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State-of-the-art and future research directions

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Review article

Driving additive manufacturing towards circular economy: State-of-the-art and future research directions

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ABSTRACT

Circular economy (CE) is critical to future manufacturing, as it will foster regenerative systems and pave the way for sustainable practices in advanced manufacturing, especially additive manufacturing (AM). Currently, the widespread implementation of CE in the field of AM has been hindered mostly by limitations in materials and technologies. More research efforts need to be dedicated to understanding and evaluating AM's role in facilitating closed-loop resource flow in industrial ecosystems. This article provides a state-of-the-art review of recently published research studies on this topic, ranging from AM recyclable material design and development to AM-assisted repair and remanufacturing. Additionally, current knowledge gaps are identified, and some future research directions are discussed. This review article is expected to serve as a valuable resource for researchers, practitioners, policymakers, and industry professionals who seek to leverage AM technologies in a sustainable manner.

1. Introduction

A circular economy (CE) "would turn goods that are at the end of their service life into resources for others, closing loops in industrial ecosystems and minimizing waste" [1], as opposed to the traditional "take-make-use-dispose" linear model. CE is usually achieved by (1) increasing product use via sharing, durability, repair, reuse, remanufacture, upgrades, and retrofits [2], or (2) turning old/waste goods into new material resources via recycling [3]. The term "circularity" emphasizes the realization of closed-loop material flow with the goal of enhancing environmental and economic sustainability. A tighter loop would retain more financial value and environmental value [4]. The concept of CE is systematic and has great potential for addressing critical challenges faced by society [5], such as waste management, resource scarcity, and sustainability.

Additive manufacturing (AM) uniquely fabricates 3D objects in a layer-by-layer fashion. Because of the layer-wise production method, AM supports high manufacturing complexity, flexibility, and efficiency. To further advance AM, numerous research efforts have been conducted to advance AM hardware, materials, and software solutions. With the increasing awareness of AM capabilities, the potential role of AM in facilitating CE has also been obtaining recognition. When studying CE, some studies employed the 9R framework ("R1 refuse, R2 rethink, R3 reduce, R4 reuse, R5 repair, R6 refurbish, R7 remanufacture, R8 repurpose, and R9 recycle") [6]. The first three Rs focus on the design phase, while R3 to R7 emphasize the consumption phase, and R8 and R9 demonstrate the end-of-life (EOL) phase. However, in the field of AM, categorizing a study into specific categories is challenging. Often, a comprehensive analysis is conducted to focus on one or multiple phases of the CE. Therefore, this article will employ the 4R terminologies ("reduce, reuse, recycle, and recover") [7].

In particular, the 4R framework includes "(1) R1 reduce, which includes discussions on rethinking, refusing, minimization, redesigning, reduction, prevention of resource use, and preserving natural capital; (2) R2 reuse, which includes discussions on reusing (waste is excluded), cycling, repairing, closing the loop, and refurbishing of resources; (3) R3 recycling, which includes discussions about recycling, closing the loop, remanufacturing, and reuse of wastes; and (4) R4 recover, which includes discussions about the incineration of materials with energy recovery" [7]. To date, several review articles have been published to summarize research efforts on the exploration and integration of CE principles in AM, but they usually focus on one aspect of the 4R

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framework. For example, Hettiarachchi et al. [8] focused on the supply chain perspective [8]; Sanchez et al. [3] and Shanmugam et al. [9] reviewed research studies on AM polymer recycling; Rahito et al. [10] focused on AM-enabled repair and remanufacturing [10].

Numerous articles have discussed how the adoption of AM technologies contribute to CE from perspectives such as product and process design, production planning, AM-enabled EOL processing, etc. The current state-of-the-art lacks a comprehensive review of the implementation of CE principals in AM, providing insights to the community. Motivated by status quo, this paper aims to offer a systematic overview of recent advances between 2018 and 2024, facilitating CE practices within AM across various domains. Specifically, this paper will focus on three main areas: methods for reducing consumption in AM, strategies for enhancing AM product life span via repair and remanufacturing, and methods for recycling AM products and materials. This paper is organized as follows. In Section 2 of this paper, the methodology adopted for searching scientific publications is illustrated. Sections 3, 4, and 5 contain detailed reviews of recent advances in facilitating CE in AM from different perspectives. The results are discussed, and prospective research directions are highlighted in Section 6.

2. Methodology

In this paper, the publications are reviewed and discussed based on the published peer-reviewed articles. The methods used for searching publications include keyword-based web searching (Google Scholar and Web of Science) and snowballing. The utilized keywords for initial screening consist of combinations involving different AM technologies or materials alongside elements of the 4R frameworks. Some examples of initially searched keywords include "additive manufacturing recycling", "3D printing recycling", "fused deposition modeling recycling", "thermoplastic recycling", "direct metal deposition repair", "laser metal deposition repair", "cold spray repair", etc.

Searching the scientific articles that fit the correct categories in the 4R framework is challenging, due to the overlapping subject areas and sometimes the misuse or inconsistent uses of terminologies. For example, the reuse of waste metal powders upon sieving is categorized by some researchers as "recycling", but by other researchers as "reusing". Upon a careful initial screening, a clear scope is determined. In this paper, "***Reduce***" entails research efforts on reducing resource consumption and its environmental impact in AM through designing new materials and structures and innovating process planning. "***Reuse***" focuses on research efforts that leverage AM technologies and capabilities in the repair or remanufacturing of worn or defective products. "***Recycle***" refers to studies that focus on the recycling process of AM wastes, sourcing from support structures, abandoned prints, failed prints, used parts, and waste powder that cannot directly be reused. "***Recover***" in the context of AM has not yet been explored. Therefore, this article will focus on three aspects: reduce, reuse, and recycle. The scope of this review is demonstrated in Fig. 1. The specific focus within each "R" category – whether it emphasizes a particular time period, material, or method – is determined by the results of initial screening and the availability of review articles.

To further refine the article searching, specific keywords are used to replace general terms initially used in screening. These refined keywords focus on distinct AM techniques, including *Fused deposition modeling* (*FDM*), *Fused Filament Fabrication* (*FFF*), *Stereolithography* (*SLA*), *Digital light processing* (*DLP*), *Binder jetting* (*BJ*), *Direct metal deposition*, *Material extrusion*, *Direct ink writing* (*DIW*), *Direct energy deposition* (*DED*), *Laser metal deposition* (*LMD*), *Direct metal laser sintering* (*DMLS*), *Selective laser sintering* (*SLS*), *Selective laser melting* (*SLM*), *Electron beam melting* (*EBM*), *Powder bed fusion* (*PBF*), *Wire-arc AM* (*WAAM*), *Friction stir AM* (*FSAM*), and *Cold spray*. Additionally, specific materials are identified through the initial screen and used for the refined search. These include *Polylactic acid* (*PLA*), *Acrylonitrile butadiene styrene* (*ABS*), *Polyether ether ketone* (*PEEK*), *Nylon*, and *Polyethylene terephthalate glycol* (*PETG*) as representatives of thermoplastics. *Polymer fibers* and *thermosets* are also designated to replace composite materials, while a focus on *metal powders* and

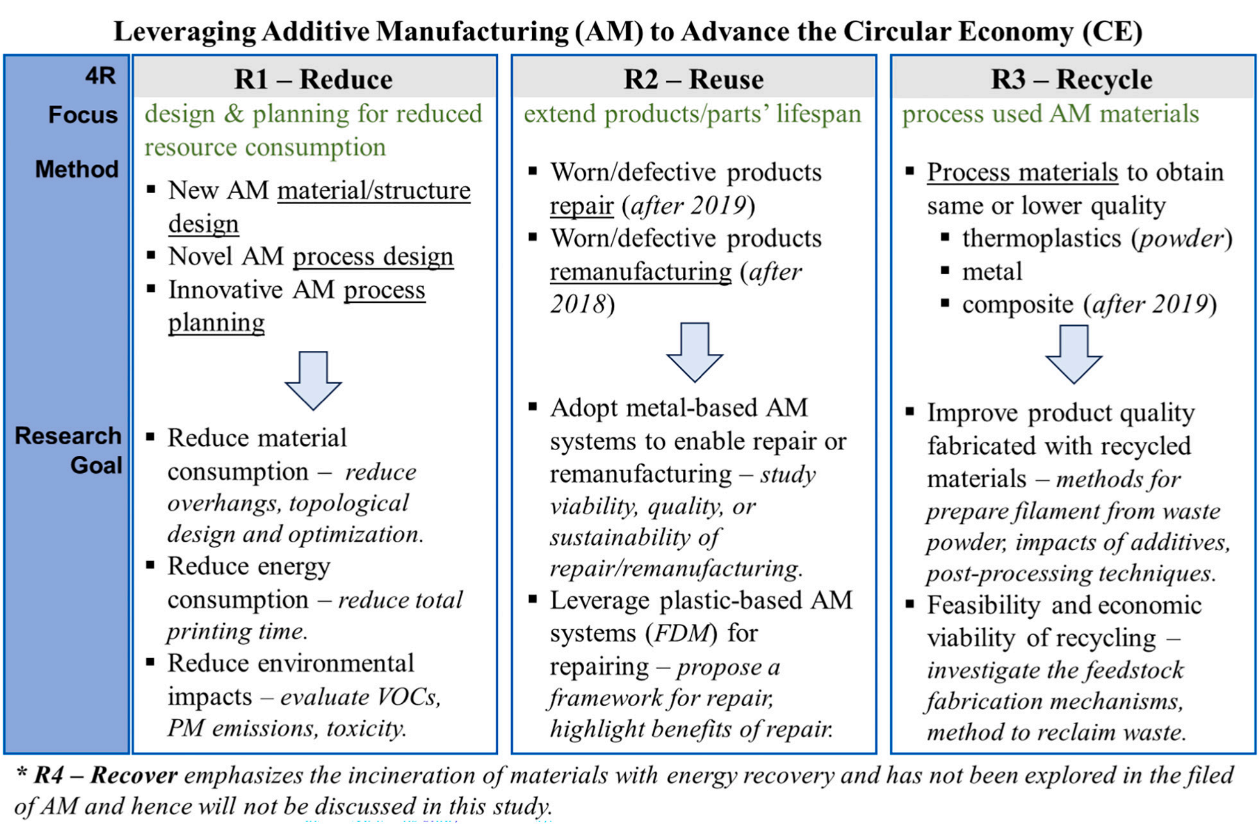

Fig. 1. Scope of the review.

alloys aims to refine the exploration of metallic materials within AM. Lastly, to refine the scope of the 4R framework in AM, the keywords "*remanufacturing*" and "*repair*" are utilized to enrich the article search process, targeting efforts in AM reuse and its applications within remanufacturing and repair domains. Upon refining the keywords, a thorough review is conducted, where the research efforts undergo detailed categorization into multiple subtopics and are summarized in Table 1.

