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CRITICAL REVIEW

Polymer 3D printing in perspective: Assessing challenges and opportunities in industrial translation against the metal benchmark

Naomi C. Paxton[1,2] · Jiachen Zhao[1] · Emilie Sauret[1]

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Abstract

Additive manufacturing is swiftly transitioning from a prototyping tool to a useful technology for industrial-scale manufacturing. As global industries seek to harness its potential, several 3D printing technologies have been successfully integrated into mainstream manufacturing workflows, based on the range of processable materials, fabrication mechanisms and integration into regulated environments. While metal 3D printing has established a significant niche in the context of aerospace and automotive manufacturing, the upscaled translation of polymer 3D printing lags, limited by several critical challenges, both in the materials domain, as well as the technical fabrication mechanisms. This article seeks to juxtapose the growth, challenges and opportunities of metal and polymer additive manufacturing, emphasizing the latter's potential for future growth in sectors such as polymer waste recycling and point-of-care medical device manufacturing. By dissecting the complexities surrounding feedstocks, manufacturing and post-processing workflows and the advances in simulations and quality control, this review provides comprehensive insights into the progression of 3D printed technologies for industrial-scale additive manufacturing into the future.

Keywords Selective laser sintering · Stereolithography · Material extrusion · Electrospinning · Biomaterials · Aerospace manufacturing · Automotive manufacturing · Medical devices · Polymer modelling

1 Introduction to industrial applications of additive manufacturing using metals and polymers

1.1 Historical perspectives on the development and industrial use of metal vs polymer AM technologies

3D printing, known formally as additive manufacturing (AM), has emerged as a transformative manufacturing opportunity, stimulating a new era of advanced manufacturing and design capabilities. Originating in the 1980s, Chuck Hull conceptualized and subsequently patented the first stereolithography (SLA) apparatus—a breakthrough that laid the groundwork for the evolution of 3D printing [1]. Following Hull's seminal invention, many diverse 3D printing techniques were developed over the subsequent decades. From fused deposition modelling, now referred to fused filament fabrication (FFF), one of the most accessible technologies in the material extrusion (MEX) class, to selective laser sintering (SLS) and other powder bed fusion (PBF) techniques, these diverse methodologies catered to an expanding array of materials and applications [2]. The expiration of key foundational patents in the early twenty-first century that truly accelerated advancements in 3D printing, where entrepreneurs, innovators and hobbyists alike were no longer constrained by patent restrictions to explore 3D printing for processing a broad range of materials with intricate precision not realisable using traditional manufacturing techniques. This transition not only spurred a surge in start-up ventures but also birthed a vibrant open-source ecosystem

✉ Naomi C. Paxton
n.paxton@qut.edu.au

✉ Emilie Sauret
emilie.sauret@qut.edu.au

1 School of Mechanical, Medical & Process Engineering (MMPE), Queensland University of Technology (QUT), Brisbane, Australia

2 Centre for Biomedical Technologies, Queensland University of Technology (QUT), Brisbane, Australia

[3]. The capability of 3D printing technologies has expanded exponentially [4], and its cost-effectiveness and versatility have made it an attractive proposition for industries ranging from aerospace to healthcare. No longer just a tool for prototyping, 3D printing is now reshaping traditional manufacturing paradigms, underpinned by digital design and manufacturing, sustainability and personalization agendas.

3D printing of metals has seen a substantial integration into industrial sectors, especially in aerospace, automotive and medical fields, where the fabrication of complex, custom and lightweight components is invaluable. The precision, ability to handle high-performance materials and freedom in design have enabled industries to manufacture previously challenging or uneconomical parts. In contrast, polymer 3D printing, despite its evident potential and versatility, remains notably underutilized in large-scale industrial contexts. While polymers have been widely used for rapid prototyping and some niche applications, their transition to broader industrial manufacturing has not mirrored the large-scale adoption observed with their metal counterparts. This disparity underscores both the opportunities awaiting optimisation in polymer 3D printing and the challenges yet to be addressed to realize its full industrial potential.

1.2 Additive manufacturing technologies

The American Society for Testing and Materials (ASTM) and International Organization for Standardization (ISO) ISO/ASTM52900-21 standard classifies the major types of 3D printing or additive manufacturing processes into several categories [5]. The seven major categories are presented, with examples of specific techniques within each category, primary mode of fabrication, processable materials and a general price point range based on commonly available commercial equipment [3, 6].

- Binder Jetting (BJ) is characterised by a liquid binding agent being jetted onto powder material. Notable examples include ColorJet Printing (CJP) and Metal Binder Jetting. This technique can process metals, ceramics, sand and polymers, with commercial printer price points typically ranging from $50,000 to over $1,000,000 USD.
- Directed Energy Deposition (DED) employs focused thermal energy, such as lasers or electron beams, to melt materials as they are being deposited. Techniques like Laser Engineered Net Shaping (LENS) and Direct Metal Deposition (DMD) fall under this category. Predominantly, metals and ceramics are the choice of materials. Commercial printers in this category are typically priced between $250,000 and $1,500,000 USD.
- Material Extrusion (MEX) involves dispensing material through a nozzle or orifice. Fused Deposition Modelling (FDM), now known as Fused Filament Fabrication (FFF) are popular examples. These printers process thermoplastics, and some even handle certain metals and ceramics, typically in composite with polymers. The price range is vast, spanning from a modest $200 to an upscale $600,000 USD.
- Material Jetting (MJ) works by jetting droplets of the build material onto the build platform. PolyJet and NanoParticle Jetting (NPJ) are representative techniques. They majorly process photopolymers and waxes, with some handling metals. These printers come at a price range of typically $50,000 to $800,000 USD.
- Powder Bed Fusion (PBF) utilises thermal energy from sources like lasers or electron beams to selectively fuse regions in a powder bed. It encompasses methods like Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM) and Electron Beam Melting (EBM). They can handle polymers, metals and ceramics. Commercial units may be priced between $50,000 and $2,500,000 USD.
- Sheet Lamination (SL) is a technique where sheets of material are bonded and subsequently cut to shape. Laminated Object Manufacturing (LOM) and Ultrasonic Additive Manufacturing (UAM) are examples. The processable materials include paper, metals and polymers, with printers may be priced from $10,000 to $500,000 USD.
- Vat Photopolymerization (VP) revolves around curing a liquid photopolymer contained in a vat using a focused energy source. Stereolithography (SLA), Digital Light Processing (DLP) and Continuous Liquid Interface Production (CLIP) are popular methods within this category. They primarily process photopolymers. Price points for these printers may vary from $250 to $600,000 USD.

These diverse technologies represent an extremely broad range of manufacturing capability and widely varying adoption in industrial contexts, with commonality limited simply in the use of additive and layer-by-layer fabrication rather than subtractive use of feedstock material to create products. Some of the most commonly used 3D printing techniques in industrial contexts include PBF fusion techniques such as SLS and SLM for processing a range of metals to create high-precision, high-strength and lightweight parts for aerospace, automotive and surgical applications, as well as SLA for producing polymer dental products. The successful translation of these manufacturing techniques beyond R&D and into mainstream industrial contexts is reflected in the development of international standards to guide and govern the implementation of advanced manufacturing.

1.3 Standards

The development of standards in industrial manufacturing is pivotal in propelling the adoption of new technologies.

These standards play a pivotal role in advancing metal 3D printing in the industrial sectors by establishing clear definitions and terminologies and providing a unified language for professionals in the field. Furthermore, they set benchmarks to gauge the efficiency of various production methodologies, ensuring that the final products meet stringent quality criteria. These standards outline precise procedures for the calibration of additive manufacturing machinery, ensuring consistency and reliability across the board. This commitment to standardisation underscores the growing prevalence and significance of metal 3D printing in industrial applications. In addition to the aforementioned ASTM ISO/ASTM52900-21 standard defining AM terminology [5], this article will include discussion of a range of other standards available in industry-specific contexts.

1.4 Aim and scope

This article seeks to review the latest developments in industrial applications of 3D printing, comparing the successful translation of metal 3D printing into several industries compared to the limited adoption of polymer 3D printing. This article aims to generate deep insights into current challenges in the field and future opportunities for the development of polymer 3D printing technologies suited to use in upscaled manufacturing contexts. Firstly, the current state-of-the-art applications of 3D printing in aerospace, automotive manufacturing, dentistry, medicine and surgery will be discussed. This defines the current state of play for industrial utilisation of 3D printing technologies and key points of distinction compared to traditional manufacturing that these have replaced. This is followed by an in-depth review of current innovation in 3D printing methodology that is specifically forwarding the industrial use of these technologies towards mainstream use. Considerations spanning material sourcing, integration within manufacturing workflows and the use of simulation and modelling are reviewed. Finally, future perspectives on the anticipated impact of 3D printing in key emerging industries will be analysed through the lens of personalisation in healthcare and manufacturing sustainability.

