—Selective Free Form Fabrication (PTA-SFFF)</td><td>MER Corp.</td><td>Wire and powder</td></tr>
</table>

† Currently in use at Fleet Maintenance Facility Cape Scott.

Wire feeding is much more efficient than powder, as typically all of the wire fed into the molten pool is melted [137]. This improves the deposition rate but tends to result in notably larger beads than when powder is used, which leads to more significant and macroscopically visible undulations corresponding to the boundaries between adjacent passes. Furthermore, the larger beads are associated with increased distortion and cause a reduction in dimensional accuracy [138]. Consequently, wire-based processes are typically considered to be “near-net shape” AM processes, as they usually require post-process machining to achieve the final dimensions [135].

The choice between powder and wire-based DED systems will also affect the cost and total time required for part fabrication/finishing. However, these effects will strongly depend on the specific feedstock(s) and part(s) being considered, and so it is difficult to make generalizations. Wire feedstock tends to be cheaper than powder [139] and can be deposited at a high rate with essentially 100% efficiency. However, wire systems almost always create parts that require further machining, increasing fabrication time and resulting in waste material that cannot easily be reused. This waste material therefore has the effect of increasing total feedstock costs. Meanwhile, powder feedstock is more expensive upfront, but is much less likely to yield parts requiring post-process machining. Although it is true that only a portion of the feedstock gets incorporated into the final product, the stray powder can largely be collected and processed for reuse on a future build, decreasing the amount of truly wasted material compared to wire. The overall benefits of reduced post-process machining, however, are negated by the facts that powder feedstocks have lower deposition rates and require time/cost to reclaim the stray powder. It is therefore not straightforward to compare total time/cost of fabrication between powder and wire-based DED, and the best choice of the two approaches will depend on the specific situation.

The choice of heat source also affects deposition rate, dimensional accuracy and surface roughness, and has an impact on the build envelope size. Typically lasers are used at relatively low power and so represent a source with low heat input [140]. Electron beams usually have higher heat input than lasers, while electric arcs provide even more heat input [135]. As heat input increases, so do the bead size and deposition rate. However, as previously mentioned, larger beads reduce dimensional accuracy and lead to more significant undulations between adjacent passes. Additionally, higher heat input tends to increase distortion, as is the case in welding [141]. This distortion must either be managed during the build or be rectified afterwards, for example via machining. Finally, each heat source has different requirements regarding the operating environment, which can impose different practical limitations on build envelope size. Laser systems typically employ hermetically-sealed chambers purged with an inert gas to limit contamination of the molten material, while electron beam systems use a sealed chamber operating at low vacuum to mitigate beam deflection (and contamination of the growing part). Plasma arc systems, meanwhile, use localized gas shielding at the arc and so very commonly do not require a sealed build chamber. Consequently, laser and electron beam systems tend to have smaller, limited build envelopes while plasma arc systems are often only limited by the capabilities of the positioning system [135].

Feedstock alloys for powder-based DED are somewhat limited. The makers of commercial DED equipment currently advertise around 30–40 alloys (if any are advertised at all). These include steels (alloy, stainless, tool), nickel, titanium, copper, aluminum and cobalt alloys. Of course, other powdered metals, such as those sold for PBF, binder jetting, powder metallurgy, thermal/cold spray, etc., may also be amenable to DED. However, testing and optimizing the processing parameters for a new alloy/powder can be a significant undertaking, since there are many variables in DED that influence the final product.

Sciaky Inc., the only seller of commercial wire-based DED systems, does not actually advertise specific compatible alloys. Instead, they indicate that the best materials for use with their systems are 4340 alloy steel, 300 series stainless steels, nickel, titanium, copper, aluminum, niobium, tantalum, tungsten and zirconium alloys [142]. Other commonly available welding wires can also be explored for use [105], and wide varieties of these are much more readily available than metal powders [138]. Of course, the use of any new material requires optimizing processing parameters. However, as there is a greater body of knowledge concerning welding with wire feedstock, the optimization of parameters may be less time-consuming than when powder feedstock is used.

When parameters are optimized, tensile strength and ductility of DED parts can be relatively high. Advertised tensile properties for the LENS process, shown in the example of Table 2, are typically similar to those of the corresponding wrought alloy [100]. In some cases, post-processing, such as HIPping, can also be used to reduce porosity and greatly improve strength/ductility even when processing parameters are not ideal [143]. Likewise, independent, experimentally-derived properties for parts made by laser consolidation [144] and EBAM [145] have proven to be comparable to wrought material. All of these results are unsurprising since DED techniques are essentially localized cladding/welding processes, which have a long track record of being capable of high mechanical performance. However, it should be noted that anisotropy in tensile properties can be considerable (i.e., > 20%) when discontinuities such as interlayer lack of fusion are present [143]. It is therefore important that mechanical properties in different directions be tested when optimizing processing parameters.

The fatigue and fracture characteristics of DED parts also have much room for variability. As is the case for metal PBF and for welding, these properties depend largely on the quantity, shape, orientation and distribution of discontinuities within a part [143, 146, 147]. In fact, DED parts could represent an even more complicated situation since the build direction can often be continuously varied, meaning that any interlayer discontinuities like lack of fusion and porosity can have multiple orientations within a single part. These discontinuities can greatly reduce fatigue performance [147]. However, when free from significant discontinuities DED parts can have greater fatigue performance than wrought material [146]. Like metal PBF, HIPping can be effective in reducing discontinuities and increasing fatigue/fracture performance [143]. DED also results in different microstructures than typical for wrought material, which can have either positive or negative effects on fracture toughness [147, 148]. The literature data thus suggests that favourable fatigue and fracture performance can be achieved using DED, but that it is important to test these properties when optimizing the processing parameters.

The pros and cons of DED for defence purposes vary depending on the specific technique being considered. For example, arc-wire systems are inexpensive, do not require a hermetic enclosure and have a wide range of available feedstocks. Wire feedstock in general is relatively inexpensive and is a safer, easier to work with product form than powder. All wire-based systems have a high deposition rate, while powder-based systems have high accuracy, low distortion and relatively fine surface finish. Powder-based systems also require minimal post-process machining, and stray powder can be largely recovered and reused. All DED techniques have the potential for repair of contoured surfaces, and the potential for varying material composition within a part. Finally, all DED techniques can produce parts with good mechanical properties, and, often, the ability to tailor these properties by locally modifying the processing parameters. On the other hand, the number of processing parameters that can be varied can make optimization more difficult. The high deposition rates of wire-based techniques come at a cost of accuracy/distortion and usually demand post-machining, which increases fabrication time and wastes material. Powder feedstocks are somewhat limited in available range, and pose health and safety hazards (i.e., inhalation, flammability/explosivity) that must be managed. Hermetic enclosures with controlled atmospheres are necessary for both powder-based and electron beam systems and these two types of systems are also relatively expensive, particularly those that use electron beams.

DED has seen some defence use with the commercially available laser/powder systems. Anniston Army Depot of the U.S. Army was using LENS as early as 2007 for the repair of worn turbine components on Abrams M1 tanks [134]. An economic assessment of this application has showed that the LENS system offers a positive return on investment versus simply replacing the worn parts [105]. The Applied Research Laboratory at Penn State has been testing and qualifying the LENS system for repair of naval aircraft components since 2016 [46]. The Royal Australian Air Force is also using DED (specifically laser powder deposition) for the repair of steel, stainless steel, titanium and aluminum components [149]. And, of course, FMFCS has used this technology since late 2011 for fabrication and repair of non-critical parts on HMC vessels [150–152].

3.7 Sheet lamination

Sheet lamination for the fabrication of metal parts has been explored using a similar approach as outlined in Section 2.7. However, instead of using adhesive to bond the layers together, techniques such as diffusion bonding or ultrasonic welding have been previously proposed [153–155]. The first commercially available metal sheet lamination system was announced by Solidica Inc. in 2001. Here the process was referred to as Ultrasonic Additive Manufacturing (UAM), and it used a combination of Computer Numerical Control (CNC) machining and Ultrasonic Welding (USW) to cut and bond the layers, respectively [16]. USW involves the use of a "sonotrode," a roller capable of applying pressure and ultrasonic vibration (typically at 20 kHz) to the metal layers [156]. The combination of pressure and vibration deform/flatten surface asperities and break up surface oxides, allowing for intimate contact between the metal layers and creating a solid-state bond [157]. USW results in a temperature increase due to frictional heating, but the temperatures involved are lower than the melting point of the material(s) joined.

Today, UAM has been improved with a higher-power sonotrode [158] and spun-off to another company, Fabrisonic LLC. They are currently the only provider of commercially available metal sheet lamination equipment. The UAM systems use metal tapes, rather than full sheets, as feedstock, and during fabrication the tapes are staggered so that the joints overlap [158]. Fabrisonic's biggest system available at this time is capable of creating parts up to 6 x 6 x 3 ft. large.

