



A review on the melt extrusion-based fused deposition modeling (FDM): background, materials, process parameters and military applications

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Abstract

The contemporary military sector needs a tailor-made product at a low cost and time. Fused Deposition Modeling (FDM) is a melt extrusion-based Additive Manufacturing technology for processing thermoplastics, composites, and biomaterials. FDM is competent in fabricating complex parts in different industries, including military, aerospace, automotive, biomedical, and jewellery. The FDM can process various materials and is ideal for fabrication prototypes, functional parts, visualization, concept proofs and fast product development. FDM is currently used in the military for novel components developments and maintenance, opening new logistics and supply chain management methods. Integrating sensors into weaponry for real-time physiological feedback and threat information is also possible. Additionally, FDM can fabricate trauma models for surgical planning and educating military surgeons. This paper presents the FDM background, filaments, and process parameters. Also, the work provides information to readers on the applications and possibilities of the FDM process from a military standpoint.

Keywords 3D printing · Fused deposition modeling (FDM) · Process parameters · Defence/Military

Abbreviations

AM	Additive manufacturing
AJM	Abrasive jet machining
ASTM	American society for testing and materials
ABS	Acrylonitrile butadiene styrene
BJ	Binder jetting
CAD	Computer-aided design
DfM	Design for manufacturing

DMLS	Direct metal laser sintering
DED	Directed energy deposition
DARPA	Defense advanced research projects agency
EDM	Electric discharge machining
EBM	Electron beam melting
FDM	Fused deposition modeling
FGM	Functionally graded material
FAA	Federal aviation administration
GMB	Glass micro balloon
GTRE	Gas turbine research establishment
HDPE	High-density polyethylene
ISO	International organization for standardization
ME	Materials extrusion
MJ	Material jetting
PBF	Powder bed fusion
PLA	Polylactic acid
PC	Polycarbonate
PP	Process parameters
ROI	Return on investment
SLA	Stereolithography apparatus
SL	Sheet lamination
SLS	Selective laser sintering
SLM	Selective laser melting
STL	Standard triangulation language

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UV	Ultraviolet
UAV	Unmanned aerial vehicle
WEDM	Wire electric discharge machining

1 Introduction

Additive Manufacturing (AM) gaining attention in all sectors due to the fabrication of complex parts directly from 3D CAD models, which is highly difficult and expensive in conventional (casting, forming, welding, injection molding etc.) and non-conventional manufacturing processes (Electric Discharge Machining (EDM), Wire Electric Discharge Machining (WEDM), Abrasive Jet Machining (AJM) etc.) [1–6]. AM processes fabricate components layer-by-layer selectively by adding the material from digital CAD data. Hence, it significantly reduces cost, time, energy, workforce, and material consumption [7–9]. AM potential affects conventional manufacturing methods in many ways, including machinery, Design for Manufacturing (DfM), logistics and supply chain etc. Another reason for the widespread AM technology is that part is created from a wide range of materials, including metals, intermetallics, polymers, ceramics, Functionally Graded Materials (FGM's), sand and glass [9–16].

According to ASTM/ISO, AM is classified into seven categories: vat-photopolymerization, material jetting, binder jetting, powder bed fusion, material extrusion, sheet lamination, and directed energy deposition, as shown in Fig. 1 [2, 10, 17, 18]. Vat photopolymerization is one of the seven additive manufacturing technologies in which liquid photopolymerization resin is filled in the vat. UV laser cures the resin layer-by-layer on the platform to build the physical object according to the scan path. Stereolithography Apparatus (SLA™) is a common technique used for rapid prototyping, concept models and end-use parts [4, 19–21]. Materials Extrusion (ME) is another additive manufacturing technology in which wire form filament is fed into nozzles via rollers. Then semi-molten material is extruded through a nozzle onto a build platform. Material extrusion is used for mould and pattern making, tooling, end-use parts etc., [22–25]. Binder Jetting (BJ) is a powder bed-based additive manufacturing process that spreads powder over the table. The print head carries the liquid binder applied selectively on the thin layer of powder spread on the table by moving the X and Y-axes. Upon finishing the first layer, the curing table goes down by a layer height. The next layer of powder spreads onto the previous layer. This action continues until the end of the object. BJ is suitable for printing moulds, patterns for casting processes, and custom organ models of patients such as heart ,

ear, and kidney [1, 23, 26]. Material Jetting (MJ) is a powder bed-based additive manufacturing process in which materials (actual deposition and support structure) are dispensed from the inkjet head. Inkjet print head moves across the powder bed along X and Y axes. A droplet of liquid dispenses (thermo-plastics or photopolymer) selectively onto the platform with support material (wax or water-soluble). These two materials are cured by UV laser, which forms the layer. Next, the print head dispensed liquid material onto a previously deposited layer and cured it with a UV laser. The procedure repeats until the end of the object [27, 28]. MJ is used to create casting patterns and models for pre-surgical and educational training purposes [29, 30]. Sheet Lamination (SL), in which thin sheets are used for the fabrication of components. Initially, an adhesive-coated sheet was laminated over the substrate or platform. After that, a CO₂ laser cut the desired shape on the surface of the sheet. A layer-height platform descends, and the rollers pass the next sheet over the previously laminated layer. Then a laser is directed to cutting the desired shape. This procedure continues until all the layers of the object are built [19, 31, 32]. Applications of SL include visualization, packaging, moulds, patterns, and tooling [33–35]. Powder Bed Fusion (PBF) is an important additive manufacturing process in which laser or electron beam energy is used for selectively sintering the regions of a powder on the bed. The powder bed technologies are Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Electron Beam Melting (EBM), and Selective Laser Melting (SLM). PBF applications include the fabrication of tools, moulds, jigs, fixtures, complex parts, biomedical, patterns for casting, and mould inserts [31, 36]. Directed Energy Deposition (DED) is the last type of seven categories of additive manufacturing in which laser, electron or plasma arc is used to melt substrate or previous layer. The powder is fed coaxially via nozzles into the melt pool created by thermal energy. DED is used to manufacture complex turbine blades, fuel injectors, and implants [37, 38]. It is also used to repair expensive components like turbine blades, propellers, and vane edges [39, 40].