2 Industrial applications of 3D printing

2.1 Aerospace industry

Metal 3D printing has revolutionised the aerospace manufacturing sector by enabling the creation of components with intricate geometries that are otherwise unachievable through subtractive methodologies such as machining. By employing techniques such as SLS and SLM, manufacturers can craft hollow structures, internal lattices and cooling channels directly within solid components, enhancing material efficiency and functional performance using sophisticated designed previously unrealised using traditional manufacturing techniques [7]. Advanced, 3D printed designs result in parts that retain high strength but are considerably lighter, a breakthrough particularly useful in the aerospace industry where strength-to-weight ratio is paramount [8] to reduce fuel consumption and as such gas emissions. Importantly, 3D printing enables part consolidation, enabling the fusion of multiple components into a singular, cohesive unit. This integration not only streamlines the design but profoundly impacts the assembly phase, drastically cutting down on time and resources traditionally expended in piecing together multiple parts [9]. Moreover, fewer components translate to a reduction in potential failure points, thereby simplifying maintenance and enhancing product longevity. The capability of 3D printing for part consolidation offers a holistic solution, enhancing efficiency from production to product lifecycle. Companies such as General Electric (GE) Aviation have been at the forefront of this revolution, with their LEAP engine incorporating fuel nozzles manufactured using SLM [10]. Airbus is another industry giant that has actively integrated metal 3D printing techniques; they have introduced more than 1000 3D printed components in the A350 XWB helicopters, contributing to weight savings and optimised supply chain processes [11]. Such implementations highlight the transformative role of metal 3D printing in aerospace, allowing for optimised design, rapid prototyping and a shift towards more sustainable aviation solutions.

Titanium allows, such as Ti6Al4V, represent some of the most commonly utilised materials in this sector, owing to their high specific strength, corrosion resistance, weldability, fracture toughness and durability [12, 13]. However, several manufacturing challenges remain the topic of ongoing research to better optimise the fabrication of high-strength components for aerospace applications. For example, the minimisation of crack and pore formation during the sintering process is vital to achieving high strength parts [14]. Zhang et al. demonstrated that through the incorporation of support structures, powder leakage holes and other design iterations, a SLM-manufactured connection seat of a recycling subsystem was successfully manufactured with an approx. 25% reduction in weight compared to the original design (Fig. 1) [14]. In addition to design and SLM manufacturing optimisation, research into the influence of post-processing procedures on structural and mechanical properties of SLM-manufactured parts is of vital importance. For example, hot isostatic pressing (HIP) is routinely employed to eliminate porosity, release residual stresses and improve the mechanical properties of the produced parts by applying high temperature and isostatic pressure [15]. A substantial body of research has demonstrated the significant benefits to employing such post-processing steps, increasing the density

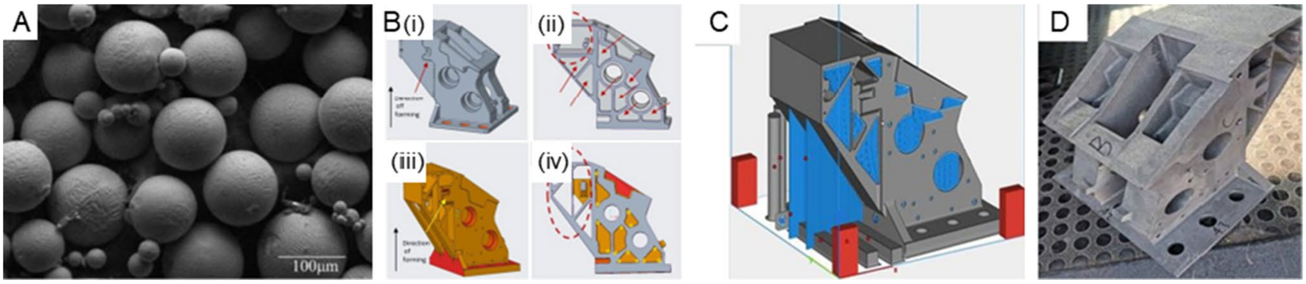

Fig. 1 Titanium alloy component manufactured using selective laser melting (SLM) in the aerospace industry. **A** Raw particles, **B** CAD of bespoke connection component, **C** addition of support structures in preparation for manufacturing and (D) final product produced using SLM. Reprinted from [14] with permission from Society of Photo-Optical Instrumentation Engineers (SPIE)

[16] and compressive properties [17] of metal alloy parts produced using SLM.

Led by organisations such as the ISO and ASTM, a diverse portfolio of standards has been developed to aid the translation of metal additive manufacturing technologies [18]. Additionally, numerous other international and national bodies, such as the National Aeronautics and Space Administration (NASA), the American Society of Mechanical Engineers (ASME), the American Welding Society (AWS) and the German Institute for Standardization (DIN), have been actively developing standards tailored to their specific needs, emphasising areas like design, testing and material specifications [19]. Their collaborative efforts have resulted in a structured approach to metal AM standards, categorised into general, application-specific and specialised standards. These standards address various facets of AM, including material characterisation, design guidelines, test methods and qualification principles [19].

2.2 Automotive industry

The automotive industry has also extensively embraced 3D printing of metals as a transformative tool in its manufacturing arsenal, offering unprecedented design latitude and accelerated time-to-market [20]. Similar to aerospace, one of the primary advantages is the capability to produce metal parts with complex internal geometries using PBF techniques such as SLS and SLM. These not only optimise material usage but also enable lightweight components without compromising on strength. In a sector where every gram counts towards fuel efficiency and performance, such weight savings are invaluable [21]. Recent studies have investigated the comparison of mechanical performance [22] as well as joining behaviour between conventionally manufactured and SLM-manufactured parts [23, 24] (Fig. 2). For example, Cecchel et al. (2022) evaluated Ti6Al4V parts manufactured from SLM versus conventional forging over a range of tests pertinent to development of products for automotive applications. Following microstructural analysis, wear resistance and corrosion resistance testing, it was found that parts produced with SLM performed comparably to forged samples [25].

Several industry leaders have showcased pioneering applications of metal 3D printing. For instance, Bugatti, a name synonymous with luxury and performance, has incorporated titanium 3D printed brake callipers, harnessing the technique's potential to create a part that is not only 40% lighter but also stronger than its conventionally manufactured counterpart [26]. Similarly, BMW has been exploring additive manufacturing to produce customisable parts,

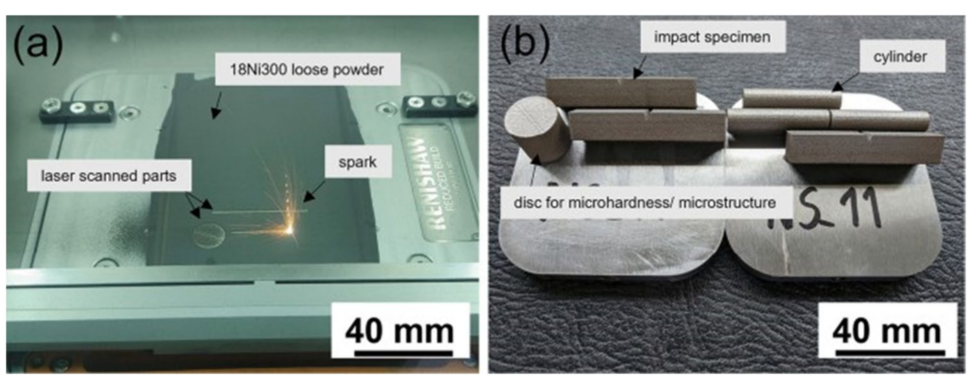

Fig. 2 **a** In situ image of SLM manufacturing process of steel (18Ni300) and **b** final fabricated produces for mechanical testing comparing SLM-manufactured parts with conventional die cast parts. Reproduced from [22] with permission from SNCSC

signalling a potential shift towards more personalized vehicles in the future [27]. Beyond high-performance vehicles, everyday cars are also beneficiaries. General Motors, for example, has been integrating 3D printed parts to reduce mass and consolidate multi-part assemblies into single components, optimizing both production and vehicle performance [28]. Furthermore, the ability of metal 3D printing to rapidly produce prototypes means that design iterations can be tested and refined in real-time, reducing development cycles and fostering innovation.

While metal 3D printing has established a considerable presence in the automotive manufacturing sector, polymer 3D printing is steadily carving its niche, presenting unique advantages and opportunities [29]. Polymers, inherently more versatile and lighter than metals, offer a wide range of material choices tailored to specific applications within the automotive sector. Utilising techniques such as FFF and SLA, manufacturers are now creating parts that marry functionality with aesthetics. For instance, complex and customisable interiors, ergonomic controls and intricate dashboard assemblies are now being 3D printed with polymers, offering both design freedom and rapid prototyping [30]. Companies like Ford have adopted polymer 3D printing for tooling, fixtures, and even some end-use parts, recognising the potential to expedite the production process and reduce costs. Beyond components, the ability to use translucent or transparent polymers has seen a rise in the production of innovative lighting solutions and indicators.