Alloys advertised for use with Fabrisonic's systems are limited. Most often, aluminum alloys and copper are used, although some stainless steels, precious metals (gold, silver), titanium and tantalum have been fabricated. The process is most suitable for relatively soft alloys; harder alloys, such as steels, are more difficult to fabricate using the current sonotrode designs [159]. In all, 18 alloys are presently listed on the Senvol database for UAM. However, with proper process development, many more alloys available as metal tape are likely amenable to the process.

Since the UAM process uses metal tapes as feedstock, strengths in the X-direction tend to be similar to those of the feedstock material. However, the mechanical properties in the transverse, Z-direction are largely a function of the bond strength between layers of tape. In turn, this strength is dependent on the degree of coverage of the solid-state bond. The term *Linear Weld Density* (LWD) is used to describe the extent of the bond, with 0% indicating no bond at all and 100% indicating absolutely no voids in the bond. Typically UAM is conducted with LWDs in the range of 40–95% [160]. Tensile properties of UAM parts are very scarce in the literature. At a LWD of ~65%, aluminum 3003 was found to have transverse tensile strength equal to only 14% of that of the base material [160]. Although not measured, ductility of the parts was also poor, as the voids between layers caused the parts to fail in a macro-scale brittle manner. Similar anisotropy and low Z-direction strength has been measured for aluminum 6061 fabricated by UAM [161]. Post-processing heat treatment has been shown capable of improving tensile properties to some degree [159, 162]. However, the issues of low strength and ductility in the Z-direction remain notable concerns when considering UAM for fabrication and when optimizing the USW parameters.

UAM has several features that make it attractive for defence applications, and these mostly stem from the relatively low temperatures involved. This makes UAM capable of dissimilar metal joining or of joining metals to non-metallics. Polymers can even be embedded in metal parts without significant degradation [159], allowing for the introduction of a strengthening phase or of integrated sensors. The technique uses metal tapes, which are relatively inexpensive and pose little health and safety concerns. If the damaged surface of a part is flat, UAM can theoretically be used for part repair without introducing distortion or significant residual stresses. The low temperatures also make precautions against oxidization and/or contamination less vital during fabrication, and so the technique can generally be performed without an enclosure. Since deposition rates are decent this feature means that UAM can be suitable for fabricating large parts. The finish and accuracy of parts can also be very high, as the process uses CNC machining. The drawbacks to UAM include the fact that the available alloys are limited, and that fabricating from alloys with high hardness is inherently difficult. The technique is also not a true AM process, but rather should be considered additive/subtractive. Therefore, depending on the part being produced, there can be notable feedstock waste. Mechanical properties are also a concern, if only because there is limited published information available. What has been published indicates that anisotropy and low transverse strength/ductility can be an issue. Fatigue and fracture data are not available, but if significant voids are present between bonded layers then these properties can be expected to be low.

UAM is a relatively niche AM technique, and so there is limited information in the literature about its current use for defence purposes. One published example is the U.S. Army's engagement of Fabrisonic in the production of rigid armour [159]. This prototype armour consists of alternating layers of aluminum and titanium and is intended to provide resistance to ballistic impact while remaining lightweight. Ultimately, applications such as this, where dissimilar metal joining is involved, or those in which embedded sensors are required appear most suitable for UAM.

3.8 Summary

Table 4 summarizes the advantages and disadvantages of each of the AM techniques for fabricating metal parts. Vat photopolymerization has not been considered in this summary, as it has yet to see commercialization for metallic parts. Only the notable advantages and disadvantages are given, and so empty cells indicate the characteristic is not a particular strength/weakness of the technique. In formulating Table 4 each technique was considered in general, rather than focusing on specific systems in each category. As such, there is some subjectivity to the summary. For a more nuanced understanding of the advantages and disadvantages of whole categories or specific outliers within the categories, the reader is directed to the text in each of the preceding sections.

Table 4: *Summary of advantages and disadvantages of AM techniques for metal fabrication. Green check marks signify notable strengths and red exes particular weaknesses relative to the other techniques.*

		Material Extrusion	**Material Jetting**		**Cold Spray**	**Binder Jetting**	**PBF**		**DED**			**Sheet Lamination**
			Suspension	**Molten Metal**			**Laser**	**Electron Beam**	**Laser and Powder**	**EBAM**	**Arc-Wire**	
Process Characteristics	Low Equipment Costs	✓				✓				✗	✓	✗
	High Build Rate				✓	✓	✗	✗		✓	✓	
	Fine Surface Finish		✓	✗			✓	✓	✓	✗	✗	
	Capable of Locally Varying Material Composition		✓	✓	✓				✓	✓	✓	✓
	Minimal Post-Processing/Machining	✗	✓	✗	✗	✗	✓	✓	✓	✗	✗	✓
	Highly Scalable				✓	✓	✗	✗			✓	
	Low Material Waste					✓			✓			✗
	Capable of Repair of 3D Surfaces	✗		✓	✓	✗			✓	✓	✓	
	Does Not Require Hermetic Enclosure	✓			✓	✓	✗	✗	✗	✗	✓	✓
Feedstock	Low Material Costs		✗	✓						✓	✓	✓
	Easy/Safe Handling and Storage	✓		✓	✗	✗	✗	✗	✗	✓	✓	✓
	Wide Range Available		✗	✓						✓	✓	
Part Performance	High Strength and Ductility As-Printed	✗			✗	✗	✓	✓	✓	✓	✓	
	Low Anisotropy	✗				✓						✗
	Low As-Built Residual Stresses/Distortion		✓			✓		✓		✗	✗	✓
	Ability to Locally Tailor Phase/Microstructure Within Part	✗			✓	✗	✓	✓	✓	✓	✓	✗

4 Indirect AM of metallic materials

In general, AM is considered most attractive as a means of directly fabricating end-use parts. In other words, AM acts as an alternative to traditional manufacturing. However, in some situations it may actually be more beneficial to use AM in conjunction with other manufacturing methods. For example, AM can be used to fabricate intermediate devices, such as moulds, cores, patterns, tooling and jigs, which then can facilitate fabrication of the finished part(s). These types of approaches, where AM supports but does not replace other manufacturing methods, are referred to here as *indirect* AM. In this section, the state of the art of indirect AM techniques is presented along with their current advantages and disadvantages.

4.1 Printing of casting moulds or patterns

Casting is one of the oldest metal manufacturing methods, a prehistoric technology [163]. The process involves pouring molten metal into a cavity that has dimensions close to those of the desired part (though typically larger to account for shrinkage during cooling). The cavity is contained within a mould, which is either permanent, or, more commonly, expendable. Casting sees widespread industrial use in the manufacture of parts ranging in mass from grams to tons. The vast majority of manufactured goods still contain components produced via casting [163], and so any benefits AM can offer to the casting industry have the potential for great impact.

Figure 9 and Figure 10 show schematic representations of sand casting and investment casting, respectively. These are two of the most common metal casting techniques, and both can be used in conjunction with AM. In each case, the creation of a mould begins first with a positive model of the desired part, known as a *pattern*. For sand casting, the pattern can be made of virtually any solid material, including wood, metal, plastic, etc., while for investment casting the pattern is typically made of wax or plastic [164]. In addition to the pattern other sacrificial features (i.e., sprues, gates, risers) necessary to introduce and control the flow of molten metal during casting are fabricated. These features are combined with the pattern to create a negative impression in the mould material, which either consists of sand or a ceramic slurry known as *investment*. The pattern is then physically removed from the mould (therefore allowing it to be reused to make other moulds) or is burned/melted out prior to casting.

The fabrication of patterns and moulds are themselves manufacturing steps, and so are potential applications for AM. Typically the use of AM in casting follows one of two approaches. The first is to use AM to fabricate the pattern (which is then used to make the mould), and the second is to skip the patterning step and use AM to directly fabricate the mould. Most commonly the first approach is used for investment casting while the second tends to be used for sand casting, but both of the approaches could be applied to either of the casting techniques.

Most of the AM techniques are capable of producing patterns for investment casting (and, indeed, sand casting), although some are better suited than others. Patterns for investment casting should be strong enough to support the thinnest design sections without bending or breaking during mould-making, be able to melt or burn out without significant volume or shape change, and should melt/burn out to leave minimal residue/ash [166]. It is also very useful if the material and AM technique result in fine surface finish (or can be easily post-processed to improve surface finish), as all of the surface features in the pattern will be reflected in the finished casting. The use of AM for patternmaking is already widespread in North America, with over 98% of non-art investment foundries using AM patterns at least occasionally [167]. Ultimately, the decision to use a particular AM technique available to a foundry depends on the characteristics of the desired part, such as geometry, size, section thickness, surface finish required, etc., and on the production volume [168, 169].