Further, additive manufacturing technologies use different states of materials [23]. The vat photopolymerization uses photosensitive resin. Material jetting uses liquid material, and binder jetting uses powders and binders. Sheet lamination methods use large-size adhesives or normal sheets. Directed energy deposition uses either powder or wire as feedstock material.

On the other hand, material extrusion uses filament in the form of a wire size of 2.85 mm/1.75 mm in diameter. Material extrusion technique processes a wide range of materials, including polymers, composites, and biomaterials [4, 10, 41, 42]. ME-based FDM is a commonly used technique due to its ease of operation, and less expensive than other technologies

[2]. Thus, capable of fabricating patterns, moulds, prosthetics, prototypes, and defence structural components [43–45]. However, to our knowledge, no work has been reported on the review of FDM technology in military applications. Therefore, this review paper aims to provide a literature review of the material extrusion-based fused deposition modeling (FDM) process background, working principle, materials, process parameters and exclusively focused on applications in the military sector.

2 Material extrusion additive manufacturing

The schematic illustration of the FDM process is shown in Fig. 2 [46]. The thermoplastic wire from the spool is fed into the nozzle via rollers. Material is heated to a malleable state and extrudes to the pre-heated platform. It is led to a bead-by-bead followed by layer-by-layer fabrication of 2D layers one upon another based on the predefined scan path. The extruded material cools and solidifies as the nozzle moves away. The nozzle temperature is controlled by a thermocouple and maintains above the melting temperature [2]. End of the deposition, 2D layers form a 3D physical object and are allowed to cool to room temperature. Then the cooled object is removed from the machine safely using appropriate tools. Later, the object is taken to the post-processing for removal of the support structure and finishing operations.

Further, various printing parameters are needed for the fabrication of the defect-free part. The parameters include layer thickness, infill density, printing speed, nozzle temperature, orientation, support structure, raster angle, perimeter raster, bed temperature, contour width etc. [2, 25, 47]. These printing parameters must be optimized beforehand for the fabrication of any component. Figure 3 illustrates the important aspects of the FDM process. The importance of process parameters is discussed in Sect. 2.3.

2.1 Filament fabrication for the FDM process

The filament is classified into two types: pure polymer and composites (polymer with additives). These filaments must be in the form of wire as FDM printers use wire form filament. The workflow of the filament fabrication is shown in Fig. 4. A set of process parameters are used for extruding the desired filament. Filament fabrication starts using pure polymer or pure polymer with additives. The required composition of pellets was poured into the extruder hopper. The hopper is conveyed to the heated barrel for melting and mixing of the material. The outer surface of the barrel gets heated up while extruding, and water or fluid cools it. The pellets are melted in the barrel and conveyed out for rolling [49]. The required shape and size of the wire extruded in rolling. The general filament is round and has a wire diameter of 2.85 or 1.75 mm.

2.2 Materials used in the FDM process

The commonly used filaments include ABS, PLA, HDPE, PC, Nylon, Kevlar, PEEK etc (refer to Fig. 5) in the FDM process for fabricating the products [43, 49, 50].

2.2.1 Acrylonitrile butadiene styrene

Acrylonitrile Butadiene Styrene (ABS) is a thermoplastic used in numerous industries due to its flexible, durable, production-grade, tough, good chemical resistance, and relatively low water absorption. It also ensures high colour fastness and antioxidants significantly improve oxidation stability [51]. Hence, ABS is a widely used material in FDM. The melting temperature of the ABS is about 200 °C [52]. Applications include body panels, helmets, instrument panels, hub caps, medical equipment, helmets, pipes and accessories, sports equipment, protective helmets, and

Fig. 1 Seven categories of an additive manufacturing process according to ASTM/ISO [4, 11]