Within the context of automotive manufacturing, 3D printing has also been used to create assistive devices for manufacturing labourers to minimise injury risk. For example, Toso et al. (2022) developed a low-cost thumb orthosis to reduce the risk of injury whilst performing a repetitive task during vehicle assembly. The product was fabricated from low-cost polymers such as PLA and TPU using a FFF printer and were deemed "comfortable" on analysis [31]. Whilst highly valuable in a manufacturing context, the authors noted limitations in upscaling manufacturing of such devices, further reinforcing the limited utility of such fabrication techniques beyond prototyping using existing low-cost FFF technologies.

2.3 Dentistry and orthodontics

3D printing has played a transformative role in dentistry, dramatically reshaping treatment pathways with its precision and efficiency [32]. Some of the most significant applications lie in the realm of drill guides, dental implants and prosthetics. Labour-intensive mouldings and prolonged waiting periods are no longer required using these 3D imaging and printing technologies. Using patient-specific digital scans, dental professionals have been pioneering the use of digital technologies to produce 3D print crowns, bridges, dentures and a host of other dental prosthetics. Studies have validated workflows for using 3D printing compared to conventional manufacturing such as milling for producing crowns, demonstrating that higher accuracy products with fewer discrepancies can be produced using DLP or SLA [33] (Fig. 3A). This technology promises not only a rapid turnaround but also an unprecedented accuracy, ensuring prosthetics that fit seamlessly, optimising patient comfort, treatment efficacy and long-term patient outcomes. In the orthodontics subfield, traditional metal braces, often viewed as cumbersome, uncomfortable and aesthetically unpleasing, are gradually being replaced by clear orthodontic aligners tailored for individual patients. Brands such as Invisalign have capitalised on 3D printing capabilities to produce these custom-fit aligners, transforming orthodontic treatment into a more discreet and comfortable experience [34] (Fig. 3B). These aligners, derived from digital dental scans, not only offer aesthetic advantages but also facilitate easier oral hygiene practices [35].

Dentistry is one of the few industries in which polymer 3D printing technologies have made considerable inroads into routine use. A variety of biocompatible polymers are employed to ensure durability and safety [36]. Photocurable polymer resins are prevalent in applications ranging from dental models to orthodontic devices. Poly(methyl methacrylate) (PMMA) is favoured for prosthetics like dentures, while materials such as polycarbonate and thermoplastic polyurethane cater to orthodontic and flexible needs, respectively. Additionally, specialised biocompatible resins, often FDA-approved or CE-certified, are essential for long-term intraoral devices, ensuring patient safety and compliance with regulatory standards.

2.4 Medicine and surgery

Common to both dentistry and surgery, the domain of diagnosis and treatment planning has witnessed considerable advancements with 3D printing's ability to produce dental or anatomical models swiftly and accurately [37]. Traditionally, creating physical representations of patient anatomy for prosthetics or moulds onto which devices could be adapted could be achieved by taking physical impressions, such as dental or ear impressions. Likewise, patient anatomy is traditionally viewed from 2D sliced scan data such as x-ray, CT or MRI, or subsequent 3D reconstructions [38]. Using digital manufacturing workflows, a digital scan can be rapidly converted into a digital and then physical 3D model using 3D printing which serves multiple purposes (Fig. 4), from aiding clinicians in visualising and planning complex procedures to educating patients about their health, proposed treatments and interventions [39]. This fusion of technology with surgical and dental practice has not only streamlined

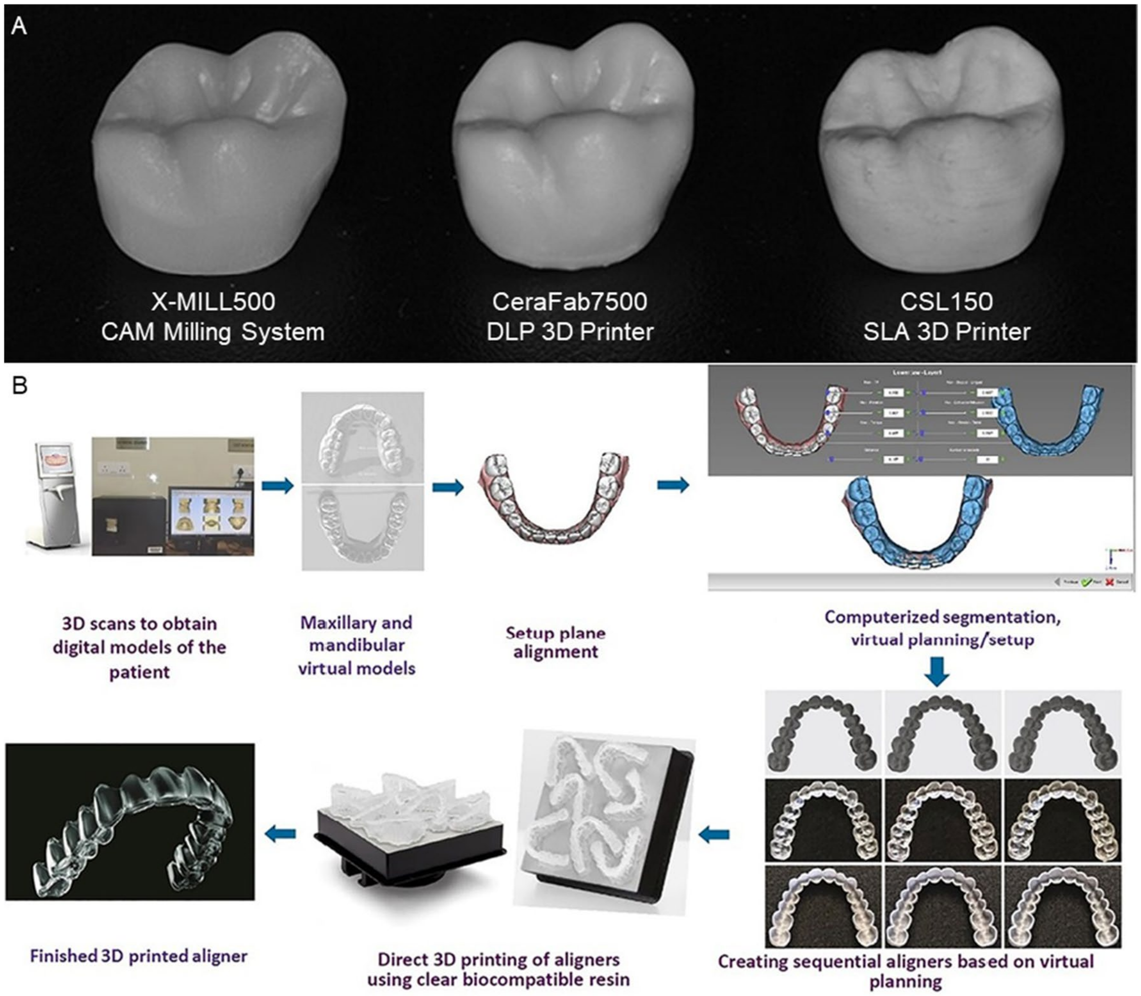

Fig. 3 **A** High resolution manufacturing of dental crowns comparing conventionally milled products using zirconia, compared to DLP and SLA 3D printed samples manufactured from alumina and zirconia respectively. Reprinted from [146] with permission from Elsevier. **B** Digital manufacturing workflow for designing and fabricating transparent aligners [147] (CC BY)

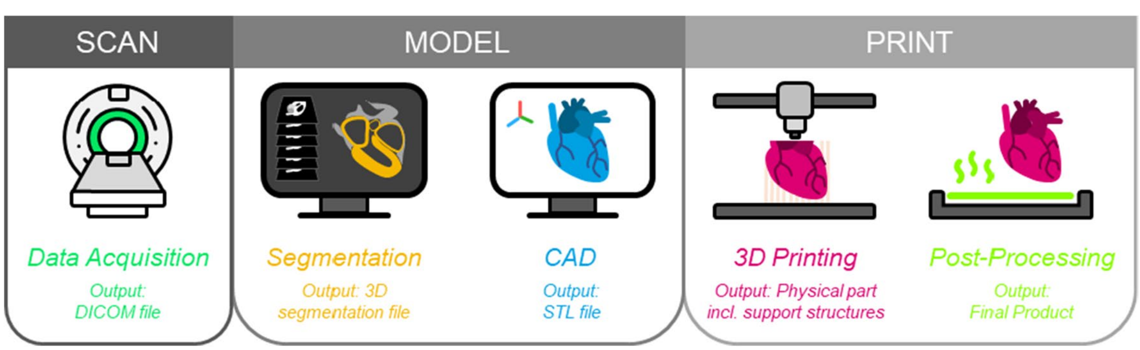

Fig. 4 Workflow for generated 3D printed products from medical scan data, spanning acquisition of scan images from CT or MRI scanning, digital identification of target anatomy and computer-aided design (CAD) to generate a digital 3D model and physical model production via 3D printing and post-processing, including sterilization if required [37] (adapted, CC BY)

processes but has also enhanced the patient's engagement and understanding of their treatment journey [40].