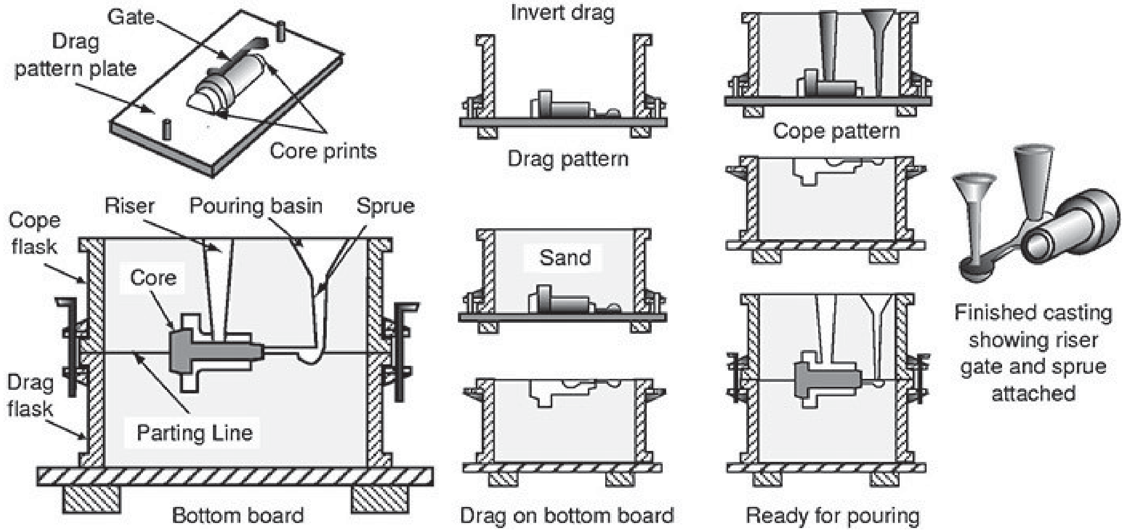

Figure 9: *Schematic of sand casting process [165].*

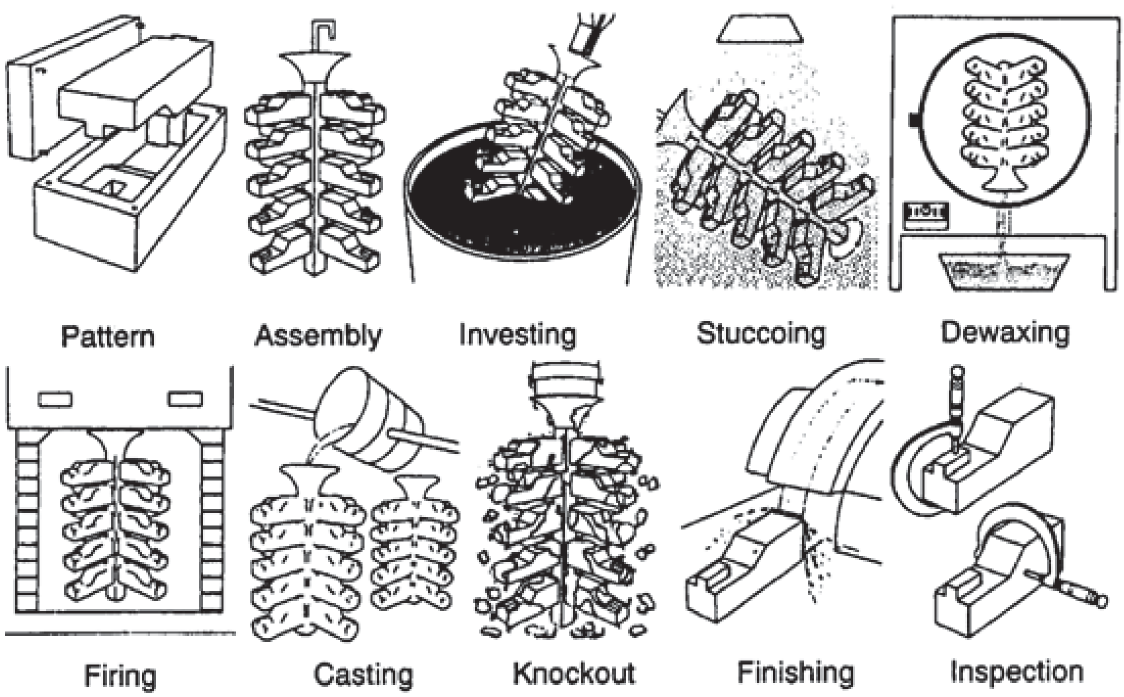

Figure 10: *Schematic of investment casting process [164].*

Patterns made by material extrusion using ABS have proven suitable for casting, however an extra step may be required to remove ash after burnout [170]. It is possible to produce hollow patterns, saving on the pattern material costs and often improving dimensional accuracy in the finished part [171]. PLA is also commonly used by hobbyists to fabricate casting patterns, and recently wax filaments intended for use in investment casting have started to be commercialized. Since material extrusion does not inherently result in fine surface finish, it is common to use post-processing to remove the visible ridges associated with each layer of filament [170]. Because of the lack of inherent surface finish and accuracy, material extrusion typically does not see much use in creating patterns for finely detailed items, such as dental castings [172].

Vat photopolymerization has a long history of use in investment casting [173]. The QuickCast process was patented by 3D Systems Inc. in 1993 [16], and is still in use today. This process uses a combination of a suitable resin and a mostly-hollow build style that allows for uncured resin to drain out during the build and for the cured resin to burn out without cracking the investment shell [174]. This has the added benefits of reducing both the amount of feedstock required and the build time for the pattern. In the year following its commercialization, the QuickCast process was successfully used to cast alloys of aluminum, steel, copper, nickel and titanium [175]. Other sellers of vat photopolymerization equipment also commonly offer materials intended for investment casting patterns. As this technique generally is capable of relatively high surface finish and accuracy, it is gradually seeing use for the fabrication of patterns for dental castings [172]. It is particularly attractive for industrial casting patterns as it has a relatively high build rate [167].

Material jetting is very well suited for fabricating detailed investment casting patterns [173]. Indeed, one of the first industrial applications of this technique was the creation of casting positives [16]. Waxes remain a very good choice for investment casting patterns and are still commonly used in material jetting systems, either as the build material or as an easily removable support material [176]. Today, there are various material jetting systems available designed specifically to print wax patterns for investment casting, be they for jewellery, dental or industrial applications. In fact, one company, Solidscape Inc., produces only high precision wax jetting systems for investment casting. Currently they advertise layer thicknesses as low as 6.35 µm [177], an attractive feature considering the high surface finishes commonly required for jewellery and dental applications. The drawback to material jetting for industrial patterns is a very low build rate, which has been estimated as only 4% of the build rate for the QuickCast process [167]. This may not be problematic if the part size is small, but can be prohibitive for larger castings.

Binder jetting is not particularly suited for fabricating investment casting patterns. The choice of materials is limited; especially considering the material must be capable of burn out without excessive volume change and ash production. Binder jetting often uses different materials for the powder bed and the binder which also complicates burn out. Far more often, binder jetting is used to skip the patterning step and fabricate a patternless mould. This topic is discussed further later on in this section.

PBF processes, such as SLS, can be used for investment casting. SLS is amenable to a variety of different polymers, although polystyrene is most commonly used for casting patterns [178]. Polystyrene specifically intended for SLS of casting patterns has been available for several years [179]. However, polystyrene may not to be rigid/strong enough for certain thin-walled structures, in which case polymer blends such as high impact polystyrene have shown potential [180]. Since PBF processes tend to result in a rough surface, the pattern finish can be improved by mechanical/chemical polishing or by infiltrating with wax or resin. SLS offers a moderate build rate for fabricating patterns; it has been estimated as five times the speed of material jetting, but only one fifth the speed of the QuickCast process [167].

Sheet lamination can also be used to make investment casting patterns, although there are some drawbacks compared to other AM techniques [181]. Sheet lamination is relatively niche today, with limited materials available for commercial systems. Paper can be used, as it has properties similar to wood when fabricated and does not expand much on heating. However, patterns made from paper typically must be sealed to prevent moisture absorption and can result in significant ash during burn out [182]. Sheet lamination with paper is therefore considered more suitable for making patterns for processes like sand casting, where the pattern is physically removed from the mould and not destroyed [183]. Alternatively, paper lamination can be used to make negative moulds that can then be used to cast positive patterns out of wax [168, 181].

As previously stated, the alternative to using AM to make patterns (which are then used to make moulds) is to use AM to make the moulds themselves. This is the so-called patternless approach to casting. In the past, there have been commercial options for patternless fabrication of investment casting moulds. Starting in 1993, Soligen Technologies, Inc. began marketing Direct Shell Production Casting (DSPC) [16]. This technique used binder jetting of a colloidal silica binder printed onto alumina powder. After heat treatment to dry and harden the shell, any number of alloys could be cast into the mould. The capabilities of this technique were somewhat limited, as the layer thickness was ~178 µm and the total build volume was 8" x 12" x 8" [184]. Soligen went out of business in 2006. Another option was Z Corp.'s direct metal casting (also known as ZCast), which was commercialized in 2003 [185]. This process used a proprietary resin binder to bond a plaster-ceramic composite (a 50–50 mixture of olivine and calcium sulphate hydrate) [186] to create moulds in a similar manner to DSPC. Z Corp. was bought by 3D Systems Inc. in early 2012 and its binder jetting systems were rebranded. Today, it does not appear that 3D Systems still offers the ZCast feedstock, instead choosing to market their processes and materials for pattern fabrication. Thus there appear to be no current commercial options for patternless fabrication of investment casting moulds. However, it has been suggested that this sort of technique may again see commercialization in the near future [167].