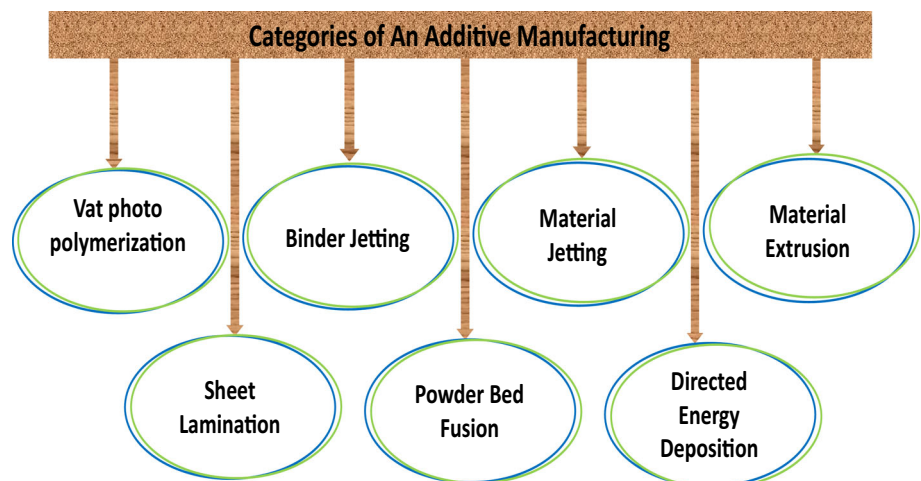


Fig. 2 Schematic arrangement of the FDM process

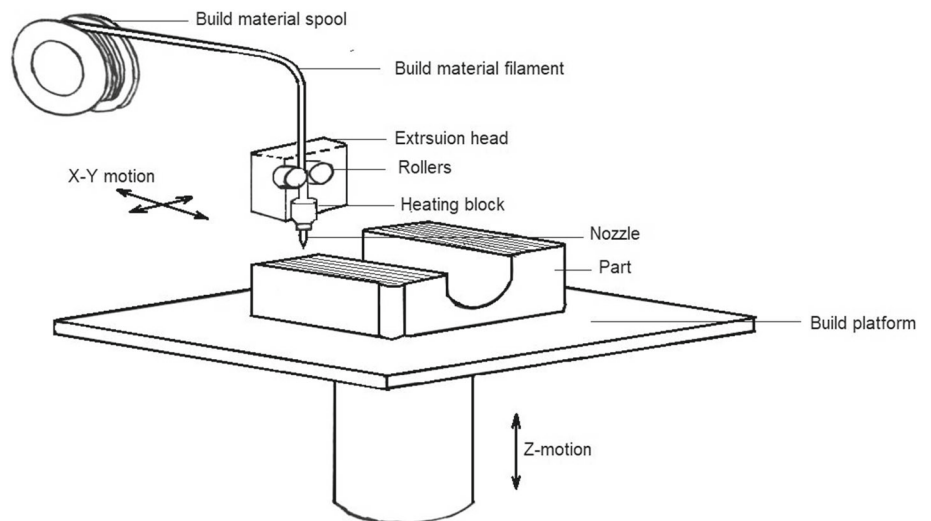
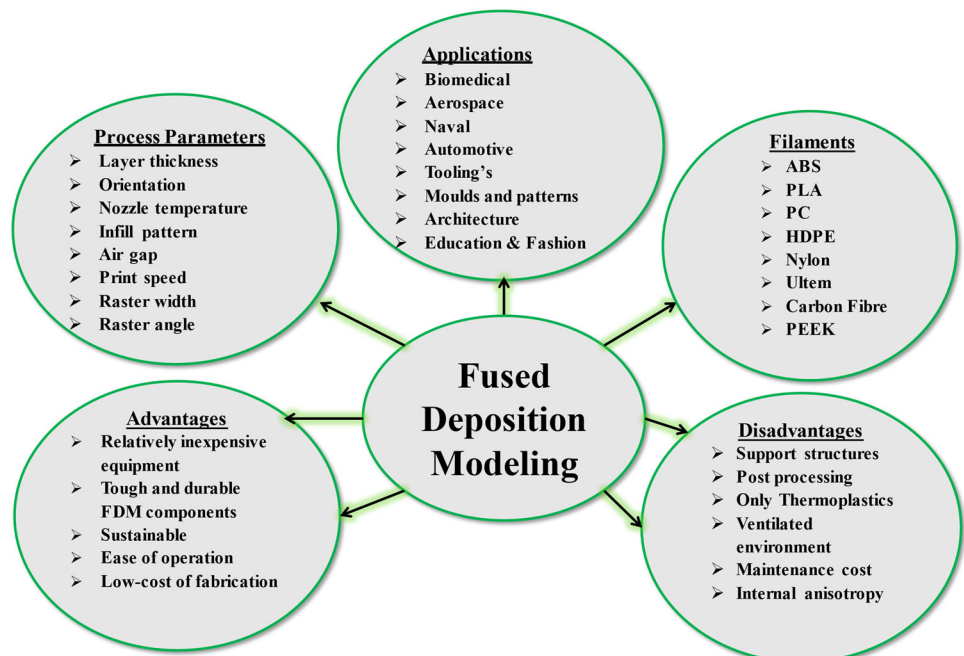


Fig. 3 Fused deposition modeling: Process parameters, filaments, advantages, disadvantages, and applications [24, 43, 44, 47–49]



household appliances (vacuum cleaners, furniture, hoses, grommets, etc.) [53–55].

2.2.2 Polylactic acid

Polylactic acid (PLA) is a renewable, biocompatible, and biodegradable thermoplastic polymer mainly made of corn starch. PLA has good processability and mechanical properties. It can be used as a substitute for petroleum-based polymers. The PLA-ABS and PLA-ISO have also been used as filaments in FDM for part fabrication. However, PLA is a hydrophobic polymer with poor toughness, slow degradation rate, and poor thermal stability [56, 57]. PLA is a homopolymer that has a melting temperature of 170–180 °C

[58, 59]. Applications of PLA include plastic films, bottles, biodegradable medical devices, and scaffolds [60].

2.2.3 Polycarbonate

Polycarbonate (PC) is a type of carbonate-bound polymer. According to the structure of the R group, polycarbonates are classified as aliphatic or aromatic PCs. PC is tough, rigid, good impact strength, dimensional stability, and heat resistance. It has excellent clarity used for water bottles. Hence, one of the strongest candidates for FDM filaments and FDM printed PC parts is strong and suitable for a functional prototype. The melting temperature is between 100 and 110 °C [59]. It has superior properties to ABS and other polymers.

Fig. 4 Filament fabrication work flow (Image is reproduced with the permission of publisher/author) [49]

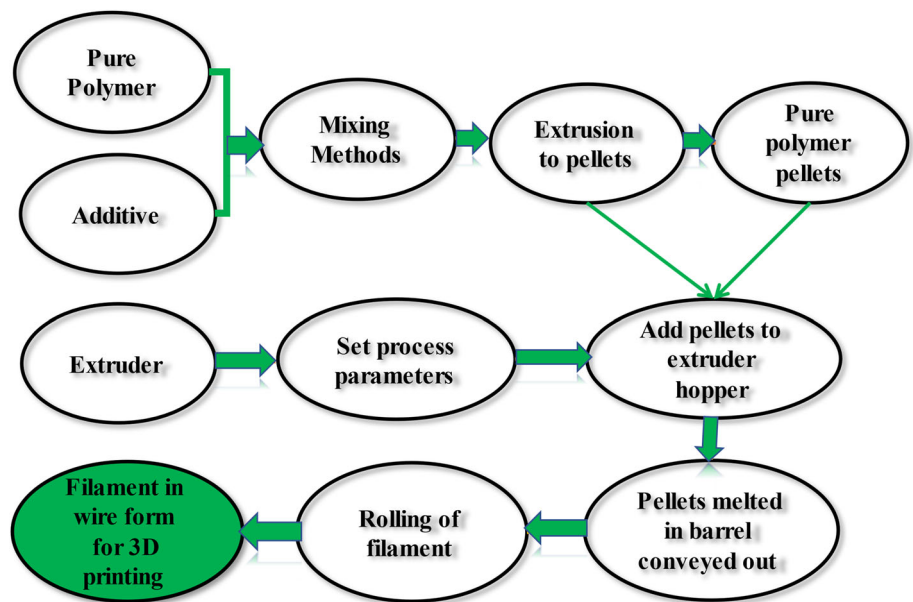
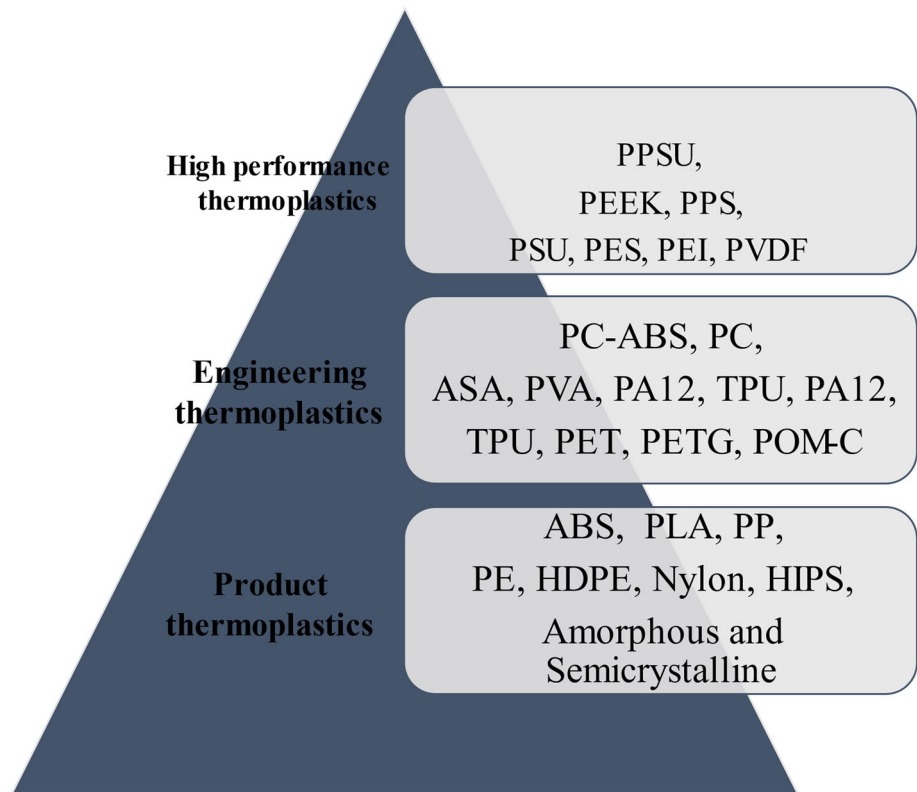