Metal 3D printing played a crucial role the medical sector, particularly in the domain of surgical implant manufacturing, by allowing the creation of patient-specific and intricately designed devices [41]. This technology's ability to craft detailed and tailored structures has made it particularly suited for orthopaedic, dental and spinal applications, where the patient-specific geometry fabricated as a bespoke product critically informs the fit of an implant and is critical to its success [41]. Several pioneering companies have incorporated patient-specific medical image manufacturing into their product offerings. One standout example is Stryker, which specialises in medical technologies, including orthopaedic and spinal implants. They have been instrumental in developing 3D printed titanium spinal implants, which benefit from the material's biocompatibility and the technique's ability to create porous structures mimicking natural bone to facilitate strong bonding to the vertebral end plates [42]. 3D printed products from other manufacturers, such as the Delta TT hemispherical cementless acetabular cup (Lima Corporate) produced using EBM have shown to facilitate improved osseointegration compared to conventionally manufactured alternatives (Fig. 5A) [43]. Many leading medical device manufacturers have transitioned to adopting metal 3D printing to produce orthopaedic and spinal implants, with the products widely demonstrating comparable or improved performance compared to conventionally manufactured alternatives due to their biomimetic structure facilitating osseointegration [44]. In addition to titanium alloys, polyether ether ketone (PEEK) is a high-strength thermoplastic widely used in surgical implants manufactured from convention techniques such as injection moulding [45]. Recently, MEX technologies have been leveraged to manufacture spinal implants using PEEK, offering new avenues in more biomimetic construct design to improve osseointegration and patient outcomes [46] (Fig. 5B). The broader promise of metal 3D printing in surgical implants lies in its potential to integrate personalization in surgical implant manufacturing. In a growing number of contexts, significantly improved patient outcomes are achieved where implants are not just generic off-the-shelf solutions but are tailored to individual patients' anatomy [41].

3 Innovations in 3D printing towards industrial use

As evidenced in Sect. 2.0, 3D printing technology has seen significant maturity in several sectors, where the focus has shifted from prototyping to mainstream production. This section discusses the innovations and challenges surrounding the scalable production of 3D printing materials and their supply chain implications, underpinning the future transition of other 3D printing technologies into mainstream manufacturing use.

3.1 Material feedstock supply and management

As 3D printing transitions from prototyping to full-scale production in various sectors, there is a growing demand for high-quality, consistent and application-specific feedstock materials. Based on the industrial application of 3D printing discussed above, the primary 3D printing methods seeing the most significant utilisation are PBF techniques for metals and polymers, as well as VP methods such as SLA and DLP and MEX techniques such as FFF. Based on these categories, a summary of the production considerations for manufacturing these feedstock materials is presented in Table 1. Metal powders, including titanium, aluminium and stainless steel, represent the most sought after materials for applications in aerospace, automotive and medical sectors. Particle size distribution remains the most critical quality control measure, informing part uniformity, density, defects and failure behaviour [47, 48]. In the polymer domain in the context of PBF manufacturing, nylon (polyamide, PA) is one of the most widely used materials offering high strength, stiffness and excellent chemical resistance, especially against

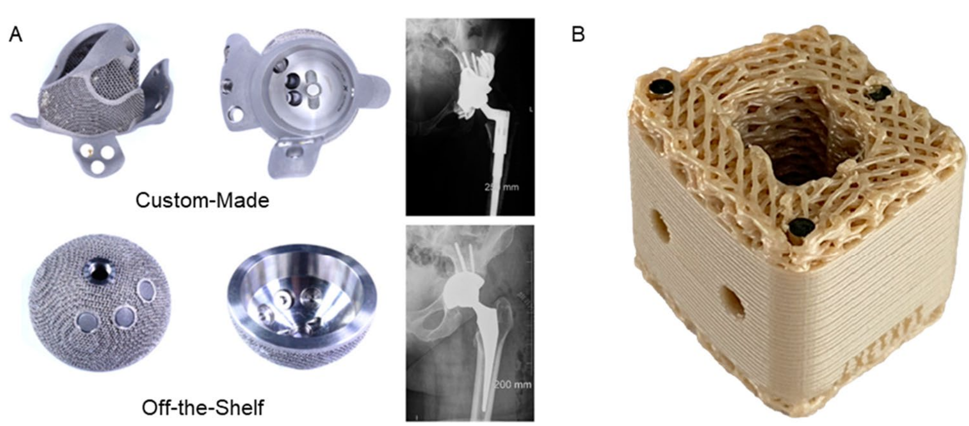

Fig. 5 Surgical implants manufactured using 3D printing. **A** Titanium implants for total hip replacement manufactured using PBF [148] (adapted, CC BY). **B** PEEK spinal fusion implant manufactured from a proprietary FFF process. Reprinted with permission from Curtiva Inc

Table 1 Examples of 3D printing feedstock, including popular materials, method of feedstock production, quality control considerations and product output

Category	Raw material examples	Feedstock production method	Quality control considerations	End product & packaging
Metal powders for SLS/SLM (PBF)	• Titanium & alloys (Ti6Al4V) • Aluminium & alloys (AlSi10Mg) • Stainless steels (316L or 17–4 PH)	Metal is melted and then formed into small particles via gas, electrolytic or plasma atomisation	• Particle size distribution and morphology • Flowability • Thermal properties	Powders are packed into bags or sealed drums depending on quality
Polymer powders for SLS (PBF)	• Nylon (PA6, PA11, PA12) • Thermoplastic elastomer (TPE) • Polypropylene (PP)	Polymer is mechanically ground into a fine powder	• Particle size distribution • Flowability • Thermal properties	Powders are packed into bags or sealed drums depending on quality
Photopolymer resins for SLA/DLP (VP)	• Monomers • Oligomers • Photo initiators • Additives such as stabilizers, pigments, fillers, plasticizers	Raw materials are mixed in large reactors to produce the resin. The formulation is adjusted based on the desired properties of the resin (e.g. hardness, flexibility, cure speed)	• Additive concentration • Rheological properties • Pigment consistency	The resin is packaged into bottles or containers, often light proof to prevent premature curing
Polymer filaments for FFF (MEX)	• Polylactic acid (PLA) • Acrylonitrile butadiene styrene (ABS) • Polyethylene terephthalate glycol (PETG) • Thermoplastic polyurethane (TPU)	Polymer pellets are melted and extruded through a die to produce a continuous filament	• Filament diameter • Air bubbles, defects • Moisture absorption	Extruded filament is wound onto spools, which are then vacuum sealed with desiccant to prevent moisture absorption

fuels and oils. While PA6 is commonly used in automotive and industrial parts, PA12 is a preferred choice for applications requiring consistent performance in diverse environments, including its widespread use in medical and surgical contexts due to its biocompatible and sterilizable properties in some medical-grade formulations [49].

The mass production of polymers includes the manufacture of photocurable resins, designed to solidify under specific light wavelengths for SLA and DLP printing methods, as well as thermoplastics that are extruded into filaments, serving as the primary feedstock for FFF printers. As 3D printing transitions from prototyping to mainstream manufacturing, the demand for these specialised polymers has surged, driving innovations in their large-scale production and quality control. The availability of soft materials, both in low stiffness photocurable liquid format and soft or highly elastic filaments, has seen a significant rise in recent years, offering versatile manufacturing capability with a class of materials that are typically challenging to handle and process. This trend is driven by the expanding applications of additive manufacturing beyond rigid prototypes to functional parts that require elasticity, such as gaskets, seals, wearable devices and medical products including prosthetics [50, 51]. Thermoplastic polyurethane (TPU) and thermoplastic elastomer (TPE) filaments have gained prominence for their rubber-like properties when used in FFF printers. SLA and DLP printing sectors have seen a rise in specialised low stiffness resins that can mimic the flexibility and resilience of natural tissues, opening new avenues in biomedical applications and consumer goods [52]. This shift underscores the industry's move towards diversifying material properties to meet the nuanced demands of end-use applications. The emphasis on sustainability has also spurred interest in naturally derived and recycled feedstock materials (discussed further in Sect. 4.1). Quality control, scalability and cost-effectiveness remain central challenges, but ongoing research and industry collaboration continue to drive innovations, expanding the possibilities of 3D printing across multiple domains.