Much more commonly patternless methods are used to fabricate sand moulds, predominantly via binder jetting. Here, binder is deposited into a bed of any of a variety of sands suitable for metal casting. The binder induces adequate cohesion of the sand particles so that they can withstand the physical and thermal forces of casting. A drying/curing process may be used after printing to remove moisture and improve strength of the mould [187]. Currently there are three main companies serving North American and European markets with patternless sand mould systems: ExOne Co., voxeljet AG and Viridis3D LLC (through partnership with EnvisionTEC Inc.). They each offer a line of systems to cover a range of build sizes. ExOne's largest system has a two chamber design, each with a build volume of 2.2m x 1.2m x 0.7m [188]. Meanwhile, voxeljet's largest system has a build chamber size of 4m x 2m x 1m [189]. Both systems are advertised for use with either silica sand or Cerabeads (spherical synthetic sand) and a furan binder. The Viridis3D systems are different from the others, instead using a chamberless approach. A combination hopper / recoater / print head is manipulated by a robotic arm, and in one pass it deposits the particulate, smooths the surface and then prints the binder. The size of mould that can be printed is thus a function of the robotic arm range and the width of the print head. Currently their widest print head is nearly one metre and it is advertised with a robotic arm offering a build envelope of 1.8m x 0.9m x 0.9m [190].

The use of patternless AM sand moulds should not necessarily be considered an exact substitute for casting procedures developed using traditional sand casting. This is because the binders used for the patternless approach tend to modify the thermochemical processes that occur between the mould and casting [187]. Changing the binder jetting feedstock, amount of binder used, or the mould curing schedule has been shown to affect the surface roughness, porosity, microstructure, and mechanical properties of castings [191]. Furthermore, the binders used in patternless sand cast moulds can produce toxic vapours and so casting into such moulds may require additional health and safety measures [187]. Ultimately, metal casting has always been a combination of science and art, and so regardless of mould material it remains vital to work with a competent foundry and to qualify the process and/or final casting as required by the criticality of the part.

Regardless of casting method used, augmenting metal casting with AM often results in significantly reduced costs and production schedules, which can make casting a viable approach for the manufacture of relatively small numbers of parts. For example, it is not uncommon for traditional investment casting tooling costs to range from tens to hundreds of thousands of dollars for a single pattern, with complex parts falling on the high end of the range [174]. Traditional patternmaking requires significant skill, and production schedules are typically measured in weeks or months. When producing hundreds or thousands of parts from a given pattern these high tooling costs and pattern fabrication times may be acceptable, as they are amortized over the production run to give a low fractional cost per part. However, when only a small number of castings are required such costs can be prohibitive. In these situations, the use of AM pattern fabrication can reduce tooling costs and the time required for first delivery of a part, by as much as 50% and 60%, respectively [175]. Patternmaking times can be measured in days rather than weeks or months [192]. Patternless processes also can provide similar benefits, with cost savings of ~37% and time savings of up to 84% reported [36, 37]. The exact breakeven point, where AM-augmented casting is more economical than traditional, generally depends on the complexity of the casting. For simple geometries AM is often more economical for up to roughly five to 10 castings, while more complex geometries may make AM economical at up to 100 castings [193].

AM for mould/pattern fabrication has one very important benefit for defence applications: castings made by these techniques can easily and quickly be qualified for use in even the most critical situations. The types of defects found in castings are well understood, as is their impact on mechanical performance. Thus, myriad acceptance standards are already available and can be applied to validate everything from the foundry, to the casting process, to the casting itself through non-destructive testing. Augmenting casting with AM therefore can reduce costs and production schedules, while still delivering a product of known quality and reliability. As for drawbacks, it is clear that AM of casting moulds/patterns does not fully exploit AM's potential, since it is at least a two-step process. Costs and lead times may not be as low as they could be through direct AM, and the geometry of parts will be limited to what can be cast. Post-processing may need to be performed twice, first on the pattern/mould and then on the final casting. More space and energy are thus needed for indirect versus direct AM, and this limits the attractiveness of this approach for making parts in-theatre.

Patternless sand casting has seen some defence use for low-volume production runs. The Naval Undersea Warfare Center, Division Keyport of the U.S. Navy has used this technology for overcoming part obsolescence [11]. In particular, the ExOne system has been used to fabricate sand moulds for A356 aluminum tail cones (22" x 22" x 22") for anti-submarine targets [36], and for leaded red brass compressor pump components (11" x 5" x 10") used on Ohio-class submarines [37]. In each case the resulting castings met the pre-existing acceptance standards, and total costs and lead times were significantly reduced compared to procurement using traditional sand casting. The U.S. Navy has also begun the process of qualifying AM sand moulds for casting high yield (i.e., HY-80, HY-100) steels [193]. As of 2017 the technique was being "prequalified" as a proof of concept, before de facto qualification of mould producers and foundries was undertaken.

4.2 Printing of tooling

Besides casting, the other traditional manufacturing techniques, namely forming, machining and joining [194], can also benefit from AM. Each of these techniques commonly involves some combination of fixtures, jigs, gauges, dies, patterns, etc., used in the production of specific parts. These items, collectively referred to as "tooling" [173], may serve, for example, to hold a workpiece in place, guide a cutting head, or to ensure dimensional accuracy of the final part. Each item of tooling must be manufactured, and thus tooling fabrication can be a source of significant time and cost [182]. When many parts are produced using the same tooling, the tooling cost per part is more acceptable. However, in situations of low volume production tooling fabrication costs and times can have an outsized impact on total manufacturing efficiency. Using AM for tooling fabrication therefore is especially attractive for low volume production, although it can still be advantageous for higher production runs.

The exact choice of AM process and material for tooling will depend on the necessary properties of the tool, which are typically driven by the process used to fabricate the final part and the required dimensional accuracy and strength/durability of the tool. For example, tooling for metal stamping must be of adequate strength and wear resistance, and the AM method used to make the tooling must result in sufficient surface finish to allow the metal to slide across the die. This can necessitate the use of metal tooling, made via PBF for example [195]. On the other hand, hydroforming of sheet metal typically only requires that the tooling have sufficient strength to resist deformation at the forming pressure [196], making polymer AM techniques an option. An example of this is the use of tooling made via polymer material extrusion for the hydroforming of aluminum [197]. There are many more examples of tooling materials and AM processes for specific applications which will not be listed here. The main point is that traditional metal fabrication techniques do not necessarily require metal tooling, and so AM can offer a wide range of options for quickly and efficiently producing tooling.

Just as for AM fabrication of casting moulds/patterns, the main advantage of using AM for tooling is that the final parts are still produced using tried and true materials and manufacturing techniques, and so can be readily qualified for use in critical applications using existing standards. Part quality is maintained while AM can reduce the time and costs associated with manufacturing. The use of AM can also make traditional manufacturing more flexible, in that design changes can more quickly be adopted by creating new tooling. The economies of scale of the traditional manufacturing techniques are also maintained. With direct AM, cost per part does not tend to decrease as many parts are produced. However, as tooling costs are amortized over the whole production run cost per part for traditional manufacturing tends to decrease. Likewise, the drawbacks to using AM for tooling are related to those of traditional manufacturing, since traditional manufacturing is not avoided but instead augmented. For example, any material wastage or restrictions in part geometry persist, despite the use of AM tooling. And all of the equipment and operator skill necessary for traditional manufacturing is still required. Therefore, indirect AM, in general, does not capitalize on most of the potential benefits of AM.

Because parts made using traditional manufacturing can easily be qualified for use, indirect AM through tooling fabrication has seen particular use for defence purposes. Custom tooling has been one of the largest applications for AM in the U.S. Navy [11], although, perhaps because this application is not considered as groundbreaking as direct AM of metals, specific case studies are not common in the literature. One available example is the use of polymer tooling produced via material extrusion by Naval Air Systems Command for sheet metal forming and for assembly guides, increasing the speed of aircraft repairs [46].

5 Current impediments to defence use of AM

As discussed throughout this report, AM offers several conceivable advantages over traditional manufacturing. Some of these benefits, however, are largely conceptual at the moment, and much more development is needed before AM's full potential can be realized. For example, AM offers the capacity for greater design freedom, as it imposes fewer constraints on part shape. Traditionally, designing a part has required knowledge of the capabilities and limitations of techniques such as casting, forging, machining and joining. Certain features, like internal structures or totally sealed cavities, are difficult or even impossible to fabricate using these methods, and so the design process has always been guided by these limitations. Exploiting AM's design freedom therefore requires new ways of thinking about design, and it will take time for such new approaches to develop and spread among current and future designers.

Another touted advantage of AM is the potential for on-site, or even in-theatre, fabrication. In some cases this has already been trialled, with material extrusion systems having been placed on ships and in expeditionary labs. While these efforts have seen some success, on-site fabrication using other AM techniques has not been explored significantly. Issues such as feedstock and consumable (i.e., shielding gas) logistics/storage, effects of abnormal environment (i.e., temperature, humidity, motion/vibration) on part quality, management of power supply fluctuations, and protocol for data transfer, retention and security must be more thoroughly addressed before on-site AM can be utilized.