Fig. 5 Material pyramid shows the FDM filament from product thermoplastics to high-performance thermoplastics [76]



It is mainly used in bottles, greenhouse sheeting, CD and DVDs, and safety goggles [61, 62].

2.2.4 High-density polyethylene

In 1953, Karl Ziegler and Erhard Holzkamp of the Kaiser Wilhelm Institute (renamed the Max Planck Institute)

invented High-Density Polyethylene (HDPE). HDPE is an engineering-grade polyethylene polymer. Material designated as PE4710 and PE100. These grades are widely used for pressure pipes and linings in the oil and gas industry. Thick-walled HDPE pressure pipes are often preferred in low-pressure manifolds [63, 64]. HDPE is mainly

used in rigid containers (such as milk bottles and household chemicals) and heavy items (such as pallets, barrels, cages, and intermediate containers) [65]. Also, glass micro balloon/high-density polyethylene (GMB/HDPE), HDPE-filled fly-ash cenosphere and syntactic foam are used in FDM as a filament [66, 67]. The melting point of the HDPE is between 128 and 138 °C [68].

2.2.5 Nylon

The world's first fully synthetic textile fibre nylon was produced in 1939. Nylon is the most popular and widely used plastic. The various grades of Nylon plastics available such as Nylon 6, Nylon 66 and Nylon 12 are under the polyamide group. The Nylon 12 has gained attention from the industry in the past few decades because of its excellent properties [69]. Nylon 12 has a melting temperature of 224 °C [70]. However, the use of nylon 12 is still limited due to a lack of strength. In the past few decades, people have studied many attempts to improve Nylon 12 by adding fillers to the matrix and successfully demonstrated remarkable results [71]. The Nylon 12 is used for gas distribution pipes, moulds, tooling, prototype and end-use parts [72].

2.3 Process parameters

Process Parameters (PP) play a significant role in 3D printing processes to fabricate defect-free parts [77]. PP drives the microstructure and mechanical properties of the components. Generally, optimum process parameters are set up via experimental trial and error methods [47]. Here, numerous process parameters are used in the FDM process for the deposition of parts. Major process parameters (refer to Fig. 3) in the FDM process are briefed as follows [78, 79].

2.3.1 Layer thickness

Layer thickness or layer height is one of the vital parameters used during layer-by-layer deposition [80]. The height of the layer is defined in the vertical direction, i.e., the z-axis (shown in Fig. 5). Layer thickness depends on the nozzle diameter in FDM. In general, the layer thickness is lower than the nozzle diameter [47, 81]. A layer thickness can be assigned via slicing software. Smaller layer thickness better the surface finish, and larger thickness results in a poor surface finish. Because the staircase effect is the major issue in layer-by-layer deposition [81, 82].

2.3.2 Build orientation

It is defined as the inclination of the building part on the platform with respect to three axes (X, Y, Z). Common three orientations for tensile sample deposition include 0°, 90°,

± 45° angles. The 0° raster angle shows the highest tensile strength and least strength found at the orientation of the ± 45°. Part orientation 90° raster angle falls between them. The strength of the part depends on the part orientation. One can consider building orientation skills while orienting the parts [83, 84]. The build part orientation depends on the height of the building part, the area of the part resting on the platform, the quantity of support structures requires for overhanging and undercuts, mechanical properties to be obtained, surface roughness would occur, and dimensional accuracy.

2.3.3 Infill pattern

The outer perimeter of the part is filled with 100% or solid fill. An infill pattern is a material that needs to be filled inside of the object [77]. There are various shapes (rasters) of infill patterns available. The infill patterns include lines, rectilinear, linear, grid, star, cubic triangle, hexagon, zigzag, honeycomb, Hilbert curve, Archimedean chords, and Octagram cubic [85]. These patterns are used to fill inside the component during deposition. Various fill densities can be chosen in slicing software (e.g., Cura, Slicer) [86]. An appropriate infill pattern decides the part strength, quality, print time, mechanical properties and materials consumption [87]. Based on the requirement, the different fill densities can be chosen. Figure 6a shows 10%, 20% and 30% infill material density. Recently, MakerBot (a 3D printing company), introduced an adaptive minfill pattern (minimum fill). The algorithm decides automatically and selects the minimum material required to fill the object. This ensures less material consumption and a short print time [88]. However, the infill pattern substantially impacts the strength of the prototype, end-use part, and service conditions [49, 79].