In SLS and SLM processes, not all the powder is sintered or melted. The unused powder can be recycled and reused in subsequent print runs. However, repeated exposure to the high-energy laser and oxygen can degrade the powder's quality. The "refresh rate" refers to the ratio of fresh powder added to recycled powder to maintain optimal print quality. Innovations in this area focus on enhancing powder recyclability, reducing waste and optimising the refresh rate to ensure consistent print outcomes [53]. For example, Carrion et al. (2019) observed a narrowing of particle size distribution and changes in flowability and fatigue properties following recycling of Ti6Al4V powder [54]. Giganto et al. (2022) studied the properties of parts manufactured with 17–4 PH stainless steel recycled up to 20 cycles (Fig. 6A), noting a

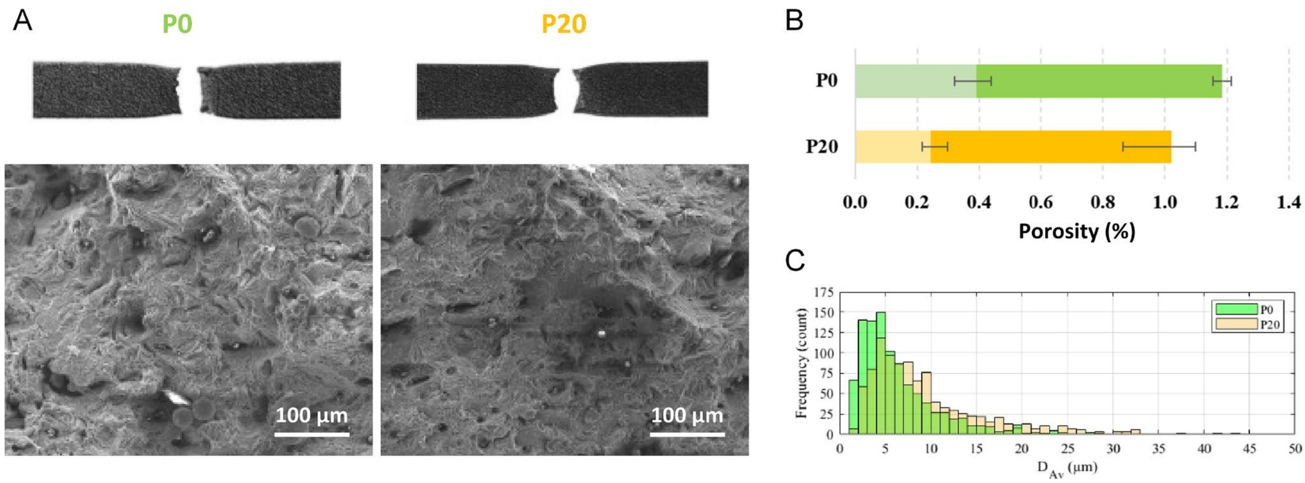

Fig. 6 Impact of powder recycling on the properties of 17–4 PH stainless steel parts manufactured using selective laser melting (SLM). P0 = virgin powder; P20 = powder after 20 cycles. **A** Comparison of printed parts following mechanical tensile testing, including high magnification images of surface roughness. **B** Characterisation of part porosity and **C** particle size distribution. Reprinted from [55] with permission from Elsevier

decrease in pore size following extensive recycling (Fig. 6B), but overall found that the properties of the printed parts were not significantly affected [55]. Importantly, standards such as ASTM F3456-22 "Standard Guide for Powder Reuse Schema in Powder Bed Fusion Processes for Medical Applications for Additive Manufacturing Feedstock Materials" have been established that inform the reuse of metal powders for medical applications, to reduce the risk of contamination and defects [18]. Further research in this space continues to underscore the importance of optimising powder reuse procedures to ensure the economic and environmental viability of industrial-scale 3D printing processes.

3.2 Integration within manufacturing workflows

Adopting 3D printing over traditional manufacturing methods presents both challenges and opportunities in the context of workflow integration. One of the primary considerations is the initial setup cost. Traditional manufacturing, especially methods such as injection moulding, requires significant upfront investment in moulds and tooling. While these costs can be amortised over large production runs [56], they can be prohibitive for short runs or custom products. In contrast, 3D printing has relatively low setup costs, as it does not require specialised moulds or tooling. This makes it particularly attractive for producing small batches or customised items [57]. For example, Telenko et al. (2012) performed a cost analysis comparison between injection moulding and SLS fabrication of nylon parts. The high cost of mould production for injection moulding manufacturing means that for low-volume production of injection moulded parts (below 300 units), SLS was more economical [58]. However, the unit cost dynamics change as production scales. As production volume increases, traditional manufacturing methods, which benefit from economies of scale, often become more cost-effective [56]. Companies must, therefore, evaluate their production needs and forecasted volumes to determine the most economically viable method.

As 3D printing becomes more prevalent in mainstream manufacturing, regulatory bodies worldwide must adapt to reflect the opportunities for advancing manufacturing using 3D printing. The precision, consistency and material properties of 3D printed parts can differ from those produced by traditional methods. This is especially crucial in industries like aerospace, automotive and medical devices, where part failure poses significant risk to human health and life. The implementation of 3D printing to supplement or augment traditional manufacturing workflows and use of novel materials in 3D printing can introduce regulatory challenges, especially if these materials have not been previously approved or tested for specific applications [59].

Once a part is 3D printed, it often requires post-processing to achieve the desired finish, mechanical properties or to remove support structures. The choice of post-processing method can significantly impact both the workflow and regulatory compliance. Heat-mediated post-processing, such as annealing, thermal curing and HIP, can enhance the mechanical properties of printed parts by relieving internal stresses or promoting material bonding. However, these methods can also introduce deformities if not carefully controlled and may alter the part's dimensions or tolerances. The techniques employed in post-processes metal 3D printed parts have a long history of use in conventional manufacturing workflows. Chemical-mediated post-processing, on the other hand, uses solvents or chemical baths to smooth surfaces or remove supports. While this can achieve a high-quality finish, it introduces potential environmental, contamination and safety concerns. Whilst in some industries such treatments are mainstream, the utilization of chemical treatment steps in workflows that previously have not considered the risks associated with the techniques can generate additional hurdles when implementing 3D printing, beyond the additive component of the workflow.

3.3 Simulation and monitoring for quality control

Due to the inherently complicated physical and engineer processes governing the 3D printing process such as material melting, solidification, deformation and temperature distribution, there are numerous mechanisms through which defects are prone to occur if the process parameters are not optimised, which significantly affects its further development into mainstream manufacturing use. To identify optimal process parameters, establish the relationship between processing parameters and properties of the printed products and print high quality and desirable products, it is crucial to use numerical simulation to model the printing process, which can significantly minimise the cost associated with trial and error experiments. For metal 3D printing, such as SLS and SLM, Finite Element Method (FEM) is the most widely used mesh-based numerical technique due to its simplicity and resource-efficient characteristics to predict the layer surface temperature, residual stresses, porosity and geometrical distortion [60]. ANSYS Additive Suite (AAS) [61], MSC Simufact Additive [62], ABAQUS AM [63], Autodesk Netfabb [64], Additive Works Amphyon [65] and COMSOL [66] are some common commercial software based on FEM for simulating the metal 3D printing process. Another commonly used mesh-based method is Finite Volume Method (FVM) [67]–[68], which is primarily employed to investigate the hydrodynamics of melt pool [69]. As for mesh-free methods, it has been shown that Discrete Element Method (DEM) can simulate the powder bed preparation, heat absorption and conduction in powder beds more accurately but is more computationally expensive than FEM [70]–[71]. Other alternative mesh-free methods capable of resolution of particle scale, such as Lattice Boltzmann Method (LBM) [72], Smoothed Particle Hydrodynamics (SPH) [73, 74] and Optimal Transportation Meshfree (OTM) [75], have shown great accuracy in describing melt pool features and the melting and solidification in the metal 3D printing process.