Table 1 highlights the predominant focus of numerous studies on three key topics: design for AM, AM production planning, and AM-enabled repair; hence they are further categorized into a few subtopics in the review. More specifically, within the realm of design for AM, efforts are delineated into process design, material design, and structural design methodologies. Reduce through AM production planning is discussed, emphasizing its role in reducing energy consumption, environmental impacts, and material wastage. Moreover, the exploration of AM-enabled repair delves into a detailed analysis encompassing various AM techniques, as outlined in Section 4.1.

Moreover, the studies aimed at advancing CE practice within the context of AM, as presented in Sections 3–5, are categorized according to the seven AM process categories defined by ASTM, as illustrated in Fig. 2. Studies that focused on general AM techniques (such as [35,37]) and material design or processes (such as [23,25–27]), as well as review articles (such as [19,28–30,38–41]), are excluded from the figure. Studies that compared two or more specific AM systems are repeatedly counted. Additionally, hybrid subtractive-additive manufacturing systems are categorized based on the AM technology applied.

It can be observed from Fig. 2 that the extrusion-based AM, DED, and PBF systems are the three most popular AM systems investigated. On the contrary, to the authors' best knowledge, there were no studies leveraged materials jetting or sheet lamination technology to facilitate CE and hence are not presented in the figure. Additionally, it is observed that studies on extrusion-based AM systems have predominantly centered around several key objectives: (1) streamlining total printing time and minimizing the use of support structures through novel process planning, (2) mitigating environmental footprints by integrating efficient filtration systems, (3) embracing AM for repair purposes in the domain of biomedical applications, and (4) exploring the utilization of recycled materials in AM. Furthermore, PBF and DED, two prominent metal AM systems, are widely explored in the context of CE. In particular, within PBF systems, research efforts have concentrated on three key areas: (1) enhancing topological design and optimization to reduce material consumption, (2) assessing and optimizing (through process planning, build volume allocation, etc.) energy consumption, cost-effectiveness, and environmental footprints, and (3) designing efficient powder recycling methods and evaluating their implications on product quality. Studies have also embraced DED systems to propel advancements in the 4R principles, notably: (1) leveraging DED or DED-assisted hybrid subtractive-additive manufacturing systems for component/product repair, (2) exploring the sustainability advantages of DED over conventional manufacturing from energy consumption, cost-effectiveness, and/or environmental impacts perspectives, and (3) developing methods for material recycling, particularly focusing on powders. Regarding research efforts focusing on SLA, BJ, and AM technologies which do not belong specifically to any of the seven categories, their scope is more limited to certain directions, with further studies being encouraged. A more detailed review can be found in Sections 3 to 5, reflecting their efforts to support the 4R framework.

Table 1
A summary of articles reviewed in this paper.

4R framework	Focus	No. of papers reviewed	Popular journal(s)
Reduce	Design strategies Production planning	26 23	Additive Manufacturing, Journal of Manufacturing Science and Engineering, Journal of Industrial Ecology, Journal of Cleaner Production
Reuse	AM-enabled repair AM-enabled remanufacturing	23 5	International Journal of Advanced Manufacturing Technology, Tissue Engineering
Recycle	Thermoplastics wastes	7	Additive Manufacturing, Journal of Cleaner Production
	Metal wastes	6	
	Composite wastes	8	

3. Literature review on reduce in additive manufacturing

The goal of enabling the "reduce" principle in AM is to prevent the use of excessive resources such as electricity, raw materials, and monetary value. Monetary value is of interest due to its strong correlation with printing time, energy consumption, and material consumption. This section contains two stages of AM activities: design (in Section 3.1) and process planning (in Section 3.2), as illustrated in Fig. 3.

3.1. Reduce: design for additive manufacturing

In the context of CE, numerous opportunities have been presented for revolutionizing AM-enabled product design, owing to the unique characteristics of AM, such as shortened production time and enhanced manufacturing complexity. Recent advances in AM process design, material design, and structural design with the goal of reducing resource consumption will be reviewed.

3.1.1. Hardware and process design

New AM process designs aim to increase the fabrication speed and efficiency. For example, Li et al. [11] designed a new SLA process that is based on mask video projection, providing continuous resin flow and light exposure, as shown in Fig. 4 [11]. Results show that this process increases the fabrication speed with good surface quality. The resource consumption of this new process has not yet been evaluated. Improving utilization is a potential approach for enhancing the process sustainability [12].

3.1.2. Material design and sourcing

A recent article has reviewed the materials used in various AM processes and discussed their advancements [13]. Efforts in AM materials design are continuing to grow, with the aim of enhancing various material properties, such as mechanical robustness, thermal conductivity, durability, and recyclability. Within the context of CE, particular emphasis is placed on material recyclability, which will be discussed in the following section.

3.1.2.1. Natural, recyclable material sourcing. The feasibility of using local natural material streams and reprintable natural materials in AM has been explored (see Fig. 5 for examples). Sauerwein and Doubrovski [14] proposed to use mussel shells locally in the Netherlands, mixed with sugar water, and make 3D printable materials for DIW [14]. These materials, if turned to waste, can be collected and easily dissolved in water. Sauerwein et al. [15] further improved this material by using reversible ion cross-linking and demonstrated the feasibility through experiments [15]. Furthermore, 3D Printed Biowall (3DP Biowall) refers to the renewable materials made by blending lignin, starch, and wood particles collected from the sawing or paper industries. Preliminary experiments were performed to assess the feasibility as well as the material properties of the designed 3DP Biowall [16].

Another promising application of AM reprintable materials is the wood construction industry. Using wood and lignocellulosic-based materials as functional additives and reinforcements in composites can potentially replace carbon or glass-filled polymer matrices, reducing

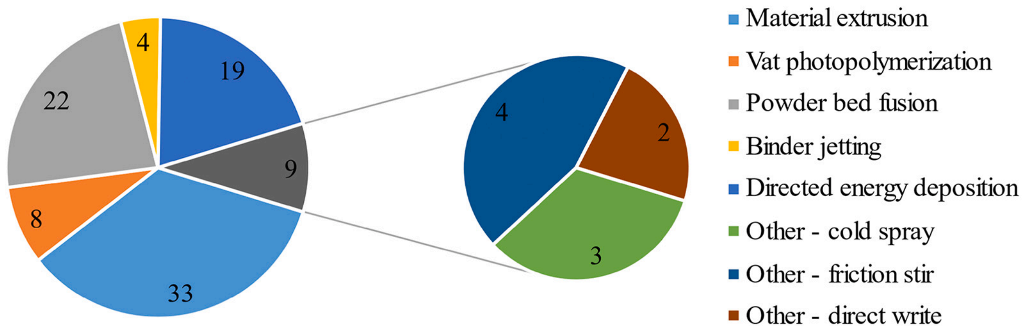

Fig. 2. Overview of efforts to advance CE based on different AM technologies.

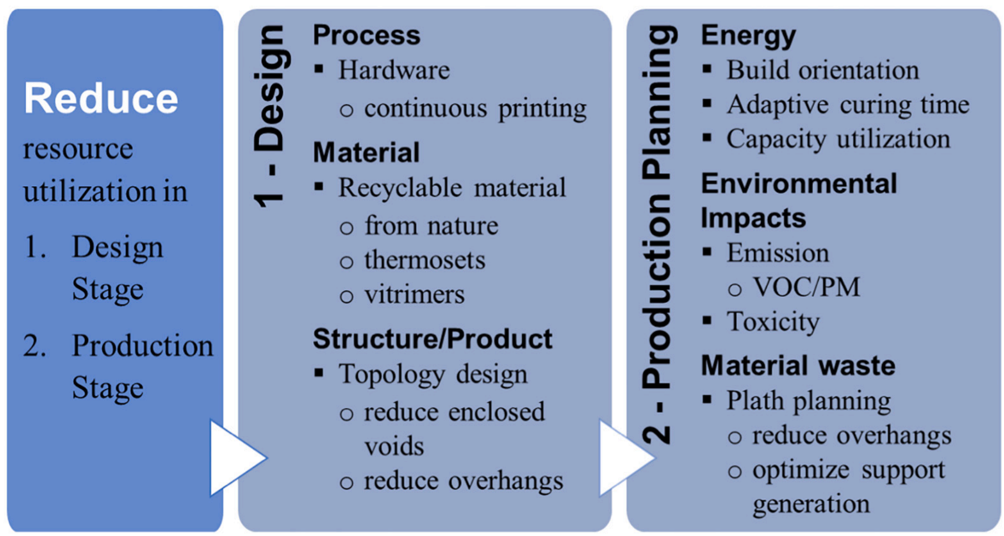

Fig. 3. Overview of reviewed articles on "Reduce" in AM.