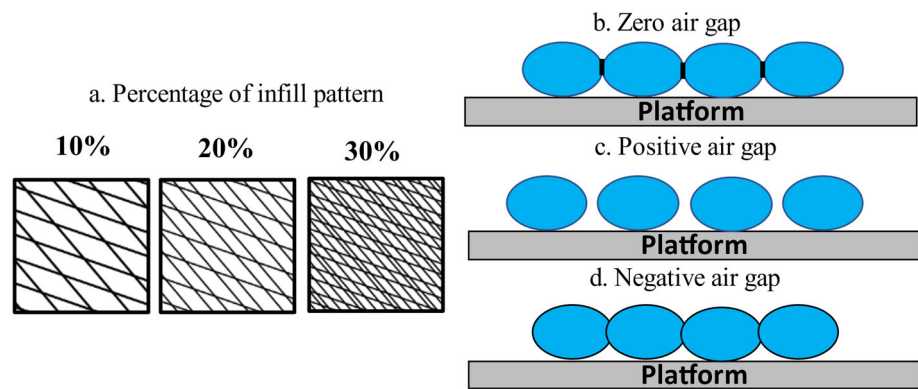
2.3.4 Extrusion or nozzle temperature

Extrusion temperature in which filament is heated above the melting temperature in the nozzle. The temperature is controlled by thermocouples attached to the nozzle. The temperature of the nozzle depends on the filament materials chosen for the deposition [77]. Improper melting may lead to partial melting or improper extrusion of material onto the platform. Every material has a different extrusion temperature and appropriate melting point used. Before actual deposition, the new material extrusion temperature must be checked with trial and error methods [47].

2.3.5 Air gap

It is defined as a gap between the two-neighboring rasters on a deposited layer. It is classified into three types: (i) zero gap, (ii) positive gap, and (iii) negative gap, as shown in Fig. 6b–d.

Fig. 6 a Infill pattern with different fill percentages, b zero air gap, c positive air gap, d negative air gap, e positive air gap, f negative air gap [85]



The zero gaps are called when two rasters are attached without overlap or gap. The positive gap results when the two adjacent rasters have a gap between them. And the negative gap is occurring when two adjacent rasters overlap each other [85].

2.3.6 Print speed

The print head speed moves under the table along the X and Y axis during deposition. The object printing time depends on the print speed and is expressed in mm/min or mm/s [2, 89]. The print speed increases lead to lower overall build time. The print speed in the FDM process can be adjusted using slicing (Like Cura) or firmware software. Generally, higher print speed is preferred over functional parts for prototype printing. Faster print speed leads to poor dimensional accuracy, defects, and weaker strength of the parts [90]. Also, print speed varies based on the material used in the building part. For instance, PLA material is printed faster, while TPU needs to be printed at a lower speed to prevent deformation or warpage of the part [91].

2.3.7 Extrusion width

Raster or extrusion width is the width of the bead, as shown in Fig. 7. The raster width depends on the diameter of the nozzle and raster orientation. If the extrusion width increases, the radius of corners increases resulting in voids formation in the object (i.e., negative air gap). The negative air gap is reduced by overlapping the rasters (Fig. 7). Also, voids are further reduced by decreasing the layer height [92].

2.3.8 Raster angle

The raster angle is defined as the angle between the raster of the nozzle and the build platform (X-axis). The raster angle of the two neighboring layers was measured to be 90° , refer to Fig. 7. Commonly angle selected is between 0° and 90° [79, 93].

2.4 Nozzle opening size and its material

The nozzle is the main part of the FDM printer, where the filament melts in and extrudes material. The brass nozzle was widely used with an opening size of 0.4 mm [94]. The brass has outstanding thermal conductivity and is commonly used to melt filaments like ABS and PLA [95]. The materials are easily processed in a brass nozzle reported in Table 1. However, to meet the requirement of high-temperature, abrasive materials processing in FDM printers. Various nozzle sizes with different materials were used [95]. The new nozzles are regularly introduced to the market made with brass, hardened steel, titanium, ceramic, stainless steel, and others. The nozzle diameter is known as the internal diameter of the extruder nozzle opening. The typical nozzle sizes include 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5, 0.6, 0.8 and 1.0 mm [94]. Understandably, a smaller diameter dispenses lower material and larger diameter results in higher build material. Hence, build time depends on the nozzle diameter used for the printing. However, a larger diameter worse the degree of accuracy of printed parts due to the width of the embossed path [96]. Several studies reported the optimal selection of nozzle diameter to affect the accuracy and properties of the printed parts [94, 95, 97].

3 Literature review of previous work on fused deposition modeling from a military perspective

The literature review focuses on FDM applications from a military (air force, land army, and navy) standpoint. Forecasting on deployable military technologies in the next two decades has been reported in Fig. 8. It was reported that several areas emerge to contribute and enhance the capabilities of military weaponry, contingency resupply, and wartime preparations. Computer and communication, artificial intelligence, projectiles, and propulsion technologies have a revolutionary impact on military systems. The report

Fig. 7 The concept of layer height, extrusion width, raster angle and air gap for small layer height [85]

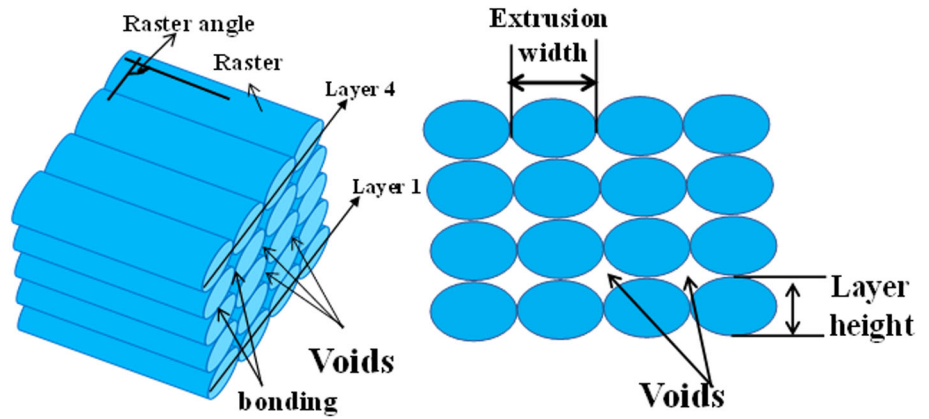


Table 1 Comparison of commercially available filaments and their properties [52, 58, 59, 68, 69, 72–75]