Modelling polymer 3D printing, however, is complex as polymers exhibit large deformations and complicated rheological behaviours that need to be accounted for in the simulation by applying appropriate constitutive model to describe the polymer responses [76]. Similar to the modelling of metal 3D printing, FEM is still the most popular among other classical numerical methods for laser or fusion based polymer 3D printing, such as SLS, SLA and DLP [76]–[77]. However, it has been shown that FEM's primary drawback lies in its implementation of volume shrinkage and the simulation of new layer deposition when compared to FVM and Finite Difference Method (FDM) [78]. As such, many studies have also employed FVM and FDM to simulate laser or fusion based polymer 3D printing process [78, 79]. Analogous to metal 3D printing, DEM has also been extensively applied to simulate the powder deposition and recoating mechanisms for powder bed preparation [72, 80]. It has been found that DEM is particularly well-suited for modelling phenomena in materials characterised by a discontinuous structure compared to the traditional numerical methods as DEM can explicitly model the particulate nature of the polymer powder and comprehensively capture nearly all physical phenomena associated with particle interactions, as well as the granular properties of the materials [80]. Monte Carlo (MC) method is also utilised to model heat absorption in the powder bed and ray tracing of energy source [81]. The simulation techniques for modelling the 3D printing process mentioned above can be summarised as Fig. 7 based on the spatial scales of the problem. For extrusion-based polymer 3D printing, such as FFF, melt electrowriting (MEW) and electrospinning, FEM remains the primary and the most popular choice for researchers to simulate the flow behaviour inside the extruder and nozzle, heat transfer, electric field distribution, solidification and fiber orientation [82]–[83] using commercial software COMSOL and ANSYS. Some particle-based methods, such as SPH and DEM, are used to analyse the polymer orientation and deformation from the particle point view [84].

Although polymer 3D printing has achieved some success in certain application areas such as prototyping and medical devices, its widespread adoption in industrial manufacturing still faces a range of challenges. These challenges include the enhancement of material properties, acceleration of printing speed, improvement of precision and reduction of manufacturing costs. Numerical simulation plays a pivotal role in addressing these challenges, facilitating the selection of potential materials and optimization of process parameters. However, modelling of polymer 3D printing is complicated as precise simulation of polymer melting, flow, solidification and cooling, is required. Furthermore, the efficiency of the simulation is another key aspect to be considered. Therefore, to facilitate the large-scale industrial adoption of polymer 3D printing, the development of an efficient and accurate numerical model is necessary.

3.4 Manufacturing accuracy and defects

Printing mechanisms significantly influence both the resolution and material properties of the produced parts. At the

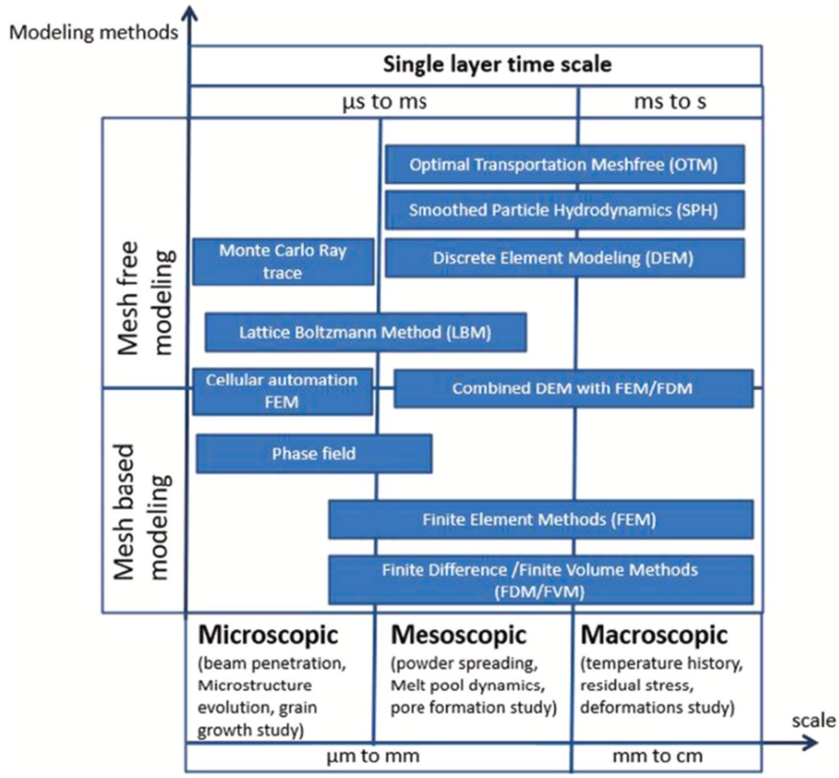

Fig. 7 Different numerical methods for simulations used in PBF methods classified according to various scales and modeling methods [149] (CC-BY)

core of this differentiation are the inherent material properties and the specific technologies employed in the printing process. PBF techniques, which can be applied to both metals and polymers, stand out for their widespread industrial adoption, primarily due to their ability to produce parts with high dimensional accuracy and low defect rates [85]. These systems, especially when used for metals, are capable of achieving material properties that meet or even exceed those of traditionally manufactured components [85, 86]. This ensures that the final products are not only precise but also robust enough for end-use applications. Conversely, polymer 3D printing, despite its ability to create complex shapes and structures, frequently encounters issues related to thermal deformation and shrinkage [87]. Such problems stem from the polymers' significant expansion and contraction during the printing process, adversely affecting the dimensional accuracy of the final product. Metal printing, while superior in terms of strength and thermal resistance, is not without its challenges. Residual stress and microstructural inconsistencies can induce warping and internal defects, compromising the integrity of the printed parts [88]. Considering the very limited overlap in materials processable via multiple techniques, direct comparison of printing resolution and defect/failure rates is not achievable. Therefore, quantifying the printing technique-specific resolution and rates of failure intrinsic to the printers remains a challenge since the results are strongly impacted by material properties.

Nevertheless, the field has seen considerable advancements in process control and post-processing techniques, as discussed in Sect. 3.2. These improvements have been pivotal in addressing the aforementioned challenges, thereby enhancing the precision and reliability of 3D printed components, regardless of the material. The strategic selection and application of specific printing technologies and materials enable manufacturers to optimize the dimensional accuracy and minimize defects, ensuring that the final products are tailored to meet the exact requirements of their intended applications.

4 Future perspectives: acceleration of polymer 3D printing technologies in industry

Over the next decade, it is expected that 3D printing will further penetrate and revolutionise manufacturing capability servicing wide ranging societal needs. The key drivers for the adoption of 3D printing across these industries will be advancements in printer technology, the development of new and diverse printing materials, cost reductions, standards and increased awareness of the potential benefits of this suite of manufacturing technologies. As these factors converge, we can expect to see 3D printing making even more significant inroads into various sectors. This section discusses the unique value proposition for 3D printing in a range of future-facing contexts, consolidating learnings from existing industrial adoption (Sect. 2) and recent technological innovation (Sect. 3) to postulate emerging frontiers in industrialised 3D printing.

4.1 Sustainability: recycled materials

3D printing is playing a transformative role in repurposing discarded plastics, a pressing global issue seeking to remedy the significant impacts of plastic waste on both human health and the environment [89, 90]. In the context of MEX technologies, which are the most readily accessible due to low cost and prevalence of open-source technologies, turning discarded plastics into quality, reproducible filament is a challenge from several perspectives. Maintaining sufficient quality of the polymers for their utility as feedstocks to produce products of value is a pressing technical issue, with polymer degradation initiated during the initial manufacturing process, over the lifetime of the product's use or during the recycling process being the primary barrier for maintaining high quality polymer properties [91]. These technical materials challenges are paired with the economic and environmental considerations of ensuring that the process does not expend more energy than its saves in a financially feasible manner [92]. Considering that commercial filaments can cost up to 200 times more than the raw plastic itself, significant investment and characterisation of quality filaments generated from recycled materials is required. The feasibility of producing recycled filaments for FFF printing has been demonstrated by several studies [93], for example with Kreiger et al. (2014) demonstrating that decentralised recycling of high-density polyethylene (HDPE), one of the most commonly produced polymers [94], could be successfully achieved using less energy than conventional recycling [95]. Their "RecycleBot" plastic extruder that facilitates filament production from recycled materials can produce filament from recycled waste plastics for 2.5 cents/kg USD, offering a favourable economic proposition [96]. For MEX technologies not requiring filament, recycled clay brick powder has also been successfully utilized for extrusion manufacturing [97]. In parallel, PBF techniques require feedstock in powder format rather than filament and opportunities for recycling products for manufacturing via this class of AM technology presents a unique set of challenges, primarily centred around the high energy consumption is required to produce the powders and stringent requirements for powder particle uniformity and thermal properties. Whilst SLS powders made from recycled plastics have been proposed [98], these have yet to see equivalent adoption and feasibility compared to recycled filaments. However, opportunities for using recycled materials interface closely with aforementioned strategies for reusing feedstock powder over multiple manufacturing batches (Sect. 3.1), particularly where careful management of diluting recycled materials with virgin feedstock is necessary to achieve sufficient part quality and reproducibility [99]. The reuse of discarded powders from PBF manufacturing have also been demonstrated to be successfully transformed into FFF filaments [100]–[101], as well as recycling of photocurable materials using chemical recycling to allow reuse of materials for SLA/DLP [102].