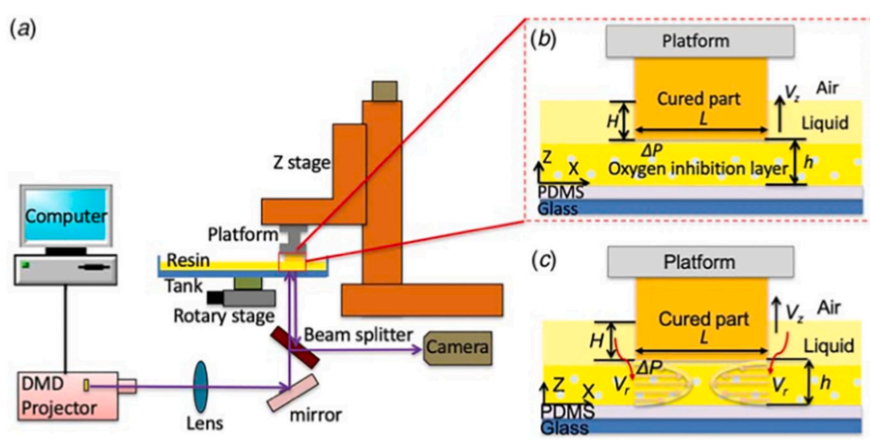

Fig. 4. Illustration of the mask video project-based stereolithography process [11].

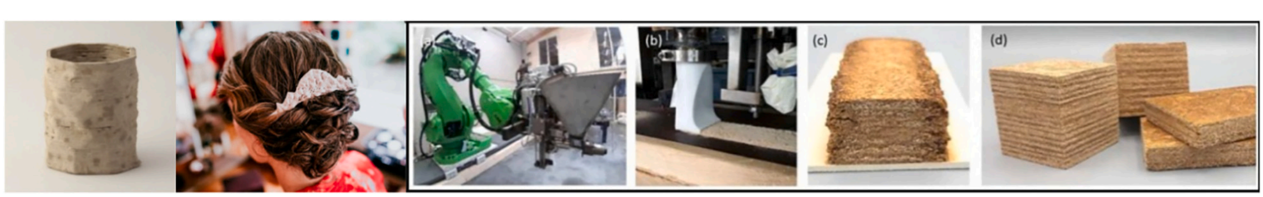

Fig. 5. Demonstrations of 3D printed parts with (left) mussel shell material [14], (middle) mussel shell-alginate material [15], and (right) 3DP Biowall [16].

material cost and adverse environment impact while ensuring the material properties [17]. Rosenthal et al. [18] explored printing sawdust with various fillers to test mechanical strength and other properties [18]. A summary of 3D printing with wood biomass and technologies employing wood particles and components was conducted in 2022 [19], focusing on the process and technology innovation in 3D and 4D printing to accommodate the new materials.

3.1.2.2. Design and development of recyclable materials

3.1.2.2.1. Recyclable thermosets. Thermoset polymers are obtained by irreversible cross-linking of a soft solid or viscous liquid prepolymer (or resin). AM thermoset materials are usually nonrecyclable because of the irreversible nature of the curing or hardening process. In recent years, research attempts have been made to design and develop recyclable thermosets (see examples in Fig. 6). Guo et al. [20] developed a conductive recyclable composite from a dynamic covalently cross-linked elastomer and hierarchical hybrid nanofillers. This composite demonstrates excellent material properties, mechanical properties, and environmental tolerance in different applications, as shown in Fig. 6. These new recyclable electronics show moderate degradability after use, providing an exciting opportunity for reducing electronic waste. In addition, Yuan et al. [21] designed a re-processible DIW ink with thermally reversible Diels-Alder (DA) reaction, and this material can be used to fabricate self-healing thermoset with a recovery rate of >85 % in terms of polymer strength with one occurrence of damage [21]. Zhu et al. [22] discovered a group of self-healing polymers, often referred to as smart materials, that feature cross-links through ionic bonding and hydrogen bonding, providing excellent recycling ability [22].

3.1.2.2.2. Recyclable vitrimers. Vitrimers are a class of plastics derived from thermosetting polymers; they have been leveraged to improve the recyclability of thermoset systems. One promising option is named “Associative Dynamic Covalent Adaptive Networks (ADCAN)” with unique features such as “stress relaxation, self-healing, and shape memory properties”. ADCAN has a dynamic nature in the cross-link, enabling the material to be reprocessed without loss of macroscopic properties. The reaction mechanisms of ADCAN are summarized in [23]. Among one of the first research efforts on 3D printable sustainable vitrimers, Niu et al. [24] developed a polyurea vitrimer with heat-driven malleability for FDM and observed excellent interlayer adhesion in printed parts and great recyclability with retained mechanical properties after being fully recycled for five generations [24]. Other types of recyclable vitrimers have also been studied, including a biobased vitrimer synthesized from sustainable sources such as itaconic acid and platform chemicals [25], a vitrimer-graphene aerogel composite [26], and a fully biobased vitrimer from glycyrrhizic acid and soybean oil [27]. Unfortunately, the 3D printability of these new recyclable vitrimers has not yet been well tested.

3.1.3. Structural design and optimization

Reducing material consumption without sacrificing the functionality of printed products can be achieved by innovating lightweight structural design. The state-of-the-art on AM topology optimization (TO) were reviewed in 2020 [28,29], and 2018 [30]. This article will focus on scientific articles on AM topology design/optimization published from 2020 to 2023. Research papers on lattice structure design and structural design for specific applications such as biomedical or purposes such as reducing distortion are not reviewed.

3.1.3.1. Reduction/elimination of enclosed voids. In powder-based AM, parts designed with enclosed voids can trap unmelted powder, leading to material waste and potentially decreased mechanical properties. Research efforts have been conducted to reduce and/or eliminate these enclosed voids (see examples in Fig. 7). Xiong et al. [31] proposed a new approach to achieve structural connectivity control (SCC) based on the bi-directional evolutionary structural optimization (BESO) method [31]. In order to eliminate enclosed voids, this approach selectively generates tunnels to connect voids with the structural boundary. In addition, Sabiston and Kim [32] proposed a particle diffusion void restriction (PDVR) method to generate designs with minimum enclosed voids [32], by adding a constraint on the maximum allowable diffusion time of all particles, treating enclosed voids as barriers to the diffusion particles. This method was demonstrated in multiple 3D and 3D test parts both numerically and experimentally.

More recently, a new fictitious physical model was proposed to add a constraint on closed cavity for AM design, leading to a new TO method with geometric constraints using a level-set-based method [33]. A new method of automatically generating channels between closed voids and outlets was also proposed in order to discharge the remaining powder [34]. This approach uses the optimized material distributions as the base for designing channels, where the paths between closed voids and outlets are generated using a skeleton extraction method and finalize the printable channels via surface extraction and Boolean operation. Five structures were used to experimentally validate the viability of the proposed method.

3.1.3.2. Reduction/elimination of overhang. In AM, overhang structures usually require appropriate support structures, causing additional material waste and sometimes limitations in structure design. In current literature, methodologies and algorithms have been developed aiming to reduce or even potentially eliminate the need for support structures by *minimizing the overhang angle*. For example, a TO filter was proposed to enforce a minimum overhang angle by detecting the overhang using front propagation and incorporating the filter into TO [35]. Challenges include efficient propagation in tetrahedral elements and parallelization of the front propagation. The developed filter was demonstrated in three numerical cases.

Some AM processes such as project-based SLA can fabricate horizontal overhangs with zero inclination angle, where the *overhang size* significantly affects the printability. In such cases, overhang angle (or inclination angle) and overhang size should be simultaneously considered in TO. A skeleton-based structure decomposition approach was proposed to separate the whole structure into multiple components according to their connectivity condition. These components were then evaluated, where those that violate the threshold conditions were

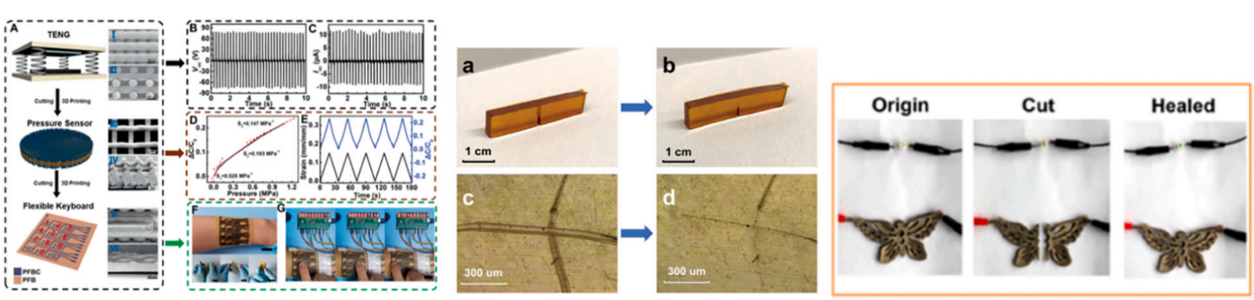

Fig. 6. Demonstrations of recycled thermoset in (left) wearable electronics [20] and self-healing (middle: [21]; right: [22]).

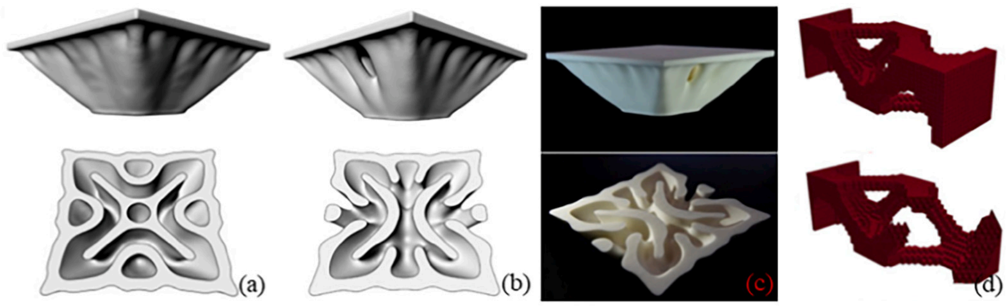

Fig. 7. Demonstrations of enclosed voids elimination (a) optimized structure, and (b) 3D printed structure [31] and void region restriction, (c) optimal design of a torsional beam, and (d) void restricted 3D printed parts (with/without supports) [32].

selected to achieve self-support [36]. This method was demonstrated on a few 2D structures numerically and experimentally (Fig. 8).