Materials	Melting point(°C)	Density (gm/cm ³)	Tensile strength (MPa)	Tensile modulus (MPa)	Tensile elongation (%)	Flexural strength (MPa)	Izod impact notched (J/m)	Izod impact unnotched (J/m)
ABS	200	1.04	22	1627	6	41	106.78	213.56
PLA	170–180	1.24	59	2700–4140	7.0	106	26	195
HDPE	128–138	0.94–0.965	29.5	620–1090	7.0–14	16.5–91	0.0750	53.40
PC	100–110	1.2	65.5	22,206.3	60	103.4	693.55	–
Nylon	178–224	1.03–1.25	30	1500	6.12	55	140	1800

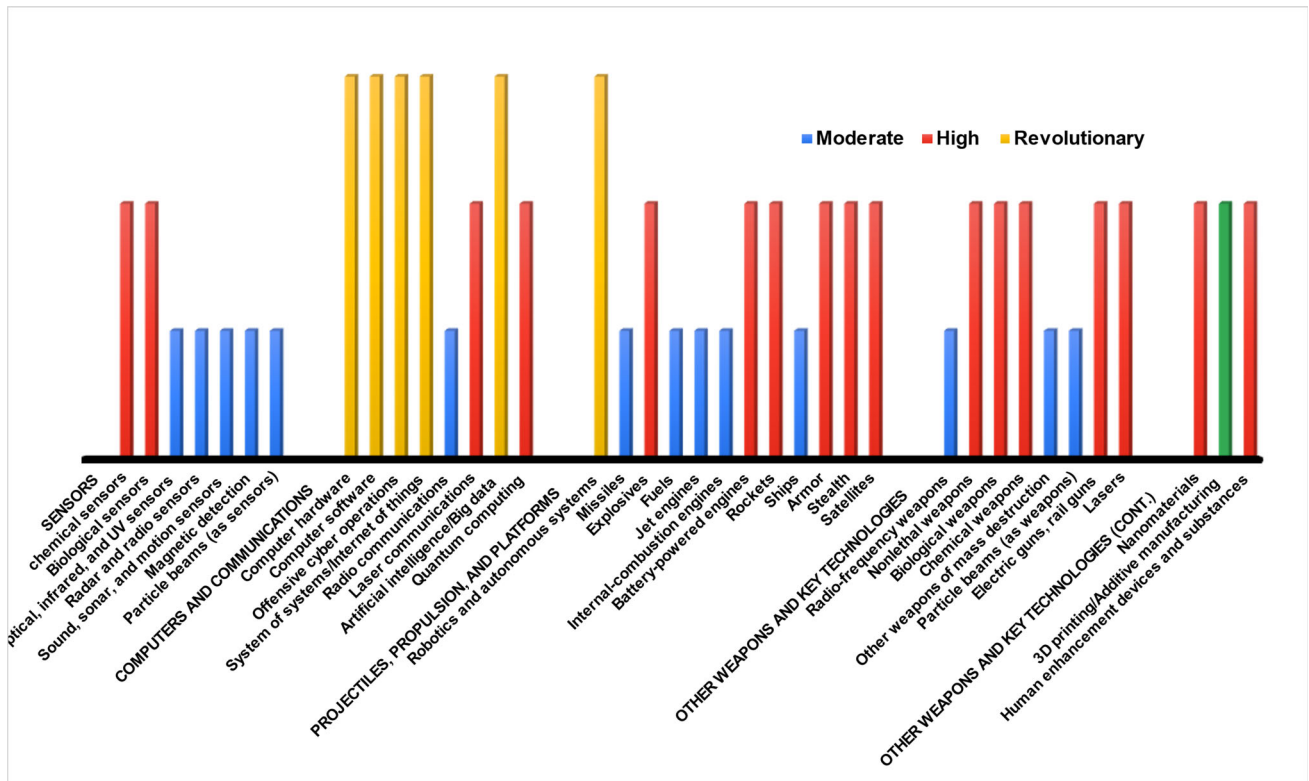


Fig. 8 Projected key deployable technologies in defense by 2020–2040 [98]

also claims that 3D printing/additive manufacturing (highlighted in green) is the highest deployable technology in the next two decades [98]. The additive manufacturing adaption in the military is about 5%, and the material extrusion-based technologies market share is about 10% [99]. This shows the growth of material extrusion in military applications. Ciobotă et al. 2019 [100] reported that Additive Manufacturing (AM) will play a pivotal role in the next decade due to its endless opportunities. AM is spreading to all the sectors such as motor vehicles, consumer products, business machines, medical, academic, aerospace, and military [8, 101]. FDM technology is one of the 7 AM technologies used for prototyping, end-use parts, visualization and tooling [19, 102]. Product development and part realization of complex shapes in the defense sector are challenging due to time and cost. Yagnik 2014 reported that FDM helped to fabricate prototypes more quickly for their jet engine parts than conventional techniques. Over 2500 Prototypes were fabricated using the FDM technique. They have concluded that FDM allows the manufacture of physical parts cost-effectively and rapidly. So that lowers product development cycle time with flexible design changes in components [24]. Brischetto et al. 2016 [103] Presented the design and development of a multi-rotor drone or unmanned aerial vehicle. The multiple parts fabrication and shape optimization of the drone was carried out via FDM technology. The developed UAV aimed to be used in surveillance, photography, filmmakers etc. Thompson 2016 [102] reported on the aircraft's parts and tooling for a new level of maintenance using FDM technology. The research paper demonstrates the importance of FDM technology in aircraft logistics and supply chain management. The study reports that the Maintenance Group (MXG) can opt for FDM technology for aircraft maintenance. It was concluded that 3D printing is leveraged as an alternative source for fabricating aircraft parts and tooling. Unlike conventional techniques, the impact of aerodynamic structures and shape optimization of UAV parts is significant due to viable FDM technology. Product development cycles (UAVs) drastically reduced and increased efficiency. Hence, FDM technology is helpful for design iterations and end-use parts for the drones used in the military [104]. Gebisa and Lemu 2018 [105] investigated the applications of ULTEM 9085 material using FDM technology in the aerospace, military and automotive sectors. They have concluded that process parameters (fill density, layer height, preheating etc.) play a significant role in fabricating defect-free parts in FDM. In another study, Easter et al. 2013 explored the FDM technology for printing UAV parts with different materials including, ABS, ULTEM, and PC. ABS has commonly used filament for actual parts and as a support structure (easily dissolvable) in FDM due to its strength-to-weight ratio. Ultem material is approved by the Federal Aviation Administration (FAA) for use in aircraft structures due to its high-strength property. Polycarbonate