A number of organisations have emerged to facilitate community involvement in decentralised recycling efforts using these filament production techniques. Open-source projects such as the Polyformer project (Yang (Reiten) Cheng, USA) and Precious Plastic (Dave Hakkens, Netherlands) are leveraging proprietary-free distribution of their technology to increase reach. Other organisations such as Reflow (Netherlands), EKOCYCLE (collaboration with 3D Systems) and university-based projects from the University of California Irvine (Closed Loop Plastics, USA) and Manchester Metropolitan University (TRANSFORM-CE, UK) offer a variety of 3D printing hardware, filament production and recycling solutions. "Print Your City!" is an initiative by the organisation The New Raw (Rotterdam, Netherlands) where plastic waste is transformed into urban furniture using 3D printing. Through community involvement, residents can design benches, planters or playground equipment using an online platform, and these designs are then printed using plastic waste sourced from the community. These tangible examples underscore the potential of 3D printing in creating a circular plastic economy, transforming discarded materials into functional and often innovative products [90].

4.2 Sustainability: decentralised manufacturing

3D printing is playing a key role in the revitalisation of decentralised manufacturing, fundamentally reshaping the traditional supply chain and distribution model and significantly catalysed by significant supply chain disruptions during the early stages of the COVID-19 pandemic [103]–[104]. With the ability to produce goods on-site or closer to the point of consumption, 3D printing offers the opportunity to drastically reduce the need for large, centralized factories, subsequently cutting down on the extensive transport, warehousing and storage costs that come with mass production [105, 106]. Rather than shipping products across countries or even continents, items can be digitally transmitted as design files and printed locally, wherever a 3D printer is available. This localised production not only translates to significant cost savings but also a potential reduction in greenhouse gas (GHG) emissions (Fig. 8) [107]. Furthermore, producing goods closer to consumers diminishes the risk of overproduction, as items can be printed on-demand, based on actual

Fig. 8 Summary of available studies estimating greenhouse gas (GHG) emissions of 3D printed products in manufacturing and construction compared to traditionally manufactured counterparts. Reprinted and adapted from [107] with permission from Elsevier

needs rather than projected demands. Consequently, there is a decrease in surplus inventory, lessening the resources expended on warehousing and minimizing product wastage [108]. This decentralised approach, facilitated by 3D printing, paves the way for a more efficient, responsive and sustainable manufacturing paradigm, where products are created with minimal economic and environmental overheads. Direct comparison between 3D printing and traditional manufacturing such as injection moulding provides valuable insights into the potential utility and scalability of 3D printing as an alternative manufacturing paradigm. Future research is critical to better understand the economic and environmental impacts of decentralized manufacturing using 3D printing, particularly compounding the impacts of sustainable material sources, transport and distribution of feedstock and equipment parts, and economy of scale [106].

4.3 Personalisation in healthcare: point-of-care manufacturing and biofabrication

Opportunities for point-of-care (PoC) 3D printing, embedding 3D printing facilities within healthcare settings, is emerging as a promising avenue for improving healthcare provision through personalised product manufacturing [109]. Polymers, given their versatility, biocompatibility and ability to be readily sterilized are particularly suited for creating patient-specific anatomical models, medical devices and tools [110]. Surgeons utilise printed models to plan and practice complex procedures, ensuring greater precision and reduced operative times [111]. Anatomical models are typically fabricated from low-cost polymers and accessible, low-cost fabrication technologies. SLA has been favoured for its high resolution, low-cost and versatility in designing parts with intricate anatomical details [112, 113] whist PolyJet printers offer unique opportunities for fabricating highly complex multicolour and multi-material models with regions of varying stiffness to mimic native anatomical structures (Fig. 9A–C) [114]. Patient-specific surgical guides are custom-made tools designed to assist surgeons during surgical procedures. These guides are created based on the individual patient's medical imaging data, such as CT or MRI scans, ensuring a precise fit and alignment with the patient's unique anatomy. By providing accurate guidance on incision locations, bone cuts or implant positioning, these tools enhance surgical precision, reduce operative times and can lead to improved postoperative outcomes and reduced complications. Nylon (PA12) is one of the most favourable materials for manufacturing surgical guides, manufactured into surgical guides using SLS, due to its mechanical durability, ability to be sterilised using mainstream autoclaving and ethylene oxide [115, 116] (Fig. 9D–F).

PoC manufacturing using 3D printing provides the opportunity to drastically reduce lead times, ensuring that patients receive timely interventions [117]. The accelerating number of healthcare settings now integrating PoC manufacturing facilities internally indicates a significant shift in healthcare innovation, brining engineering design innovation to solve critical healthcare challenges back to within healthcare settings rather than third party manufacturers and medical device companies. However, the rise of PoC 3D printing centres has blurred the boundaries between healthcare providers, medical centres and device manufacturers, motivating innovation in medical device regulation [118]. While the FDA currently oversees 3D printed devices via existing medical device regulations, there is a growing interest in formulating guidelines specifically tailored for PoC 3D printing, given its swift adoption in healthcare settings. By analysing these regulations and

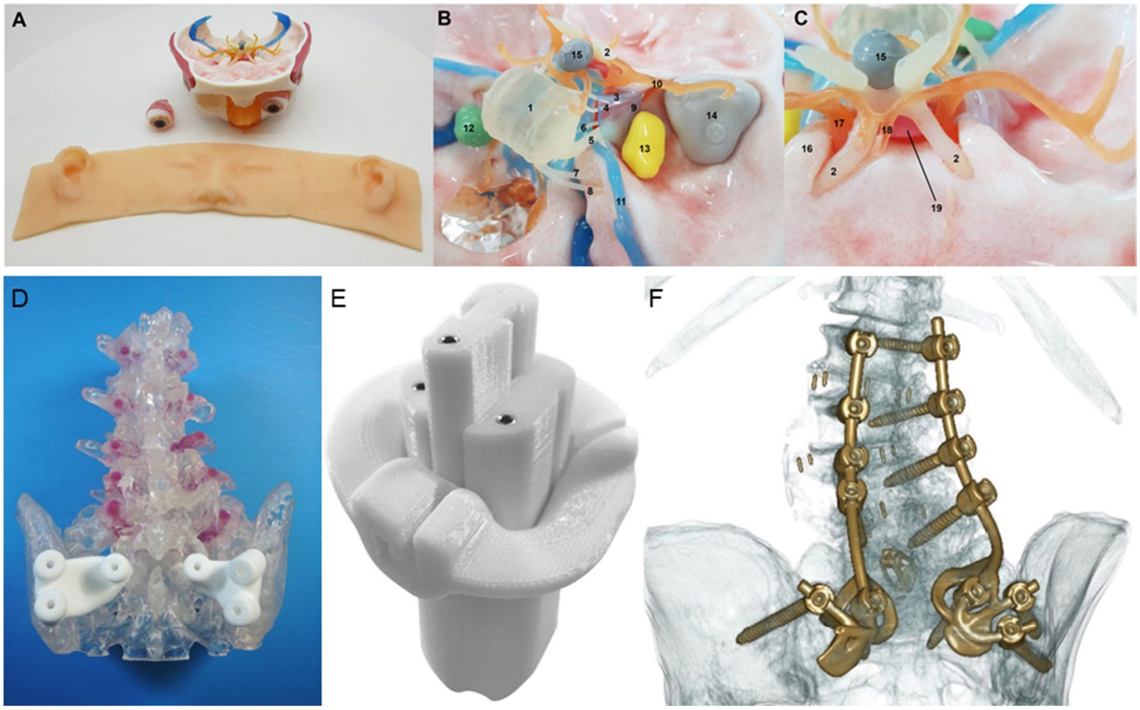

Fig. 9 **A**–**C** High-precision surgical training models for neurovascular surgery fabricated using a J850 Digital Anatomy Printer (Stratasys) using PolyJet technology [114] (CC BY). **D**–**F** Nylon (PA12) surgical drill guide for spinal surgery and postoperative CT reconstruction showing final placement of screws using the patient-matched guides [113] (CC BY)

consulting with 3D printing regulatory experts, the FDA offers best practice recommendations for PoC medical 3D printing, ensuring that institutions harness this transformative technology safely and effectively [59]. The goal is to provide clarity and guidance, which, in turn, will likely accelerate the adoption and implementation of polymer 3D printing in hospitals and other healthcare settings into the future.