Some research studies simultaneously consider the overhang angle and size. As demonstrated in Fig. 9, an overhang angle control approach was proposed for enclosed voids by identifying enclosed voids through a nonlinear virtual temperature method (N-VTM), identifying the overhang interface through a multiple filtering/projection process, and controlling the overhang angle via enabling a logarithmic function-based constraint [37]. Numerical case studies were conducted on different structures such as the Messerschmitt-Bölkow-Blohm beam (MBB) design problem, T-shaped beam, and cantilever beam.

3.2. Reduce: production planning for additive manufacturing

In current literature, review articles have been published to overview the AM process emissions in 2021 [38], control strategies of particle emissions from FDM in 2022 [39], and AM life cycle inventory/assessment [40,41]. This paper outlines AM production planning efforts towards CE from the perspectives of energy consumption, environmental impacts, and material waste. Research studies with a supply chain scope (such as [42]) and comparative studies on AM and traditional manufacturing are not reviewed in this paper.

3.2.1. Energy consumption

Electricity is the major resource consumed during AM production, and it's tightly linked with production time and cost. Electricity usage contributes the most to AM's environment impact, comparing to material impacts, waste, toxins, printer machine production, and transportation [12]. For a certain process and material, the energy intensity required for printing is strongly linked to production rate [43]. Paul and Anand [44] adopted a convex hull-based approach to mathematically quantify and optimize the energy utilization in SLS, leading to the conclusions that the impacts of build orientation and laser energy on energy consumption vary with part geometry [44]. This research group later adopted a computational approach to estimate the required energy [45]. Xu et al. [46] developed an energy consumption model for BJ printing to establish the relationship between part geometry and energy consumption with experimental validation [46]. Griffiths et al. [47] adopted the design of experiments (DOE) approach to optimize the energy consumption in FDM and concluded that layer height has the most evident impact on energy consumption [47].

From the production time perspective, Zhao et al. [48] proposed a dynamic curing method that adopted multiple values of exposure time in SLA process to reduce the total fabrication time considering quality measures such as dimensional accuracy and hardness. The proposed dynamic curing approach was proven to be effective in saving the total production time by comparing its performance with conventional constant-time curing [48]. In addition to finding the optimal printing parameters, increasing research efforts have discussed the impacts of capacity utilization in different AM processes on sustainability [48–50]. Yang and Li [49] mathematically quantified the total cost in SLA process when fabricating a mixture of different geometries in one batch [49]. The proposed mixed geometry production method was examined to be cost-effective compared to single-job printing. Baumers et al. [51] assessed the electricity consumption for several popular AM processes and reported the varying levels of effects of capacity utilization on energy efficiency [51]. Later, this group further evaluated the energy consumption and production cost of DMLS, finding that the adoption of a high level of capacity utilization advances the economical behavior of AM [52]. When build failure is considered in the printing process, it was observed that optimal cost occurred below the maximum machine capacity reached due to larger batches leading to an increased risk of failure [53]. Moreover, Faludi et al. [54] reported that electricity usage is the dominant factor in affecting printing efficiency, indicating a reduction in energy consumption greatly alleviates environmental burden [54]. Shi and Faludi [12] further performed life cycle

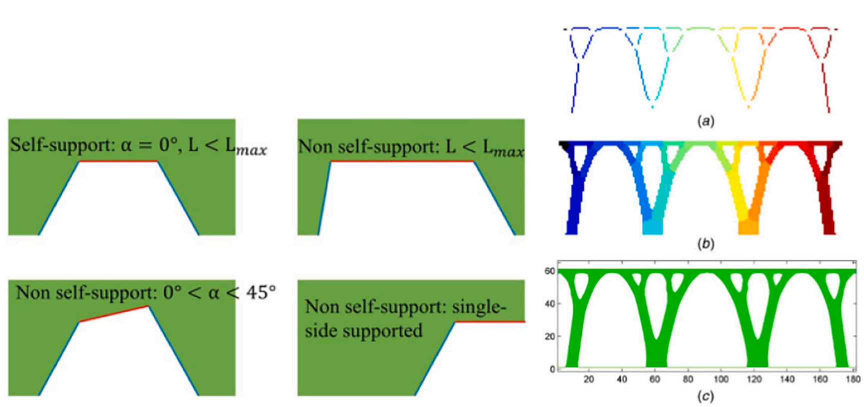

Fig. 8. Illustrations of (left) overhangs with close to zero inclination angle and (right) optimization results: (a) segmented structural skeletons, (b) segmented structural areas, and (c) self-support design [36].

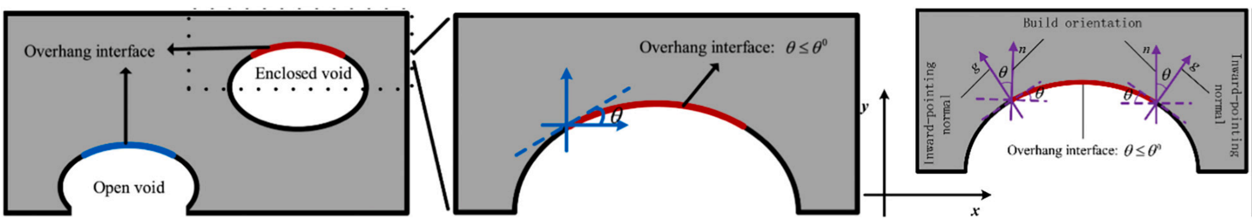

Fig. 9. Illustration of the overhang angle minimization approach [37].

assessments (LCAs) to explore the impacts of utilization (both temporal and spatial) on environmental impacts, and the results suggested energy and material selection should be simultaneously considered together with utilization for higher efficiency [12].

3.2.2. Environmental impacts: toxic emissions

AM process emissions have attracted increasing interest. As one of the first attempts, Afshar-Mohajer et al. [55] conducted real-time measurements to quantify the aerosol and volatile organic compounds (VOCs) emitted from a 2-hour continuous BJ printing with the setup shown in Fig. 10(a) [55]. The results indicate a significantly higher level of emission than the standard and the need for proper ventilation to reduce potential health risks. Yang and Li [56] evaluated the total VOC concentration caused by SLA printing of thermosets and proposed approaches to potentially reduce the VOC emission: titanium dioxide photocatalytic oxidation and activated carbon absorption [56]. These two filters were adopted to the prototype and proven to be effective in reducing the total VOC. More recently, Han et al. [57] experimentally investigated the total VOC concentration caused by SLA printing of thermo-responsive materials [57]. The results suggest that changing stimulus conditions can reduce total VOC emission.

The particulate matter (PM) emission from FDM has also been studied [58–60]. Kwon et al. [58] explored the use of different filters to reduce PM emissions and concluded that HEPA filters is the most effective in reducing nanoparticles compared with using low-temperature, low-emitting materials or using an enclosure around the printer [58]. Sittichompoo et al. [60] performed thermogravimetric analysis to understand particle formation during FDM and studied the correlation between process settings and ultra-fine particle emission, where the printing temperature was found to be the dominating factor [60]. Oskui et al. [61] experimentally assessed the toxicity of SLA and FDM printed parts using Zebrafish embryos [61] and concluded that exposing SLA-printed parts to ultraviolet light can mitigate toxicity.

3.2.3. Material waste

AM material waste is often caused by support structure, low powder usage ratio, and low process reliability. In some cases, material waste can be reduced via proper process planning. For example, Coupek et al. [62] proposed a path-planning algorithm for building cylindrical axes in multi-axis FDM by reducing overhangs and replacing infills with pre-manufactured thermoplastic insertions, aiming to reduce material consumption and production time [62]. Jiang et al. [63] developed a path planning method to optimize the support generation for parts with flat features. This method is also applicable to multi-part production by combining parts based on their geometries while optimizing the build direction and part combinations [64]. Moreover, a new strategy was proposed to determine the layer-wise filling area based on the feasible overhang angle as well as the bridge length constrained by the machine. This approach was experimentally validated to optimize the print path and build orientation, leading to minimized support structure usage and reduced printing time and consumption of materials and energy [65].

4. Literature review on additive manufacturing reuse

This article considers AM reuse in two scenarios: (1) repair, where AM technologies are leveraged to restore the damaged or worn-out components directly or upon certain pre-processing to their original function, and (2) remanufacturing, where parts of or entire discarded products are processed using AM to restore functionalities [7]. To illustrate the two concepts discussed in this work, Fig. 11 is presented. Additionally, Rahito et al. [10] reviewed AM repair and remanufacturing from 2011 to 2018 [10]; therefore, this article focuses on publications from 2019 to 2023.

4.1. Additive manufacturing enabled repair

AM is suitable for repair because of its high manufacturing complexity and flexibility. In some cases, reverse engineering and redesigning are required [66]. Several review papers have outlined some existing efforts on using AM in repair. Research efforts on metal repair using DED published prior were reviewed in 2019 [67]; publications on repair using cold spray and FSAM were summarized in 2021 [68]; scientific studies on metal repair using cold spray were reviewed in 2018 [69]; and research efforts on LCA and cost analysis of AM-enabled repair were reviewed in 2022 focusing on mold repair [70].