Design freedom and on-site fabrication are thus two potential benefits of AM that will take time to fully exploit. But, even if never realized, these capabilities are not *required* to use AM for defence applications, as parts with traditional designs can still be built in more comprehensive, central manufacturing facilities. There are, however, other aspects of AM that pose real impediments to the immediate and widespread use of AM for defence parts, even without design changes or on-site fabrication. These include lack of qualification standards and Non-Destructive Evaluation (NDE) approaches, limited material selection, and the difficulty with which processing parameters are developed and optimized for new materials. Each of these impediments is further discussed in the following subsections.

5.1 Lack of qualification standards

A lack of meaningful qualification standards is the biggest impediment to routine use of AM for defence structural fabrication and repair. Here, *standard* refers to a set of rules governing any aspect of the manufacturing process, including fabricator credentials, equipment used, raw material properties, workmanship, NDE, quality assurance testing, record keeping, etc. Regardless of manufacturing technique used, it is usually too costly and time-consuming to exhaustively analyze and/or proof test each resulting part prior to service. Thus standards are used to help ensure that sound practices are employed in the fabrication of each part, to help mitigate the inherent risks of putting parts into service. When such standards are followed it reduces the likelihood of manufacturing-related flaws, and also increases the probability that any single part is representative of the whole batch. Qualification testing can therefore be conducted on a smaller subset of a batch of parts with reasonable assurance of part-to-part consistency.

Presently, there are few technical standards governing AM processes, and the ones that do exist are either general guidelines or tend to be limited to specific combinations of material and technique. For instance, ASTM International, developer and publisher of over 12,000 technical standards, currently only publishes 18 standards related to AM. Of these, several concern more conceptual aspects of AM, including terminology [198, 199] and electronic file formats [200]. There are guides for characterization of metal powders [201], evaluation [202] and reporting [203] of mechanical properties of AM parts, DED of metals [204], design for AM [205] and purchase of AM parts [206], however these are merely guides and not prescriptive rules. For example, ASTM F3122-14 provides a list of existing standards that "may be applicable" when determining specific properties of AM parts [202], while not indicating that any particular test is necessary or that a specific performance level be demonstrated.

In terms of actual AM *specifications*, currently only nine are published by ASTM. These types of standards are typically used by purchasers and fabricators to help in clearly defining and communicating required properties of parts. Still, the available specifications are limited only to PBF of specific materials, including Ti6Al4V [207, 208] and other titanium alloys [209], nickel alloys [210, 211], stainless steel [212], cobalt-28 chrome-6 molybdenum [213], and plastics [214]. There is also one specification outlining post-process heat treatments for a similar set of metal PBF alloys [215]. There are no specifications currently offered by ASTM governing other alloys processed by PBF or any material processed by the other AM techniques.

ASTM is not a particular laggard in AM standardization. Other standards organizations, including those responsible for defence standards, typically have an even larger range of AM topics not currently covered by their standards. Whenever a particular technical aspect is not covered by any standard, but should be, we can say that a *standards gap* exists. A recent analysis involving input from representatives of over 150 organizations identified a total of 89 current AM standards gaps [216]. These are further broken down by topic category to: design verification and validation (26 gaps); feedstock (seven gaps); process control (17 gaps); post-processing (six gaps); finished part properties (five gaps); quality assurance (15 gaps); NDE (five gaps); and equipment maintenance (eight gaps). Based on this analysis there is clearly a long way to go towards AM standardization, and it will take considerable collaboration between equipment manufacturers, AM service providers and purchasers of end-use parts to create meaningful and achievable standards.

In the absence of applicable standards AM parts are still seeing use in commercial and defence applications. However, final approval of these parts typically follows organization-specific or ad hoc procedures, which tend to be much more resource-intensive and time-consuming than if standards were available. Without standards, approval of new materials and manufacturing processes becomes heavily skewed towards testing of the final product, which demands many samples be tested to ensure statistical significance.

The drawback to a statistics-based approach to part approval is illustrated by the Federal Aviation Administration (FAA) rules on the use of AM for commercial aircraft. The FAA has taken the tack that no new standards are required for AM [217]. Instead, AM materials will have to meet the same requirements as traditional materials used for commercial aircraft. In other words, the performance of AM materials must be established on the basis of experience or tests, while accounting for the effects of environmental conditions, and must be shown to meet the design intent [218]. While this approach circumvents development and publication of new standards, it definitely does not simplify the approval of new materials or processes. For example, to ensure that "A-Basis" design values[1] [219] are met a minimum of 299 samples of an unproven, isotropic material must be tested. However, as discussed in

[1] "A-Basis" criteria apply to aircraft components with a single load path (i.e., no redundancy), and where failure would result in loss of structural integrity. This situation requires at least a 99% probability of a given sample equaling or exceeding the design value, with 95% confidence.

Sections 2 and 3, most AM techniques result in bulk materials that are anisotropic. In these cases, 299 samples could be required in each unique orientation in order to qualify a process/part for airworthiness [220]. Thus, even if orthotropic properties are assumed (i.e., properties vary in three distinct directions), 897 samples would be required to be manufactured and tested before a single part enters service. While this level of rigour generally results in low failure rates in practice, it obviously complicates the qualification of new AM parts for use on commercial aircraft [221].

The FAA approach illustrates the importance of standards to the widespread use of AM parts for defence applications. Many envision AM as an ideal, flexible approach to small-batch fabrication/repair of obsolete or legacy parts used on defence platforms. However, such components typically have very stringent requirements, as the consequences of their failure can be severe. Without meaningful and effective standards the risks of failure can only be managed through extensive data collection. The notion of AM as offering quicker and cheaper parts is thus obliterated if almost 300 or 900 samples must first be built and destructively tested before a single critical part can enter service.

5.2 NDE of AM parts

NDE is somewhat related to the topic of qualification standards (Section 5.1) in that it represents a means of managing the risks of putting parts into service. The term *NDE* encompasses a range of techniques that can be used to detect discontinuities (i.e., porosity, cracks, inclusions) in a material or component, without damaging the component. When discontinuities are deemed unacceptable they are called *defects*. NDE can be conducted on every single part during or prior to service, or, if part manufacture is conducted following a comprehensive standard, on a small, representative subset of a batch of parts to check for defects. Since parts can be used after testing, NDE is particularly suitable for high-value, small production-run components, such as those often used for defence applications.

AM actually presents new opportunities for NDE. In traditional manufacturing, NDE is usually performed on the feedstock and/or the final part. It is very difficult to monitor local material properties and the emergence of discontinuities during, for example, the casting or forging process. However, since AM involves incremental growth of a part it is much more amenable to real-time monitoring and online NDE. PBF is particularly suited to real-time monitoring and can employ thermal or optical snapshots taken of each individual layer, which can highlight abnormal melt pool temperatures, porosity, lack of fusion, etc. And with an appropriate feedback mechanism, real-time monitoring could potentially allow defects in a layer to be fixed before the next layer is begun.

Nonetheless, there are still outstanding issues to be addressed before there is widespread agreement on NDE approaches for AM parts. These issues exist due to a lack of data on the correlation between discontinuities and material performance, and due to unknown probabilities of discontinuity detection using the various NDE techniques. For NDE to be effective these need to be well understood, so that there can be both a high confidence of detection and a well-founded prediction of discontinuity consequences. Without this information it is difficult to decide on meaningful criteria for conducting NDE and classifying defects. For the traditional manufacturing techniques this knowledge is well-developed, arising, for example, from historical experience [222] and scientific analysis [223], and so these approaches will also likely need to be taken to develop NDE for AM.

A lack of well-accepted and documented NDE approaches is thus a current impediment to widespread use of AM for defence applications. Until NDE criteria are developed and standardized, evaluation of parts intended for service will likely be conducted in an ad hoc manner, increasing the engineering burden and impeding the uptake of AM. For much more information on the challenges, opportunities and current state of NDE development for AM, the reader is directed to a recent comprehensive review [224].

5.3 Material selection

Table 1 and Table 4 summarize the strengths of the various AM techniques and highlight those that currently offer a "wide range" of available feedstocks. This label, however, is used only in the relative sense, and should be understood to be comparative to the other AM techniques. In reality, for each type of AM the unique materials available numbers in the tens. The feedstocks that are offered tend to be focused on those amenable to AM that are also commercially viable. Thus ABS and polyamides (i.e., nylons) represent a large portion of advertised polymer feedstocks, while nickel, titanium and stainless steel alloys comprise over 60% of metal feedstocks for PBF (of those listed on the Senvol database).

Meanwhile, there are *tens of thousands* of polymers available for conventional processing [41] and a similarly large number of metal alloys. There is simply no comparison between the selection of AM materials and those for traditional manufacturing. Consequently there are many materials used for defence applications that are underrepresented in the currently available AM feedstocks. These include aluminum and copper alloys, structural steels, polyoxymethylene (acetal), PMMA, polyesters, polyimides, etc. Whole classes of materials, such as reinforced plastic composites, ceramics and glasses are also poorly represented by today's AM feedstocks.