is clear and has superior impact strength used in biomedical. They have concluded that design freedom, low cost and end-use parts are possible for UAVs via the FDM process [106]. Balasubramaniam et al. 2019 [107] have studied the surveillance quadcopter with PLA parts produced via FDM technology. Also, FDM-printed PLA parts are subjected to electrochemical deposition. They have found that 22% parts reduction and 18% of weight saving. Further, it was reported a 10% increment in tensile, flexural and impact properties due to the electrochemical coating. Booth et al. 2018 [108] have reported the potential of AM systems to produce smaller and lighter weaponry in army aviation, missile research and autonomous air/ground systems. Specimens were prepared according to ASTM (D3846-02 and ASTM D5379) using FDM technology. Specimens include ABS, PLA, and HIPS materials subjected to in-plane and out-plane shear properties characterization. It was found that FDM printed parts have shown better shear properties than the conventionally processed ones. Hence, FDM could be utilized for fabricating various parts for military. Edwards 2017 [109] investigated FDM technology for nano-based sensors and components to improve army weaponry. Integrating nanotechnology into weaponry systems will reduce weight, size and cost. It was concluded that nanotechnology and 3D printing might revolutionize weaponry systems.

Also, FDM is used in the medical field for treating warfighters from their head injuries. Because military surgeons carried out complicated head trauma operations. Proper surgical planning is required for the safety and success of head trauma. To address these constraints, FDM-printed neurotrauma models were focused on training the non-neurosurgeons. The models of the actual neurotrauma cases were fabricated using CT scans and FDM technology. 3D models represent details such as the cranium, the lesion, and anatomical information. These details help in addressing actual issues in neurotrauma. They have concluded that FDM technology can fabricate trauma models for surgical planning and educating military surgeons. The CT scan data to FDM printed trauma models [110]. In another case where Defense Advanced Research Projects Agency (DARPA) fabricates an on-demand surgical tool kit using FDM technology (Stratasys μ Print Plus) with a thermoplastic ABS material. It was found that the sterility of the printed samples is high and suitable for making the medical aid parts quickly [111].

Another military platform, the Navy, already started using FDM technology for rapid prototyping, custom tooling, designs, and product development purposes [112]. Hence, melt extrusion technology is widely used in the US Navy. The US Navy demonstrated FDM technology for their functional prototypes, concept models, and a few end-use parts [112, 113]. This cloud-based software was developed to identify the cost and benefit analysis of AM technologies in various stages of defense logistics [114]. Cunningham et al. 2015

researched multidimensional analysis of additive manufacturing for future naval supply chain management. They have reported that the manufacturing of naval products depends on various materials, minimization of manufacturing lead time and saving costs. Thus, FDM technology was used by the Netherlands armed forces to fabricate the naval parts [115]. Material extrusion is the best choice for polymeric fabrication of various non-critical defence structural components [116]. On the battlefield, safety, real-time physiological feedback, and threat information are crucial for the warfighter. To address these issues and enhance performance. The material extrusion emphasizes the resolution, safety, and sensitivity of sensors and faster production. They have witnessed customizable, tuneable, accurate, reduced labour work and steps to develop sensors. These sensors were also made at a low cost and showed better adhesive properties with parts [22, 117]. Including the above applications; operation Iraqi Freedom like a situation of army logistics has also been analyzed. On-site fabrication of new parts/replacement as soldiers desired. Adaptivity and utilization of FDM technology for contingency resupply have been found satisfactory [118].

Nonetheless, some of the land, naval and air force original equipment manufacturers (OEMs) are no longer running businesses. Thus, parts of the equipment must be repaired, or reverse-engineered using old drawings. It is a cumbersome process of fabricating parts to replace, repair and maintenance. Hence, 3D printing is used for repair, tooling, moulds, patterns, and end-use parts. Overall, FDM technology helps the fabrication of military parts at a low cost and time [119]. The following case studies demonstrate the importance of FDM in military applications.

3.1 Case study 1: successful use of FDM technology in the product development cycle

Gas Turbine Research Establishment (GTRE) is the national lab in India. The Kaveri jet engine is one of the vital projects of GTRE. The design and development of the Kaveri jet engine are planned for marine and aeronautical applications. For the prototyping, traditionally were used many conventional manufacturing methods. The product development stage is a traditional route that is time-consuming and costly. Conventionally building physical prototypes and assembly requires a minimum of 12 months and at the cost of \$60,000. However, due to the time and cost of product development time. They have installed FDM Titan technology for the fabrication of quick prototypes and end-use products [24]. Because of the FDM technology making of prototypes and assembly time was reduced to 1.5 months and \$20,000. The cost comparison of conventional and 3D printed prototype activities at GTRE is presented in Table 2. Tremendous success has been achieved using FDM technology in terms

Table 2 Cost comparison of conventional and FDM prototypes in Kaveri jet engine [24]

Method	Cost estimate	Time estimate
Conventional methods for fabricating the physical prototype	\$60,000	12 Months
3D printing of physical prototypes with FDM	\$20,000	1.5 Months
Savings	\$40,000 (60%)	10.5 Months (87.5%)

of cost, and product development cycle time of the Kaveri jet engine. Assembled Kaveri jet Engine with FDM-printed physical parts is shown in Fig. 9. The output of the case study is that a lighter engine validates cost-effectively within a short time This case study shows FDM capability in product development cycles in defense applications.