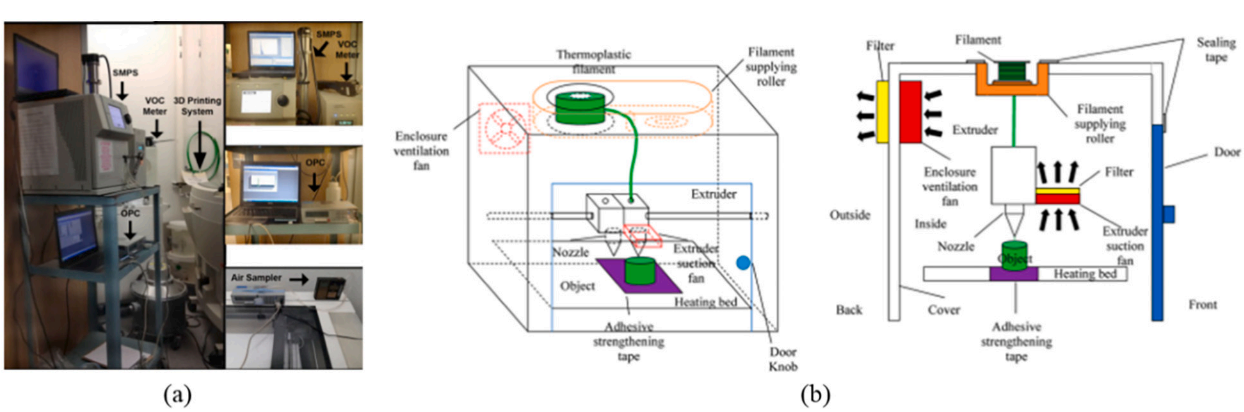

Fig. 10. Illustrations of emission measurement for (a) BJ [55]; and (b) FDM processes [58].

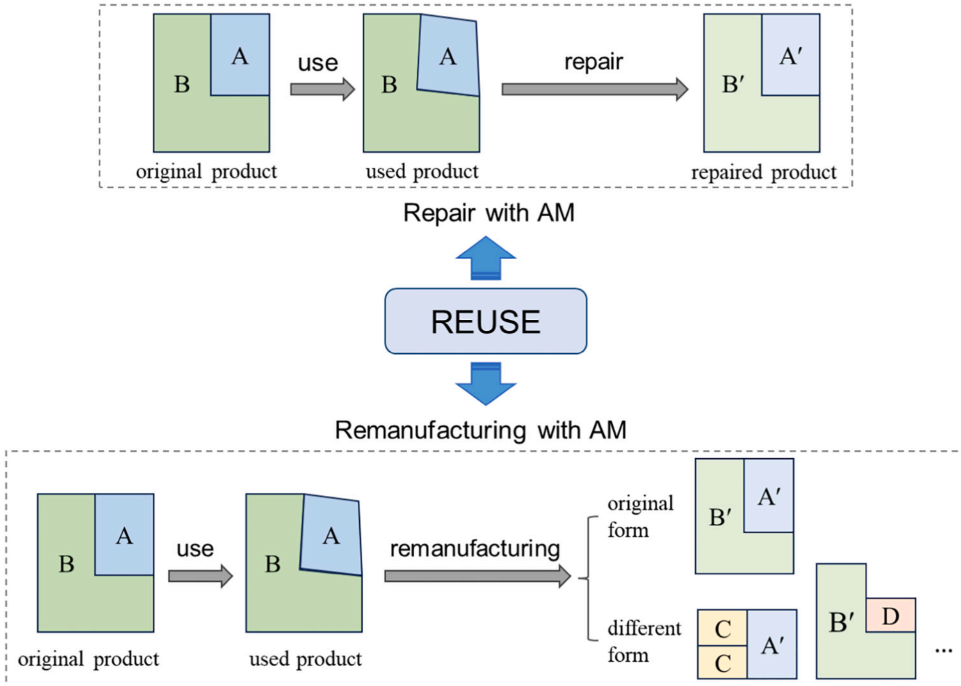

Fig. 11. Definition of Reuse within CE.

4.1.1. Powder-based metal additive manufacturing

Research shows that powder-based LMD or DED achieves high-quality repair. However, the repair quality of the LMD process is contingent upon many factors such as optimal process parameters, defect zone preparation, powder quality, and process consistency; among them choosing appropriate process parameters is key. Several research efforts have been noticed in the literature dedicated to attaining the optimized processing parameters and identifying their effects on the repaired structure. For example, Onuike et al. [71] studied the impacts of DED process parameters, build orientation, and defect zone preparation on repair quality [71]. Shuai et al. [72] focused on laser powder fed fusion (PBF)-fabricated Zn-2Al parts for bone repair applications and studied the energy density during fabrication and how it affects the achieved microstructure and mechanical properties [72]. Rauch et al. [73] determined the optimal parameters through the analysis of porosity and macrostructure for Ti-6Al-4V repaired parts and proposed a semi-automatic repair method to identify the edges and volume of the cavity for a more reliable and accurate repair [73]. Moreover, the effects of various DED repair process parameters, including initial substrate temperature, hatch pattern, number of deposited layers, substrate thickness, and interlayer dwell time on microstructure, porosity, hardness deposition, and mechanical properties were experimentally investigated. It was observed that the depth of substrate thickness significantly affects the Ti-6Al-4V repair performance [74].

In addition to finding the appropriate parameters, researchers also focused on data-driven modeling and numerical simulation to aid the LMD-based repair leading to reduced repair cost and improved repair quality. For instance, Perini et al. [75] conducted a study to identify the damages and automatically create a model for LMD repair by comparing the worn and original components, aiming to decrease the cost of repair [75]. Li et al. [76] proposed an algorithm to advance automated damage detection and reconstruction in the repair process [76] with thermo-mechanical simulation to understand deformation and residual stress in the repaired structures and quality evaluation through microstructure characterization and hardness test.

4.1.2. Wire-based metal additive manufacturing

WAAM is another well-explored approach for repairing metal components. Wanjara et al. [77] experimentally examined the feasibility of repairing metallic materials using wired-based electron beam AM through characterizations of microstructure, mechanical properties, and failure mechanisms of the repaired structures [77]. The results suggest that the proposed repair method is beneficial and effective in reducing high-value material waste, production time, as well as manufacturing costs. Lee et al. [78] experimentally characterized the effects of process parameters on mechanical properties of WAAM-repaired components [78]. Marenych et al. [79] studied the effects of post-weld heat treatment on the microstructure and hardness of the repaired Monel alloy components [79]. Zhuo et al. [80] focused on the repair of TC17 titanium alloy blades using WAAM with Sn/Cr powder addition as shown in Fig. 12, and the effects of the microstructure and mechanical properties of three deposition samples with the additions of Sn and Cr were experimentally analyzed [80].

The sustainability of the WAAM-enabled repair has also been discussed in the current literature. Pagone et al. [81] assessed the life cycle environmental impact of WAAM-repaired components with a real-world case study by using cumulative energy consumption and carbon dioxide emissions as two indicators in the sustainability evaluation for repairing a driver disk [81]. Furthermore, life cycle energy and carbon emission assessments were conducted to evaluate the repair operations and develop repair procedures for WAAM-repaired mold inserts [82].

4.1.3. Cold spray

Current literature also delves into the repair of components through the utilization of cold spray AM. As shown in Fig. 13, cold spray AM was introduced to reinforce composite coatings and implemented to examine its feasibility for repair [83]. The repair quality was examined for microstructures, mechanical properties, and corrosion behaviors of the CuMC coatings, and found that a good repair quality can be achieved using the mixed powder of 55 vol% Muntz and 45 vol% Al_2O_3.

4.1.4. Friction stir additive manufacturing

Due to the solid-state nature, FSAM (illustrated in Fig. 14) has been considered to have a great potential in achieving high-quality repair

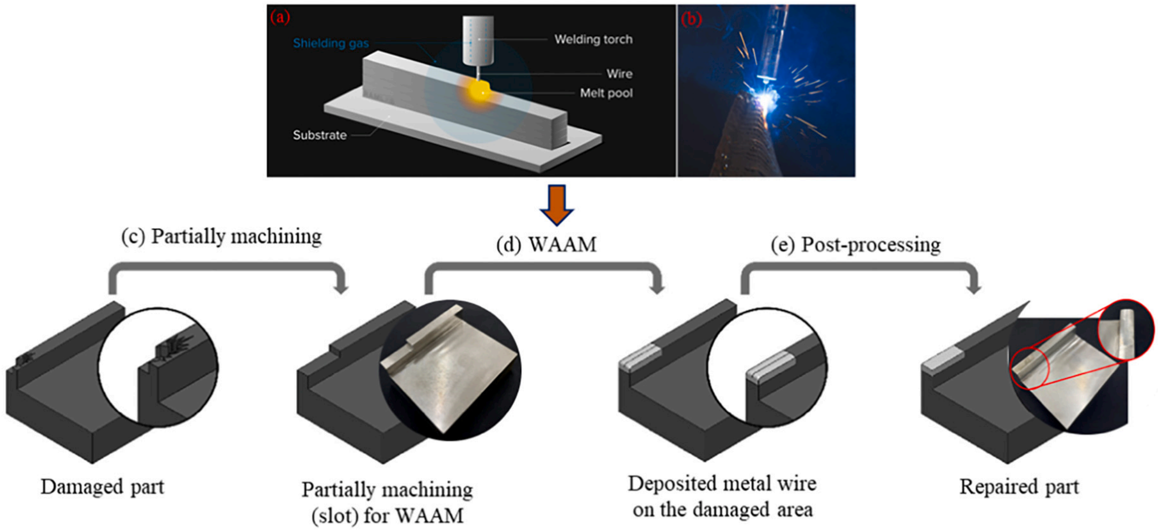

Fig. 12. Illustration of repairing damaged part using WAAM [78].

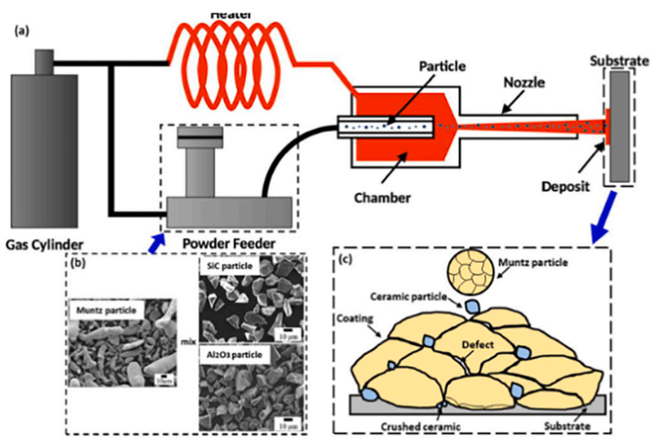

Fig. 13. The overview of the cold spray AM system using mixed powder [83].

with strong bonding and low level of hot cracking and residual stress. However, this technology is yet to be explored. Griffiths et al. [84] conducted a comparative study to investigate the effectiveness of adopting FSAM for the repair of 7075 aluminum alloy considering the effects of various process parameters, filling types, and repair dimensions [84]. The results show that FSAM is effective in filling the entire damaged volumes of through-holes and wide grooves in the components. However, a decreased hardness with an ordinary quality of the repaired components was also reported which shows the future research avenue. In addition, a friction stir-enabled solid-state repair technique was proposed to repair defective components in ultrasonic AM (UAM) where the ultrasonic sensor was completely embedded in a solid aluminum block and the sensor was set in immersion mode to prevent the vibrations produced during UAM processing from affecting the coupling [85]. Adopting the friction stir process as a repair tool, the microstructure of the damaged UAM components was retained while overall quality was improved.