This limited material selection makes using the current AM techniques for direct replacement of traditional manufacturing difficult. As an example, consider the situation where a small number of legacy parts need to be replaced and suppliers no longer exist. While this may seem an ideal application for AM, it all depends on the material/alloy specified on the part drawing. Even if the specified material is one of the handful presently available as feedstock, then it would still be necessary to perform destructive testing to ensure that the combination of feedstock and AM equipment settings gives mechanical properties equivalent to the original material standard. Furthermore, if the original material is not available as AM feedstock then a different material (from a relatively small selection) must be substituted. This can require a deeper understanding of the part and its use to ensure the new material will perform adequately under the expected loading and environmental conditions. Such an engineering change involves more time and effort and must be signed off by the approval authority for the system.

To supplant traditional manufacturing, the range of AM feedstocks will therefore need to be continually expanded to cover more of the conventional materials. However, material development for AM should not stop there. AM techniques can present unique processing routes, with energy input, thermal cycling and heat flow incomparable to traditional manufacturing. Just as the same nominal alloy can often have slight variations when used in cast, forged, wrought and powder metallurgy forms, unique formulations for AM will likely also be beneficial. It may also be possible to develop new alloys that respond well to AM but that cannot be effectively processed by the traditional routes. Material development for AM is thus an area for considerable growth.

5.4 Processing parameter optimization

In most cases, the production of the raw feedstock is not the main obstruction in expanding the range of AM materials (with the possible exception of photopolymerizable feedstocks). The production of metal or polymer wire/filament, sheet or powder is relatively straightforward. Instead, the difficulty usually lies in the AM processing itself. Each AM technique has a variety of equipment settings, or *parameters*, which must be adjusted and optimized for each new material to determine if, and how, sound parts can be created. Unsurprisingly, techniques that have a smaller number of parameters, such as material extrusion, or those that can draw upon knowledge from traditional manufacturing, such as wire-based DED, tend to have wide ranges of feedstocks available. Developing new sets of parameters is usually easier for these techniques.

On the other hand, techniques with a large number of parameters and no real analogue in traditional manufacturing, like PBF and powder-based DED, present greater difficulty in developing new materials. Not coincidentally, these techniques tend to be the most attractive for defence applications, partly because of their ability to tailor material properties. However, choosing the best parameters based on trial and error becomes more time-consuming and wasteful of material as the number of variables increases, and this task is often complicated by the fact that parameters can be interrelated [144, 225, 226]. This difficulty in optimizing parameters poses a significant barrier to using AM for the niche materials often used in defence applications.

Unfortunately, the manner in which parameters are optimized is a topic not often openly shared by AM equipment manufacturers and material suppliers. They may simply use trial and error or they may have more systematic approaches to parameter optimization. Either way, the Intellectual Property (IP) comprising equipment settings for each feedstock can be a valuable commodity, and so businesses usually would rather not assist the end-user in using third-party feedstocks. Those wishing to conduct AM with a new material are therefore faced with two options: either work with the equipment manufacture and/or material supplier to have the parameters optimized, or optimize the parameters themselves. Both options represent roadblocks to greater AM use.

The process itself of optimizing parameters is thus an area where more work would greatly facilitate AM uptake. The development of efficient, systematic approaches to parameter optimization could decrease the time and material required compared to trial and error or other current approaches. This would expedite the availability of new materials and feedstocks, increasing the viability of AM for both fabrication and repair. To the same end, physical modelling is an attractive area for research as accurate models could ultimately enable the calculation of optimized parameters without the need for significant experimental testing.

6 Recommendations for a DND/CAF AM strategy

To best balance the potential risks, costs and benefits related to AM adoption, the Department of National Defence (DND) and Canadian Armed Forces (CAF) should develop an AM strategy. Such strategies exist to steer foreign defence agencies [227]—or whole countries [228]—and are intended to focus and coordinate efforts towards a common goal, improving efficiency by avoiding unnecessary or duplicate work. While it is outside the scope of this report to define the DND/CAF strategy, an understanding of the current capabilities and limitations of AM can offer ideas of what such a strategy could entail. These ideas are outlined in the following subsections.

Section 6.1 summarizes the current usage of AM for defence applications and suggests possible minor changes to DND/CAF AM use in the near-term. Section 6.2 outlines three example *visions* that could steer an AM strategy, and the potential benefits and risks of each. Finally, Section 6.3 presents the R&D areas most important for defence AM, and explains how these areas contribute to the three visions. This section will facilitate definition of a specific defence AM research plan once the DND/CAF strategy is chosen.

6.1 Current and near-term AM defence use

Despite the variety of commercially available systems, foreign defence agencies have so far limited AM work to certain techniques and applications. For polymers, material extrusion and PBF are used most often, with vat photopolymerization a distant third. Typical applications have been fabrication of prototypes/models, tooling/moulds and some end-use parts. AM work is either contracted out or performed at dedicated facilities, with material extrusion being the only technique significantly trialled for remote production (i.e., at sea or in-field) of non-critical parts.

AM of metals is even more limited. Two techniques, PBF and DED, dominate, both for repair or manufacture of small, usually non-critical parts, although cold spray has also seen some use for repair. No work has been published on metal AM in remote locations, and such endeavours are unlikely to be attempted until more robust equipment is available.

In Canada, defence AM activity has been minor, with uncoordinated efforts to date, and this situation is unlikely to change in the very near-term. As the Quality Engineering Test Establishment (QETE) recently determined, investment in AM R&D within the Canadian defence community has not been adequate to mature the technology for widespread uptake [229]. As mainly a purchaser of goods, it is possible that DND/CAF may see gradual increases in the use of AM parts reflecting the growth in the manufacturing sector. However, unless AM is made a very high priority and given adequate resources it is likely that any growth for defence use will be minimal and gradual.

Despite being unprepared for widespread AM uptake, there are some areas in which AM can be used more frequently under current DND/CAF practices. These areas involve the indirect AM techniques (see Section 4), and represent the “low hanging fruit” of AM. In indirect AM, moulds and tooling are printed, augmenting traditional manufacturing techniques. Because the casting, forming, machining and joining processes are not fundamentally changed, parts made via indirect AM can usually be qualified using existing standards. Such an approach can therefore realize two potential benefits of AM in specific situations (i.e., reduced manufacturing costs and lead time) without sacrificing assurance of quality.

6.2 Long-term DND/CAF development of AM

Any new technology comes with potential benefits, which are typically well advertised, but also risks. While these risks are usually less apparent they are no less real. AM's benefits are related to lower manufacturing costs, quicker production times and increased design freedom. Meanwhile the risks include uncertainty regarding part quality, data security and IP, increased potential for counterfeiting and allocation of liability after part failure. There is, of course, also a risk in not pursuing AM, as this could leave an organization disadvantaged compared to their competitors.

In order to best engage AM it is therefore necessary for DND/CAF to weigh these benefits and risks, and in doing so define a sound strategy for the future. In developing this strategy it must be understood that significant organizational changes are required to exploit all of the potential benefits of AM. Without any changes AM may still be applicable in certain situations, but its use will not flourish and many of its benefits will remain unrealized.

The following subsections outline three visions for AM that can be used by DND/CAF to develop a more specific strategy. Of course, many details and nuances are left to be defined but these examples represent, in broad terms, three distinct directions that can be taken with AM.

6.2.1 Vision 1: Status quo

The simplest AM strategy is to make no changes and continue with business as usual. In practice that means that AM may be available for niche DND/CAF use but that the supply system and design philosophy will remain unmodified and unprepared for widespread AM uptake. "Status quo" may be a temporary strategy; as the technology improves and is more established then the choice to engage further with AM can remain open. However, choosing to maintain the status quo would be a clear admission that AM development will be left to other entities at this time.

Realistically, this is the path taken by most organizations when confronting a new, potentially disruptive technology. Reasons for this include organizational inertia and the difficulty in justifying the costs of change. Ultimately, organizations choosing the status quo perceive the risks and costs of a new technology to be greater than its potential benefits. There may also simply be a disbelief in the hype surrounding the new technology.

Maintaining the status quo comes with its own risks, however. If the new technology truly does live up to the hype and is disruptive then late-adopter organizations are at a clear disadvantage. Not only will they have missed out on perhaps years of technological benefits, they eventually must undergo organizational changes anyway to stay relevant. Except after the disruption they must do so from a position of weakness rather than of the strength of early adopters. Indeed, there are many examples of strong organizations ruined by a hesitance to adopt new technology.

Over-delaying adoption of AM is obviously not an existential threat to DND/CAF, but it still presents a risk. If AM growth continues, as industrial trends have suggested, then DND/CAF will miss out on the various benefits offered by AM for some time. Component costs and lead times could be higher than need be in such a scenario, potentially impacting materiel readiness. Since governmental defence agencies are typically less agile than even the largest private companies, eventual DND/CAF adoption of AM is unlikely to be quick. Waiting until AM can no longer be ignored would tend to exacerbate this issue.