Leveraging precision fabrication of biomaterials and biological components, biofabrication presents an emerging opportunity that will likely see significant commercial translation and scalability in the coming decade. Biofabrication is an interdisciplinary research field that focuses on the production of complex biological products from raw materials such as cells, biological molecules and biomaterials [119]. The products can range from tissues and organs for transplantation to novel drug delivery systems, and even food products such as lab-grown meat. Biofabrication combines principles and techniques from biology, material science and engineering to create these products, using 3D printing to provide precision structural arrangement of these components [120]. Whilst not yet widely translated to commercial scales, there are some promising indications of the significant disruptive impact that biofabrication will have in healthcare and sustainable food production sectors. Lab grown meat is an evolving industrial application of 3D printing, primarily using naturally derived polymers, muscle cells and other biological factors to recapitulate the composition, hierarchical structure and texture of meat [121, 122]. Whilst at the research level, advances in materials, manufacturing technologies and reagent sourcing have accelerated the development of realistic meat substitutes, there remain several critical challenges to increase the scalability of such in vitro techniques, namely cell expansion technologies and cost [123]. As innovations in bioreactor technology continue to expand, the much-anticipated entry of 3D printed meats into the mainstream market holds huge promise towards a new era of sustainability and animal welfare in food production [124].

In parallel, tissue engineering and biofabrication technologies to produce personalised synthetic tissue and organ substitutes offers the immense promise of completely overhauling medical and surgical interventions using personalised, regenerative products. Biofabricated skin tissues for treating burns, wounds and ulcers are among the more mature applications in the field [125]. Biofabricated cartilage and bone tissues are also being developed to treat joint injuries and degenerative diseases [126, 127]. These products are particularly promising for orthopaedic applications, where there is a significant demand for effective treatments and alternative to joint replacements [128]. Whilst the translation of advanced combination products featuring resorbable 3D printed biomaterials, autologous cells and biologic therapeutic ingredients face a plethora of technical and regulatory challenges before mainstream adoption, the use of tissue engineered, personalised tissue analogies for drug screening offers an exciting avenue with a substantially lower bar to translation [129]. Biofabricated tissues can provide a more accurate representation of human physiology compared to traditional cell cultures or animal models. This can lead to more predictive drug screening, potentially reducing the cost and time required for drug development or more targeted therapeutic selection [130]. The potential benefits in terms of patient outcomes, sustainability and ethical considerations make it a compelling area for continued research and development, and accelerating avenue for the upscaled adoption of 3D printing.

The translatability of biofabricated products as implantable medical devices into clinical use faces significantly steeper challenges compared to other applications of 3D printing, primarily due to the stringent regulatory oversight governing medical devices [131]. The adoption of 3D printing offers a more direct digital manufacturing workflow for producing patient-matched or custom-made products compared to traditional manufacturing techniques. Emerging regulatory guidance in many jurisdictions is now allowing the establishment of a "design envelope" to encompass many iterations of a product design matched to individual patient anatomy [132]. In addition, biofabricated products containing one or more biological components in addition to a 3D printed structure may be considered "combination products" and therefore undergo rigorous regulatory consideration spanning multiple regulatory pathways compared to products using a single mechanism only [133]. The complexity of ensuring safety, efficacy and quality control for such tailored and multifaceted products necessitates an often more complex regulatory approval process. This reflects the unique challenges of integrating 3D printing technologies with biological materials in a way that meets the high standards set for medical applications.

4.4 Artificial intelligence-driven design and manufacturing

Artificial intelligence (AI) is seeing exponential rise in utility and adoption within the digital manufacturing sector. AI is a branch of computer science focused on creating systems that can perform tasks that would ordinarily require human intelligence, such as decision-making, pattern recognition and language understanding. In the context of digital manufacturing, AI serves to optimise various aspects of the production process, from design and material selection to quality control and supply chain management. By leveraging data analytics, machine learning algorithms, and real-time monitoring, AI may enhance efficiency, reduces waste and enables more customised and innovative products. Hunde & Woldeyohannes (2022) provide a series of examples of the utilisation of AI-driven tools in CAD software [134], including the increasingly prominent capabilities of generative design.

Generative design is a design methodology that employs algorithms and computational techniques to automatically generate design solutions based on predefined constraints and objectives. In this approach, designers define a series of input parameters, such as material type, weight limitations, strength requirements and cost constraints, into a generative design software. The software then uses these parameters to automatically generate a variety of design solutions that meet the given conditions [135, 136]. Unlike traditional design methods where designs are manually created and iterated, generative design can explore a much larger design space in a fraction of the time. Generative design is particularly beneficial in fields where optimal performance, material efficiency and lightweighting are crucial, such as aerospace, automotive design and architecture [137]. Due to its ability to rapidly explore multiple design possibilities, it is also increasingly being used in product development, healthcare applications and even in digital art and graphic design. In addition, the accelerating adoption of advanced text-based AI models offers the ability to utilise text prompting to generate new designs [138], rather than being entirely reliant on CAD. This may offer opportunities to significantly lower the barrier to entry for non-specialist workers to engage in digital manufacturing.

Beyond advanced design capability, AI is playing an increasing role in print process optimisation as well as quality control. AI algorithms analyse data from cameras, sensors and other monitoring devices in real-time to inspect products and processes [139, 140]. If any inconsistencies or defects are detected, the system can send alerts to human operators or even make immediate adjustments to the machinery to correct the issue. Over the next 5 years, it is anticipated that AI technology for 3D printing is likely to become more integrated and sophisticated, enabling real-time optimisation of design, material selection and printing processes for greater efficiency and customisation. Advancements in machine learning algorithms and data analytics will further propel the development of new materials, automated quality control and predictive maintenance, making 3D printing more accessible and versatile across various industries.

5 Conclusions

Through review of the trends in industrial adoption of 3D printing to date, coupled with in depth discussion into current research contributing to the scalability of not yet industrialised 3D printing techniques, clear value propositions have emerged that will guide the emerging adoption of 3D printing in mainstream manufacturing contexts. Whilst metal 3D printing, as a highly reproducible and reliable manufacturing method for high strength parts with intricate internal geometries offers an invaluable design freedom-based value proposition for high strength-to-weight ratio parts in aerospace and automotive manufacturing, the ability to produce bespoke, customised or personalised devices with very low initial manufacturing set up costs has appealed strongly to the dental and surgical implant manufacturing sectors. Through the lens of sustainability, the opportunities for decentralising manufacturing are providing avenues to transition from society's reliance on costly and environmentally unfriendly transport and supply chain networks to localised recycling and manufacturing capability. This is further reinforced by the high value proposition for utilizing 3D printing in healthcare, where manufacturing low volumes, or even just single units, or personalised products offers significant clinical benefits, in addition to building momentum in localised PoC manufacturing.

Central to the value proposition for the integration of 3D printing in industrial manufacturing activities is economic considerations. Without the significant tooling costs associated with manufacturing techniques such as injection moulding, 3D printing has been widely positioned as a valuable prototyping and low-volume production manufacturing tool [57]. For example, cost comparison studies have evaluated that for a part costing under $20/unit when manufactured via 3D printing, it is only more economical than injection moulding in production volumes under 200 units [141]. The materials for 3D printing can be more expensive on a per-unit basis than those used in bulk traditional manufacturing processes. However, 3D printing comparatively reduces material waste by building objects layer by layer, potentially offsetting the higher volume of materials used in subtractive processes. 3D printing feedstock materials can be more expensive on a per-unit basis than those used in bulk traditional manufacturing processes [142], particularly in the generation of particles for sintering processes, as well as filaments, photocurable materials and high-purity materials as discussed in Sect. 3.1. Such factors, in combination with initial set up, labour and assembly costs require critical consideration in the implementation of 3D printing in manufacturing workflows.

Looking ahead, the translation of 3D printing into mainstream manufacturing is poised for a transformative trajectory. Metal 3D printing, with its impressive track record to date, has established a robust foundation, showcasing the potential of this technology in high-demand sectors such as aerospace and automotive. However, the accelerating opportunities for polymer 3D printing lie in versatility of the technique for fabricating materials from a wide variety of sources, from biomaterials and naturally derived polymers, to recycled plastics and high-strength materials. The synergistic development of advances in material formulations, fabrication technologies, advanced modelling technologies, AI-driven design, fabrication and quality control technologies, and manufacturing standards will underpin its accelerating adoption in a range of industries. Emerging R&D activities in the development of active material structures [143], “4D printing” materials with responsive properties [144], and a host of diverse metamaterials by exploiting both the diversity of fabrication technologies for materials of widely varying strength and elasticity, as well as leveraging complex infill patterning to engineer precise mechanical responses [50, 145]. Whilst largely still in early technology readiness, these technologies have substantial promise for being integrated in industrial manufacturing activities in the future. Polymer 3D printing will further revolutionise bespoke device production, especially in sectors such as PoC manufacturing in healthcare. As the technology matures, we can anticipate a more substantial impact from polymer-based processes, complementing the strides made by metal 3D printing. Together, these advancements signal a future where 3D printing is not just an alternative but a mainstay in global manufacturing paradigms.

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