4.1.5. Hybrid metal additive manufacturing

Hybrid manufacturing integrates AM and other manufacturing techniques on one single platform (usually robot arm or CNC), and it has the capability of both removing the damaged areas and adding materials or features. The current literature is focused on evaluating the feasibility and economic competitiveness of leveraging hybrid AM in repair. For example, Oyesola et al. [86] established a cost model with activity-based

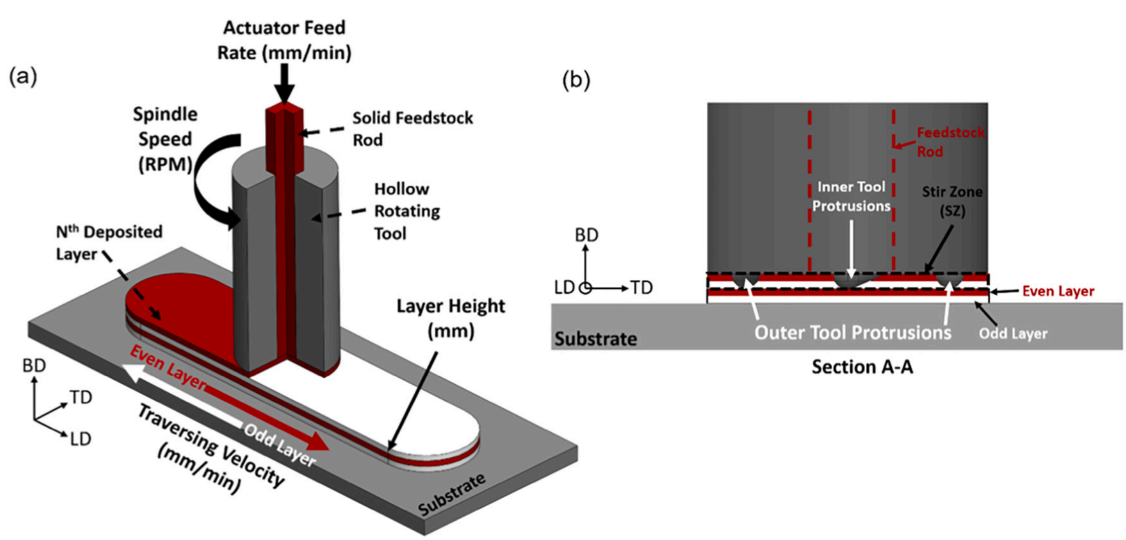

Fig. 14. (a) Illustration of FSAM process and (b) Toolhead interaction with the previously deposited layer [85].

costs to evaluate the economic competitiveness of using hybrid AM in the aerospace industry for maintenance, repair, and overhaul [86]. Al-Badour et al. [87] evaluated the feasibility of using hybrid AM and friction stir to repair cracks in Aluminum alloys through microstructure characterization, microhardness test, scanning electron microscopy, and energy dispersive X-ray spectroscopy [87].

4.1.6. Thermoplastics additive manufacturing

Plastic materials used in AM often end up in landfills without proper EOL treatment. With the raising awareness of CE, efforts on repairing high-value plastic components have received considerable research attention. A framework for repairing polymer-based components using FDM was proposed [88]. Upon analyzing the required cost and time, damaged features of the component, and the performance of the scanned copy, the proposed methodology was applied to decide the necessity of replacement or repair and the method (AM-based or non-AM-based) for repair. Three case studies were performed, and the results reported the feasibility of repairing plastic parts using FDM with ABS, PLA, and PETG. AM-assisted repair is also widely used for medical products, and a review paper focused on bone repair using AM technique has reported the feasibility of repairing polymer-based components [89]. Other studies also reported the advantages of using FDM for bone repair; particularly, in increasing the strength of the bone [90], speeding the repair process [91], and extending product service life [92,93].

4.2. Additive manufacturing assisted remanufacturing

Remanufacturing in CE refers to the process of replacing damaged components with functional subassemblies. The majority of the existing studies on AM-enabled remanufacturing focus on (1) investigating the performance of products remanufactured by AM to promote its implementation; (2) proposing a system-level framework to advance product remanufacturing; and (3) analyzing the benefits of remanufacturing from a supply chain perspective. In the current literature, researchers often combined repair with remanufacturing; for example, a review paper had been published in 2019 on AM-enabled repair and restoration in remanufacturing reviewing the articles from 2011 to 2018 [10]. Additionally, a recent article highlighted the advancement of adopting AM for remanufacturing applications; however, its definition of remanufacturing (i.e., restoring the original function of used products and components as they are or in a new product) is mixed with repair in the context of CE [94]. Therefore, the following section summarizes the studies on AM-assisted remanufacturing (i.e., restoring the quality of parts from a used product to integrate them into a new product with the same function) after 2018 [94].

4.2.1. Process-level remanufacturing

In 2022, Barragan De Los Rios et al. published a research article on process-level remanufacturing [95]. In this research, a hybrid manufacturing process combining DED and high-speed machining (HSM) was employed to remanufacture a worn carbon steel (AISI 1045) injection molded part with the AISI 316L stainless steel. The restoration process was performed following three stages as shown in Fig. 15. Initially, the worn AISI 1045 part was machined, and worn features were removed by 5 mm from the top of the part. Next, utilizing the DED process the new materials of AISI 316L were deposited by approximately 7 mm on the AISI 1045 part. Finally, the restored part was machined again to improve the surface quality. The result suggested that the corrosion resistance of the reproduced part had been improved compared with the original part due to the use of stainless steel. In addition, the final component demonstrated higher hardness and similar microstructure to the original AISI 1045 part.

4.2.2. System-level remanufacturing

Research efforts have also been dedicated to AM-aided remanufacturing from a system perspective. An enhanced "Teorija Rezhenija Izobretatelskih Zadach" (TRIZ) matrix was proposed to address contradictions in remanufacturing design and facilitate the AM implication [96]. The proposed method was evaluated by two case examples for its effectiveness to improve product re-manufacturability and enhance the implementation of AM for remanufacturing. Additionally. remanufacturing using hybrid subtractive – additive manufacturing has also been widely explored as it enables the removal of damaged features and the addition of new features to the defective regions. For example, a design for remanufacturing approach that combines structural topological design and process planning was proposed to generate the optimal remanufacturing strategy using a hybrid subtractive-additive manufacturing technique [97]. The proposed algorithm was experimentally examined and proven to be effective in identifying features to be removed and added while sustaining the functionality of the products. Moreover, a cost-driven process planning approach was proposed to determine the optimal sequence for a hybrid subtractive-additive with an automated feature extraction process to identify components for remanufacturing [98]. One case study was carried out to evaluate the proposed method starting from the geometry modeling of the used part and feature extraction for remanufacturing. The DED nozzle collision issues were considered in the method and a cost model was developed to convert the process planning to an integer programming problem and find the optimal solution to remanufacturing.

4.2.3. Supply chain level remanufacturing

Hybrid AM systems have great application potentials in remanufacturing. One explorative study was performed to investigate the use of hybrid AM systems in small and medium enterprises [99]. In this research, an uncapacitated facility location (UFL) model and a p-median model were developed to determine the locations of the remanufacturing hubs considering a range of data from geography, demand, fixed cost, and transportation cost. The proposed models were implemented in a case study in aerospace, suggesting economic feasibility of the studied remanufacturing service and potential benefits of using hybrid AM in repairing parts and tools. This research also reported a reduced fixed cost in the remanufacturing hub, in comparison with the manufacturing hub; and fewer remanufacturing hubs were needed for high-value parts.

5. Literature review on additive manufacturing recycling

Enhancing recycling practices in the context of CE typically emphasizes processing materials to the same or a relatively lower quality.

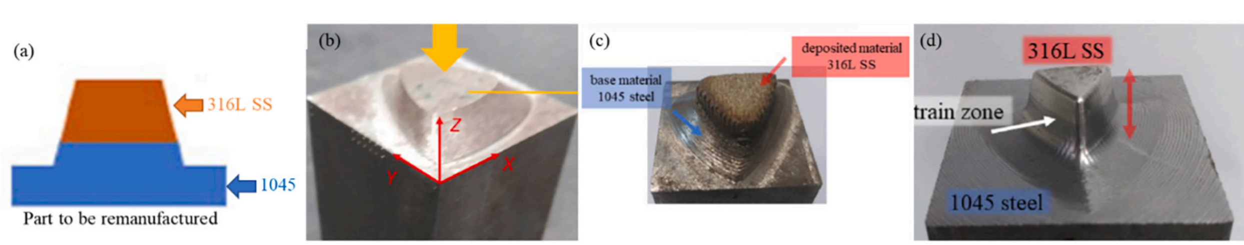

Fig. 15. Illustration of remanufacturing stages (a) Schematic of the part to be remanufactured, (b) AISI 1045 part after machining, (c) Restored part with 316LSS deposition, and (d) Final machined part [95].