In summary, status quo would continue to offer no mechanism for the widespread AM part procurement and no well-defined risk management process for AM parts entering service. Despite this, some AM parts may see use, but each would require ad hoc approval by the system authority, involving protracted activities such as engineering analysis, destructive testing, modeling, etc. The effort required for each approval would necessarily constrain AM part use. Consequently, the benefits of AM that could be realized would be limited to minor reductions in manufacturing costs, minor reductions in lead times and a slight increase in the ability to repair parts. The overall positive impact on materiel readiness would be low.

6.2.2 Vision 2: Modify procurement practices to accept AM parts

Rather than maintain status quo, a second option is to modify procurement, quality assurance and resource management practices to facilitate—even encourage—widespread AM uptake. This involves recognizing that AM parts may have different failure modes, and perhaps different levels of risk/severity of failure, compared to traditionally manufactured parts. Specifications and acceptance standards (see Section 5.1) used to manage the risks of putting such parts into service must therefore be adapted. These standards must clearly define requirements to vendors in order to ensure a common, meaningful and acceptable level of oversight and quality assurance.

Developing such requirements is not expected to be undertaken by DND/CAF alone. Currently the Canadian defence community applies a variety of foreign defence, domestic and international standards. It is likely that AM will not change this situation. However, DND/CAF may either take a more active role in providing input into standard development, or spend more effort assessing emerging AM-related standards and choosing which to apply.

Beyond standards, digital record-keeping practices should be modified to enable recognition and performance monitoring of AM parts. The currently used Defence Resource Management Information System (DRMIS) could be amended or a new tool developed. Regardless, practices should aim to not only document the use of AM parts, but also to link the associated records (i.e., design files, feedstock data, equipment settings, build parameters, NDE results, etc.) of each part. Since AM parts have minimal application history data to draw upon, this information would support the evolution of AM procurement and acceptance practices over time. After part failure, good record-keeping would also facilitate "closing the loop," providing lessons for the future. Alternatively, if part quality is in question a good AM management system could prompt for time-based inspection or part replacement, decreasing the likelihood of failure in service. Finally, integrating the AM management system into DRMIS could help capture cost and time savings, which could contribute to cost models and decision tools for AM use.

Development of standardized AM procurement, acceptance and record-keeping practices would give a mechanism for AM uptake, but may not enable AM use in all situations. For example, due to IP or standing offer constraints, DND/CAF may be required to use a specific supplier or Original Equipment Manufacturer (OEM) for certain parts/systems. While that supplier/OEM may be encouraged to use AM, there may be no legal basis for requirement of AM parts. However, for parts/systems with no such constraints, including those maintained internally by DND/CAF, procurement modifications would give much greater ability to explore AM applications.

The possibility of inferior parts entering service is the main risk of promoting AM uptake. Obviously standards will aim to mitigate this risk, but without a significant history of AM use it will be difficult to set perfect qualification criteria off the bat. Realistically, this risk will probably yield overly-conservative standards in the near-term, because the fear of part failure is strong. A secondary risk surrounds the effort needed for this endeavour. Substantial time and labour is required to modify standards, procurement practices, record-keeping systems, etc. If AM does not live up to the hype and AM parts never see much use then those costs may not be recouped.

However, modification of procurement and acceptance practices would unlock several potential AM benefits. Significant reductions in costs and lead times would be more possible, potentially having greater positive impact on materiel readiness. Additionally, sound acceptance practices would start to build in-house AM knowledge, helping advance towards the goal of fabricating parts in-theatre.

6.2.3 Vision 3: Leverage AM to improve part design/performance

One aspect not covered by the first two visions is the design freedom offered by AM. While widespread AM uptake could offer cost and time savings, these technologies have greater impact potential. Rather than simply copying a traditionally manufactured part, AM can be used to combine discrete parts, reduce weight, embed sensors, or to locally tailor material properties. A third vision thus exists, wherein the full potential of AM to improve part performance and/or functionality is unlocked. Since wider procurement/acceptance of AM is necessary regardless of design, this vision would include all of the goals, risks and benefits of Vision 2 described above.

While this vision offers great potential benefits, it also poses great challenges and uncertainties in implementation. DND/CAF is predominantly a purchaser of equipment, with limited in-house design expertise. Much of the design work may thus fall on suppliers/OEMs. However, an unmotivated supplier/OEM may mean that user-based design changes, perhaps conducted by a third party, are required. This could also necessitate investment in in-house design capabilities, including reverse-engineering and reengineering. Most importantly, a thorough exploration and understanding of the complicated legal issues surrounding IP and data rights, including in situations of obsolescence, would be critical to this path.

Regardless, it is obvious that not every part need or should be redesigned. The time and cost spent on redesign must pay significant dividends, be they in cost, weight, endurance, performance, etc. Parts that are already lightweight, inexpensive, readily available and single-function may not be beneficial to modify. This vision, therefore, requires a means of easily selecting the best candidate parts for design improvements. Development of this means, which may draw from databases such as DRMIS but would likely also involve more detailed cost-benefit analyses, is a crucial task.

After a suitable part has been chosen for redesign, DND/CAF must also make design and subsequent approval effective by promoting sound practices. This may involve development or endorsement of off-the-shelf design software, AM modelling tools, design standards, digital security protocols, etc. Essentially part redesign must have enough oversight to manage the risk of putting a new design into service. Developing, enacting and enforcing this oversight would constitute a significant, ongoing level of effort.

Accessing the design freedom of AM comes with the greatest risks. All of the risks for Vision 2 would apply and be amplified due to the increased effort and organizational change required. Furthermore, new legal risks related to IP and liability allocation are presented. For example, if a system containing a part redesigned not by the OEM but by the user or a third party fails, how is responsibility apportioned? Data security risks would also likely increase if multiple parties are involved in the design, modelling, simulation and qualification of parts.

The risks are significant, but so are the potential benefits. All of the attractive features of AM are unlocked by mechanisms to not only put AM parts in service but also to redesign them. AM efforts could be better tailored to each application, reducing costs and lead times for some parts or enabling improved weight, functionality or performance for others. Developing design expertise and sound design practices would enable the real game-changing aspects of AM, such as the ability to efficiently design and fabricate parts on-demand in remote locations, allowing materiel requirements to be addressed directly at the point and time of need.

6.3 R&D topics

Adoption of a unified AM strategy would not only better coordinate exploitation of AM by DND/CAF, but would also help steer supporting R&D efforts. In the following subsections the important R&D topics as anticipated for defence AM are discussed. The likely avenues and partners for conducting these activities are provided, along with commentary on the relationship between each R&D topic and the three visions described in Section 6.2.

6.3.1 Application-specific AM development

Much current defence AM work is not really fundamental research in the processes and underlying science. Instead it is often tangential to AM and more focused on applications. This work typically involves exploring the use of AM systems (usually commercially-available), for example, in fabrication of surgical instruments, printing of weaponry components, repair of metallic structures, improvement in transducer architecture, etc. This work may involve optimizing, benchmarking and/or validating AM procedures, even if the system in use is expected to be effective. However, because of the varied goals it is difficult to develop research plans explicitly defining these activities. This application-specific AM work is nonetheless useful in advancing the utility of AM for defence purposes. It may simply make more sense for these activities to be defined in domain-specific research plans, rather than in an AM research plan.

R&D partners for application-specific work will depend on the degree of commercial expertise available for the application and material of interest. For structural parts made from common alloys/polymers, contracting an AM equipment manufacturer or service bureau for sample fabrication would suffice. Here it is reasonable to expect the contractor to perform minor process optimization and troubleshooting. On the other hand, for non-structural applications, perhaps using functional/electronic materials, food, drugs or textiles, there is much less commercial expertise to access, and AM companies may not be set up or motivated to do such R&D. In these cases, more traditional R&D partners can be more suitable, such as academia or government (i.e., DRDC, National Research Council, CanmetMATERIALS, etc.).

Application-specific AM development work is valuable regardless of AM strategy. Even for status quo, AM may offer great enough benefits to a particular part or system that it is worthwhile to conduct ad hoc approval for implementation.

6.3.2 Facilitation of AM uptake by DND/CAF

As discussed in Sections 5 and 6.2, there are several impediments to widespread defence uptake of AM. These include a lack of standards/specifications, need for improved digital record-keeping practices and software tools, lack of material feedstocks for traditional defence analogues and difficulty optimizing their processing parameters. These constitute important R&D areas.

For AM standards, DND/CAF will likely apply rules developed by other organizations, or, less likely, document their own rules. Either way, scientific support may be necessary, in the form of critique or recommendations on the content of such standards. Knowledgeable organizations such as DRDC can provide advice in these situations.

Digital record-keeping and software tools could be procured off-the-shelf or otherwise built under contract. Likewise, it may also be necessary to benchmark prospective tools as part of the decision process, and this work could also be contracted out.