3.2 Case study 2: reduction of time and cost for design and development of unmanned air vehicles (UAVs)

The novel routes to make energy-efficient, cheaper, lighter UAVs are extensively explored in military sectors for different purposes [120]. Leptron Inc. is a leader in developing remote unmanned aircraft and helicopters. The company used an FDM printer in their UAV and tooling design and development activities (supported by Stratasys Inc). They have developed RDASS4 the UAV armoured for inspecting terrain and border [121]. RDASS 4 has several parts: a compact case, electronic housing, battery box, bracket, etc. Conventionally injection moulding method was used for the fabrication of fuselage components at the cost of \$250,000 and 14 months. The major problem was that complications in adopting design changes to the tooling are expensive. This resulted in greater time for product development and delays in reaching the market on time. Later, John Oakley, chief executive of Leptron, identified the FDM technology for this project. The core components of RDASS4 took 48 h, and smaller parts were built at 36 h of printing time. The prints are used for testing, fit evaluation, functional prototypes and end-use parts. Finally, prototypes and production parts were fabricated at the cost of \$103,000 in 8 months. During the project, 200 design iterations were to improve the aerodynamic performances. Another flexibility was enjoyed; each part was made four times design changes without much time and difficulty, unlike conventional methods. Cost and time comparisons of the traditional and FDM printed parts are shown in Table 3. FDM technology has reduced the greater

Fig. 9 Assembled Kaveri jet engine prototype with 2500 FDM printed parts (Image is reproduced with the permission of publisher/author/GTRE) [24]

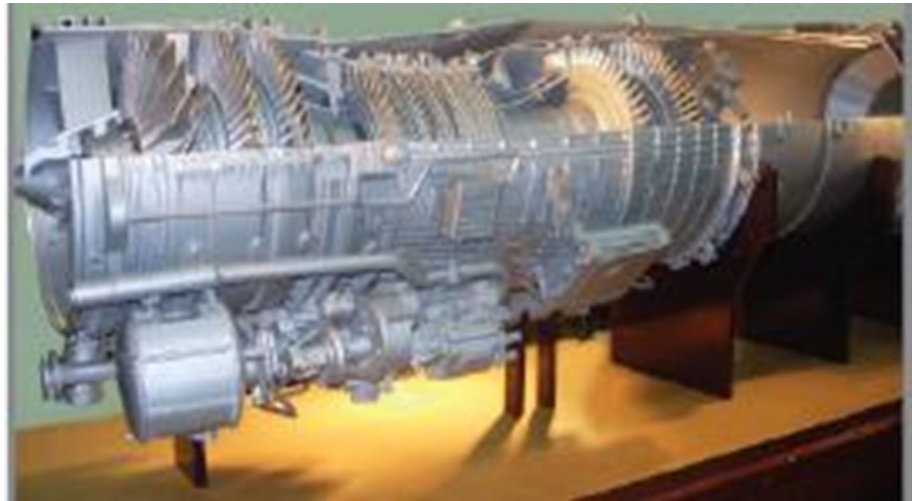


Fig. 10 RDASS4 parts and case **a** electron housing, **b** battery box, **c** compact case [121] (Courtesy: Leptron Inc.)

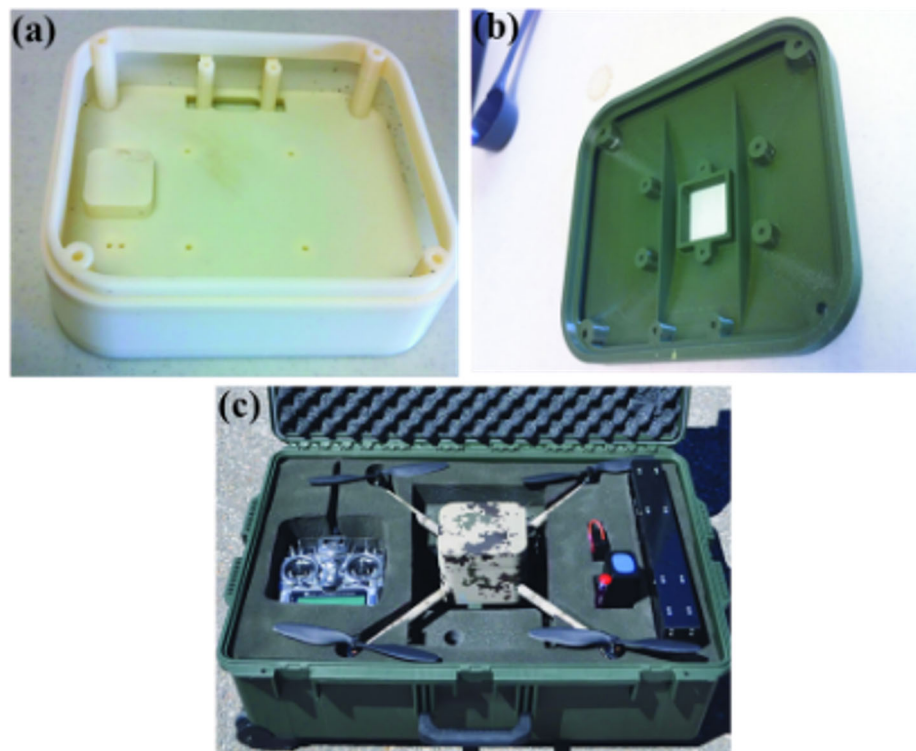


Table 3 Cost and time comparison of conventional and FDM printed UAV parts [121]

Method	Cost estimate	Time estimate
Injection molding with CNC machined tooling	\$250,000	14 Months
FDM end-use parts	\$103,000	8 Months
Savings	\$140,000 (59%)	10.5 Months (43%)

time and cost. The various FDM printed parts such as electronic housing, battery box and compact case are shown in Fig. 10 [121].

4 Conclusions

Consolidation regimes associated with fused deposition modeling and its applications in the military sector. The following conclusions were drawn:

- FDM is a low-cost printer, with ease of operation and processes a wide range of materials and process parameters play a pivotal role in the fabrication of defect-free parts;
- The military is one of the core sectors that use FDM technology for various purposes including non-negotiable product development cycles, end-use parts and integration of sensors with weaponry. Additionally, FDM is capable of fabricating trauma models for surgical planning and educating military surgeons;
- FDM prototypes greatly reduce design-to-production time and improve higher return on investment (ROI);
- Case studies on the use of FDM technology prove that conventional methods show the higher saving in product development time and cost;
- Thus, 3D printing (FDM) is a futuristic deployable technology in the military. One can utilize the work to understand the importance of the FDM process, its capabilities, the various materials it can process, and exclusive FDM work in the military sector.

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Declarations

Data availability No data set is available with the article because no new data were created/analyzed in this study.

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