With the focus on AM in this work, recycling is defined as processing waste and used AM materials, rather than processing waste materials using AM techniques. The widely explored waste AM materials for recycling purposes are illustrated in Fig. 16, which includes plastic, metal, and composites. According to this figure, studies have also been conducted on recycling thermoset materials, which were previously widely believed to be non-recyclable. Recent advancements in this area have highlighted that the inclusion of dynamic covalent bonds to replace static crosslinking functionalities allows for polymer chain rearrangement under certain stimuli, such as heat, light, or chemical catalysts, thereby enabling material recycling [100]. Research in this domain is currently limited and in its early stages, making it not the primary emphasis of this section. Notable attention is directed towards exploring recent advancements in the recycling of thermoplastics, metals, and composites.

5.1. Recycling thermoplastic in AM

Thermoplastics is one of the most popular AM materials due to its low-cost production and diverse application [101]. However, if the thermoplastic wastes from AM are not properly recycled or treated at EOL, they can result in adverse environmental impacts, threat to human health, and the entire ecosystem [102,103]. Existing research efforts on AM thermoplastic filament and resin recycling were reviewed in 2022 [104] and 2021 [105], respectively. Hence, this article only focuses on powder-based AM thermoplastic recycling.

In SLS, around 70–80 % of the consumed powder remains unused in each fabrication [106–109]. The unused powder can be recycled back to SLS or for other purposes. However, recycled powder yields downgraded parts which is not desired. To improve the part quality fabricated with recycled powder, researchers investigated several techniques which are reviewed in this section. For example, Kumar and Czekanski [110] developed a method to prepare FDM filament from PA12 waste powder collected in SLS. Tungsten carbide (WC) was added to the filament to improve the mechanical properties of FDM prints using recycled material. The addition of WC increases the glass transition temperature and improves the strength compared to the existing filaments as shown in Table 2.

Weinmann and Bonten [107] studied the thermal aging process of recycled Polyamide (PA) 12 powder from SLS process and proposed adding a powdery low molecular agent to function as the chain splitter to the long polymer chain and enable reverse thermal aging (illustrated in Fig. 17). The flow properties of the recycled PA12 are contingent on the concentration of the added chemical agent. This approach can achieve part fabrication using recycled PA12 with smooth surfaces and identical mechanical properties as virgin powder.

Table 2
Mechanical properties of recycled PA12 mixed with WC at various weight ratios [110].

Filament composition	Youngs' modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
100%PA	700	25	Did not break
87.5%PA + 12.5% WC	800	30	700
75%PA + 25%WC	920	40	400
62.5%PA + 37.5% WC	1170	45	300
50%PA + 50%WC	1300	60	260

Yang et al. [111] proposed a novel post-heating approach for SLS AM to recycle PA 12 powder where they developed a customized SLS 3D printer with a post-heating mechanism [111]. The collected unused powder was categorized as extremely aged PA 12 powder that was adjacent to the heat-affected zone (HAZ) and the aged PA 12 powder that was far away from the HAZ. The powder was then sieved with a mesh size of 200 μm to remove the large particles and debris and then mixed with virgin powder in different ratios. During fabrication, the post-heating mechanism keeps the part at a preheated temperature. The proposed method demonstrates the surface quality of the recycled part improves significantly by reducing surface roughness, porosity, and unmolten powder.

Due to its cost-effectiveness and biodegradability, PLA is extensively utilized in extrusion-based AM processes, prompting widespread exploration into its recycling methods. For instance, Romani et al. [112] conducted a study characterizing the property degradation of mechanically recycled PLA after multiple 3D printing and recycling iterations [112]. Their findings revealed trends in property degradation and highlighted that granulated recycled PLA feedstock is less affected by thermomechanical degradation in large-scale AM processes that utilize pellet or granulate feedstock compared to desktop-sized extrusion AM systems, which employ filament extrusion.

5.2. Recycling metal wastes in AM

The low-yield/high-waste industries such as aerospace, automotive, and medical are in the early state of transition to adopting metal AM due to the distinct characteristics of AM technology, which offers design freedom. Aerospace is one industry where AM consistently lowers the environmental impacts of part manufacturing by replacing the machining of complex forms from blocks of metal with high embodied

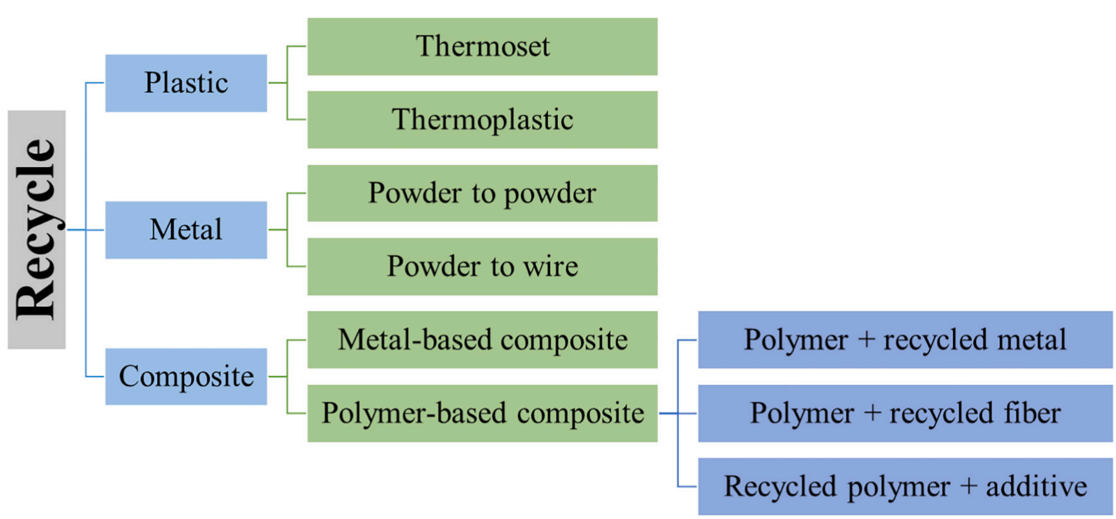

Fig. 16. AM material recycling.

Fig. 17. Reversed thermal aging in PA12 [107].

impacts, like titanium [113]. In metal AM, the material is used mainly in powder form. Metal powder is highly expensive and recycling it can provide a significant economic benefit. Research shows that the material cost can be reduced by up to 92 % if the waste powder is reused 15 times [114]. Metal powder waste includes the unused powder generated during the AM manufacturing process which experiences an extremely high-temperature environment and deteriorates chemical and physical properties which limits its recyclability as these potentially affect the part quality by creating severe porosity, microcracks, and a high amount of partially melted powder. In the current literature, research efforts are noticed dedicating to the development of approaches to improve the quality of recycled parts. Maamoun et al. [115] proposed thermal post-processing to obtain microstructure homogeneity and reduce defects formation of the parts fabricated from recycled powder [115]. In this research, the fabricated part went through thermal processing i.e., annealing, solution, and T6 heat treatments leading to an improved microstructure and part quality. Garboczi et al. [116] developed a method to recondition Ti and Ni alloy powders using an inductively coupled plasma process (ICP) [116]. The proposed process enables the conversion of irregular and agglomerated powder particles found in the recycled powder into more circular and spherical shapes as shown in Fig. 18. The reconditioned powder shows significant improvement in porosity which potentially enhances the microstructure homogeneity and mechanical behavior of the recycled components.

Moreover, Weiss et al. [117] studied the influence of AlSi10Mg powder recycling and found that applying the coarsening approach in powder recycling, potentially improved the mechanical performance of the components fabricated using the recycle powder [117]. Powder waste cannot be completely avoided in the PBF-based AM process even if waste powder is recycled multiple time. Research shows after some rounds of recycling, the waste powder is no longer usable as multiple recycle degrades the part quality immensely. Instead of multiple rounds of recycling, a single round of recycling yields a comparable part quality. The approach of fully recycling the waste powder in a single round brings a remarkable advantage to the AM industries. In 2020, Smythe et al. developed a method to produce wire feedstock from recycled titanium powder which next feeds into the extrusion-based metal AM (fusion welding process and DED) to produce near-net shape components [118]. The proposed feedstock fabrication mechanism is shown in Fig. 19. This approach allows them to recycle the waste powder as close to 100 % which identifies as a promising addition to sustainable manufacturing leading to a CE.

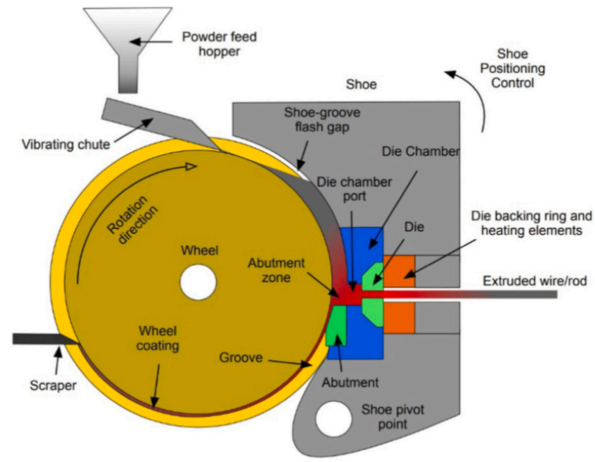

Fig. 19. Schematic of the Conform™ employed to produce wire feedstock directly from the recycled powder [118].

5.3. Recycling composite wastes in AM

AM technologies open up a new avenue to the composite manufacturing industries which allows faster and more efficient fabrication of composites. The traditional composite manufacturing process is quite tedious and intricate which requires expensive tooling and high skilled workers whereas AM reduces these barriers significantly. The composite industry is very large and every year tons of composite parts are produced. A vast amount of composite materials waste is accumulated every year due to the EOL of the component, and failed and defective parts which are threatening manufacturing sustainability. Hence, recycling waste composites is immensely important to achieve the sustainability goal. In the recent decade, research efforts are noticed in the literature dedicated to recycling composite waste using additive manufacturing technologies. Ujeniya and Rachchh [119] published a short review article examining the recyclability of 3D-printed composite materials. Thus, this article presents an exhaustive review of the latest research on composite waste recycling since 2019.