Development of defence AM feedstocks and their optimized processing parameters is a similar situation to application-specific R&D (Section 6.3.1). The easiest route is to directly contract feedstock or AM equipment manufacturers as applicable, as these organizations already do this work to commercialize new materials. However, contractors need a sound business case to take on such work, and they may not see much benefit in developing niche materials with limited sales potential. Thus, if no contract can be reached at a reasonable cost, then this work may be directed to a non-profit agency (i.e., DRDC, National Research Council, CanmetMATERIALS, etc.). Note that in these cases it would be more beneficial for the non-profit partner to focus on developing efficient, systematic protocols for parameter optimization (perhaps using process modelling—See Section 6.3.4). Such protocols would have greater utility than a single set of optimized parameters.

This R&D in facilitating AM uptake is required for strategies that align with Visions 2 and 3.

6.3.3 NDE for AM

The development of NDE techniques, both for post-process validation and on-line monitoring, is very much an open area of research. Sound NDE practices require sufficient understanding of the relationship between discontinuities and AM technique, the effects of discontinuities on part performance and the probability/limitations of discontinuity detection. This understanding is far from developed, and therefore should be pursued through R&D considering both traditional and emerging NDE methods.

It may be possible to contract some of this activity out to AM or NDE equipment manufacturers, but given the vagaries of the task it would likely be better suited to an academic or governmental research agency. DRDC would be suitable for this work due to an existing expertise in NDE for defence applications.

Improved NDE capabilities for AM are applicable to strategies aligning with Visions 2 and 3.

6.3.4 Modelling and simulation of AM processes

Most of the process-related challenges of AM, such as development of new feedstocks, optimization of processing parameters and understanding of discontinuity formation, would be well served by improved

AM modelling and simulation tools. Accurate models would also expedite qualification of AM materials and processes. Consequently, this is also an area of active R&D in academia, government and industry, for example at the University of Waterloo, National Research Council and companies like ANSYS/3DSIM. Some modelling tools are already available commercially but tend to be aimed at the more common AM techniques, like PBF. Development of modelling tools for more niche AM techniques, such as LC, could involve significant research activity necessitating a motivated partner. DRDC has some experience in thermomechanical modelling and so may be a suitable partner, as would academic institutions.

Modelling and simulation of AM processes supports strategies aligned with Vision 2, but is better aligned with Vision 3.

6.3.5 AM alloy development

AM presents a unique approach to fabrication and yet the alloys commercialized thus far generally have origins in the traditional manufacturing techniques. That is, alloys developed for, say, casting or forming have directly influenced those available for metal AM. Nonetheless, some high-performance alloys that can be successfully fabricated by traditional means are not capable of being produced via AM. Such alloys can be susceptible to cracking or hot tearing under the unique thermomechanical cycles applied, and so must be modified for AM use. On the other hand, AM thermomechanics can actually open the door to new alloys not amenable to other manufacturing processes. The opportunity exists to explore the development of new alloys particular to AM to potentially reduce costs, improve performance or expand functionality.

Alloy development for AM, considering both of the above situations, is an emerging area of research. As such, R&D would most likely be conducted through academia. DRDC has limited experience in alloy development.

Alloy development for AM would support strategies aligned with Vision 3.

6.3.6 Integrated computational materials engineering

Integrated Computational Materials Engineering (ICME) is an emerging field concerned with optimizing part design over a range of scales. The relationships between materials processing, microstructure and properties are considered alongside design, rather than as a static input to the design process. By controlling the thermomechanical history during fabrication the desired properties can be modified over various scales, enabling new, optimized part designs. At the same time, ICME can help expedite the insertion of new advanced materials into materiel, even using traditional manufacturing [230]. However, because of the ability to locally vary processing parameters, this design approach could also be particularly effective for AM.

There are some software tools available for modelling microstructural evolution during processing, which can contribute to ICME activities. However, ICME requires an interdisciplinary approach, and the successful demonstrations of the concept have typically involved multiple parties from academia, government and private industry [230]. ICME R&D for DND/CAF would thus likely require a similarly large scale effort with multiple partners.

ICME would contribute to AM strategies aligned with the most complicated aspects of Vision 3.

7 Conclusions

The field of AM is broader than the simple description "3D printing" suggests, with several classes of techniques available for polymers, ceramics and metals. Furthermore, within each AM classification there are many systems to choose from, each with their own combination of capabilities and drawbacks. Since the AM landscape is both varied and continually evolving, even those working in the field may find it difficult to keep up to date on the newest developments in commercially available systems and feedstocks.

Meanwhile, those new to the field can be in danger of missing the full breadth of AM technologies available, as well as being unaware of the nuances of each technique. Relying only on marketing materials for information may lead to an underappreciation for the drawbacks to certain systems. There is also the potential for "tunnel vision," where only the most common techniques/systems are focused on even when a lesser-known technique is more appropriate.

This report summarizes the current state of the art of AM for defence applications, for both AM novices and those experienced in the field. The techniques are described, and a discussion of the types of feedstock materials used, resulting surface finish/accuracy and achievable mechanical properties is provided. Material anisotropy and fatigue/fracture data is also included, when available. Perhaps most importantly, the advantages and disadvantages of each technique are presented and compared with other techniques, and the typical usage of techniques/systems for defence applications is given. Finally, the most important impediments to widespread AM use for defence applications are summarized and commentary on potential strategies for AM use in Canadian defence applications provided. This report thus offers significant information on AM to those responsible for coordinating the fabrication or repair of structural components. And, since the knowledge gaps for each AM technique are discussed, the report also serves as a useful resource when developing near-term AM research activities for defence applications.

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List of acronyms/initialisms

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
CAF	Canadian Armed Forces
CNC	Computer Numerical Control
DARPA	Defense Advanced Research Projects Agency
DED	Directed Energy Deposition
DMD	Direct Metal Deposition
DMLS	Direct Metal Laser Sintering
DMT	Direct Metal Tooling
DND	Department of National Defence
DoD	Drop On Demand
DRDC	Defence Research and Development Canada
DRMIS	Defence Resource Management Information System
DSPC	Direct Shell Production Casting
EBAM	Electron Beam Additive Manufacturing
EBM	Electron Beam Melting
FAA	Federal Aviation Administration
FDM	Fused Deposition Modelling
FFF	Fused Filament Modelling
HIP	Hot Isostatic Press
ICME	Integrated Computational Materials Engineering
IFF	Ion Fusion Formation
IP	Intellectual Property
LAM	Laser Additive Manufacturing
LENS	Laser Engineered Net Shaping
LMD	Laser Metal Deposition
LMF	Laser Metal Fusion
LOM	Laminated Object Manufacturing
LPF	Laser Powder Fusion
LWD	Linear Weld Density

MEM	Melt Extrusion Manufacturing
NDE	Non-Destructive Evaluation
OEM	Original Equipment Manufacturer
PBF	Powder Bed Fusion
PEEK	Polyether Ether Ketone
PLA	Polylactic Acid
PMMA	Polymethyl Methacrylate
PTA-SFFF	Plasma Transferred Arc – Selective Free Form Fabrication
PVC	Polyvinyl Chloride
QETE	Quality Engineering Test Establishment
R&D	Research and Development
SHS	Selective Heat Sintering
SLA	Stereolithography
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
UAM	Ultrasonic Additive Manufacturing
USW	Ultrasonic Welding
UTS	Ultimate Tensile Strength
WAAM	Wire + Arc Additive Manufacturing

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Additive manufacturing (AM) techniques are seeing increasing use for the fabrication and repair of commercial engineered components, and could offer significant advantages over traditional manufacturing methods for defence use. However, the field of AM is broad, and it can be difficult for the non-expert to separate the hype from reality. Parts used for defence applications are often critical and operate in demanding environments, and so knowledge of AM capabilities is necessary in order to choose the best option. This Scientific Report summarizes the current state of the art of commercially available AM techniques, focusing on their applicability and usage in defence structural applications. Particular attention is paid to the variety of material feedstocks available and the resulting mechanical properties, anisotropy, residual stresses, and fatigue and fracture performance of each technique. The relative pros and cons of each technique from a defence standpoint are also addressed. This report thus offers useful guidance to the novice and expert alike when considering AM for defence structural components.

Les techniques de fabrication additive (FA) sont de plus en plus utilisées pour fabriquer et réparer les composants techniques commerciaux et pourraient offrir des avantages considérables pour la défense par rapport aux méthodes traditionnelles de fabrication. Toutefois, comme les pièces utilisées dans les applications de défense sont souvent cruciales et employées dans des milieux exigeants, il est essentiel de connaître les capacités des différentes techniques de FA pour choisir les meilleures options possible. Le domaine de la FA étant vaste, il peut être difficile pour le profane de distinguer le mythe de la réalité. Dans cette perspective, le présent rapport résume les techniques de pointe en matière de FA actuellement offertes sur le marché et s'attarde sur leur applicabilité, ainsi que leur usage dans des applications structurelles de défense. On prête une attention particulière à la grande variété des matières premières qui peuvent être utilisées, à leurs propriétés mécaniques et anisotropiques, aux contraintes résiduelles, ainsi qu'à la résistance à la fatigue et à la rupture associée à chaque technique. Les avantages et les inconvénients de chaque technique du point de vue de la défense sont également abordés. Le présent rapport renferme donc des indications utiles autant pour les profanes que pour les experts lorsqu'on envisage l'utilisation de la FA pour les composants structuraux de défense.