Singh et al. [120] designed a metal matrix composite (MMC) by using a novel route of investment casting (IC) for the FDM process [120]. The MMC is fabricated using recycled low-density polyethylene (LDPE) collected locally in granules form and reinforced with ceramic of SiC and Al_2O_3 which prepares the cast with aluminum (Al) alloy. They successfully fabricated the metal matrix composite which is expected to

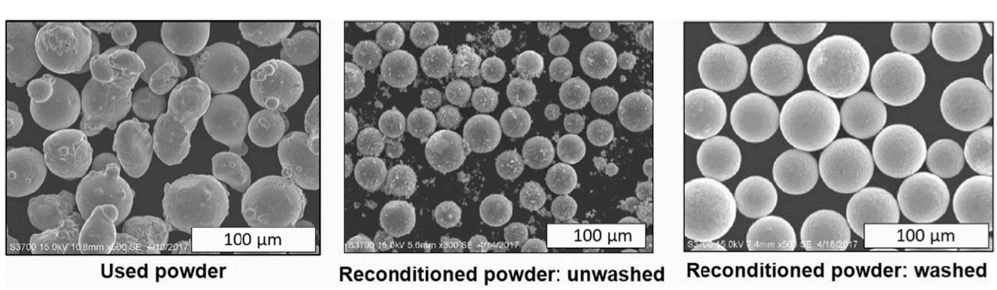

Fig. 18. Morphology of Inconel 718 particles at different states of reconditioning [116].

exhibit enhanced mechanical performance and metamaterial behavior. Another research team in the same year (2019) proposed a systematic scheme to recycle waste reinforcement fibers used in fabricating wind turbine blades using the FFF process [121]. The recycled fibers are reclaimed using mechanical grinding as well as a double sieving mechanism and mixing them with plastic pallets fabricates filaments. The reinforced composted shows higher elastic modulus and ultimate tensile strength compared to the commercially available PLA filaments. H. Huang et al. [122] investigated a novel approach to recycle Carbon Fiber Reinforced Polymer (CFRP) waste and transform it into composite filament for fabricating three-dimensional parts [122]. They separated the Carbon Fibers (rCFs) from the waste using supercritical n-butanol and mixed it with the PEEK powder to form the composite filaments. The recycled composite outperforms the pure PEEK while comparing the flexure strength and flexure modulus. However, the enhancement effect i.e., tensile strength is lower than the counterpart. S. Ding et al. [123] developed a recycling process for carbon fiber-reinforced nylon composite and studied a novel geometric structure i.e., plain weft knitted structures fabricated using a 3D printing process [123]. The recovery process of the composite significantly improves the performance of the recycled carbon fiber reinforced composite, allowing a high nylon matrix infiltration into the carbon fiber surface as shown in Fig. 20. This allows the composite to achieve a superior tensile strength (16.7 % higher) than the original composite.

In the same year, W. Liu et al. [124] proposed a novel approach to reclaim carbon fiber reinforced polymer (CFRP) waste and recycle it by mixing it with Poly-Ether-Ether-Ketone to fabricate 3D components using AM process [124]. The reclaimed carbon fiber enables excellent thermal and mechanical properties which consequently improves overall part quality. In the following year, N. Al-Mazrouei et al. [125] investigated the mechanical and thermal behavior of the recycled composite produced using reinforced composite waste, carbon fiber, and glass fiber [125]. The composite filament is then used to create parts using the 3D printing process and further perform thermal and mechanical analysis which indicates that the recycled composite gains higher mechanical properties such as elasticity modulus, tensile strength, toughness, and extended thermal behavior. K. Chawla et al. [126] studied secondary recycled ABS polymer reinforcing it with industrial Fe waste powder [126]. Filaments are prepared using a standard plastic extruder with the waste from FDM-printed components, and 3D objects are created with different weight ratios of ABS and waste Fe powder for mechanical property analysis. The proposed composite filaments demonstrated enhanced heat-carrying capacity, which is promising in nonstructural engineering applications. Simon et al. [127] investigated the potential of incorporating copper powder to enhance the mechanical properties of recycled PLA filament [127]. They found that the addition of copper effectively improved the tensile strength and fracture toughness compared to commercially available virgin 60 wt% copper/PLA. However, the results also indicated that further efforts are needed to improve the tensile modulus and flexural strength, where the recycled PLA composite is underperforming.

6. Discussions and future work

AM has been considered as a sustainable solution to manufacturing complex geometries, because of its layer-wise production method and therefore reduced consumption of resources in comparison with traditional subtractive manufacturing. Recent research efforts have revealed that AM is not always a green, sustainable manufacturing technique, and there are many opportunities to enable CE in AM from multiple stages such as design, planning, production, and EOL. This study provides a comprehensive review encompassing diverse strategies within AM to bolster CE practices, drawing insights from extensive open literature. It reviews and discusses recent endeavors focusing on reducing resource consumption, AM-enabled repair and remanufacturing, as well as AM materials/composite recycling. Encouraging future research directions are highlighted in this section to guide researchers, manufacturers, and stakeholders towards sustainable manufacturing practices and contribute to the CE.

6.1. Reduce

Significant strides have been made in recent years towards conserving resources and preserving natural capital in AM by focusing on process, material, and structural design. Currently, the emphasis on material design and acquisition primarily revolves around exploring compositional designs or alternative materials for AM thermoplastics. Conversely, recycling or substituting metals and alloys poses challenges due to their inherent difficulty in being recycled or replaced by new alternatives. Moreover, recent research breakthroughs in recyclable thermosets and vitrimers have emerged. However, the efficiency, economic feasibility, and environmental impacts of recycling raise significant concerns due to the need for infrastructure, the lack of standardized processes, and technical challenges in recycling waste materials. Additionally, although much attention has been directed to designing and developing new materials, the feasibility of recycling these materials, the performance (including the fabrication quality and mechanical properties) of recycled materials, and the process mechanism of recycling these materials remain underexplored. In addition, novel topology optimization algorithms have been developed to enable lightweight designs and reduce material consumption/waste. However, extended efforts are required to transition these algorithms from addressing 2D problems to 3D challenges. Also, validating these algorithms through 3D printing is imperative and requires collaborations between researchers in the design field and the manufacturing field. An integrated process of topology optimization and process planning would be promising to simultaneously consider both aspects for a more comprehensive analysis.

In addition to designing towards CE within AM, various production planning methods have been employed to reduce energy consumption,

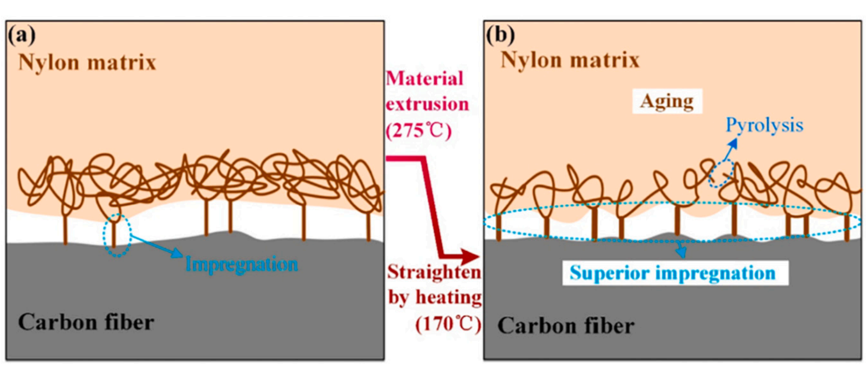

Fig. 20. Carbon fiber and Nylon interfacial bonds: (a) original composite and (b) recycled composite [123].

environmental impacts, or material consumption. Existing efforts primarily focus on process parameter optimization, lacking a more systematic approach. Further explorations are needed focusing on (1) developing advanced production planning models that go beyond simply quantifying relationships between print settings and resource consumption. Extending the scope to encompass various manufacturing environments and integrating production scheduling strategies would facilitate the implementation of AM across different production scales. (2) Conducting a comprehensive analysis of environmental impacts that integrates a detailed examination of printing material compounds. (3) Exploring and implementing material consumption reduction strategies using advanced methods (e.g., topology optimization, digital technology), while simultaneously extending the scope to include standardized cleaning processes alongside the printing process. Lastly, (4) guidance for a standardized AM process with the best practices to achieve desired product performance needs to be developed.

6.2. Reuse

Extensive studies have been conducted to facilitate the metal and plastic components repair enabled by various AM techniques. Most of the existing studies focused on analyzing the effects of various process parameters on the repair quality or evaluating the feasibility of using AM for repair, in-depth discussion is limited to addressing the quality uncertainty of the returned products and process efficiency. Moreover, a comprehensive study that jointly considers the pre-repair process and post-process from a holistic view is promising. Other topics in the domain of AM-enabled repair that need extensive research attention include (1) exploration of real-time monitoring and adaptive control systems in AM repair for better quality, (2) utilization of machine learning algorithms and/or artificial intelligence to analyze extensive datasets from the AM-enabled repair process for defect and failure detection, (3) assessment of economic viability and sustainability of AM-enabled repair compared to other conventional methods and EOL strategies, (4) development of consistent quality standards for adopting the repair methods across various industries, and (5) establishment of comprehensive repair framework in AM that integrated the evaluation of repair quality and efficiency.

Apart from the component repair, studies have also been carried out to advance CE through remanufacturing. While current studies have experimentally evaluated the quality of the remanufactured products and discussed the economic effectiveness of AM-assisted remanufacturing, the scope is limited to hybrid subtractive–additive manufacturing based on conventional machining and DED process. Extended research efforts are needed to explore alternative am processes for remanufacturing such as SLM, EBM, or BJ, and discuss the changes in efficiency and resource utilization. Furthermore, discussing how to leverage AM techniques to enhance the disassembly process, a prerequisite and essential step for remanufacturing, is particularly worthwhile, especially considering the integration of smart materials. Developing systems that can autonomously identify components suitable for remanufacturing, streamline the process, and ensure consistent quality while minimizing waste is also essential and encouraging.

6.3. Recycle

The current progress on AM thermoplastic recycling has demonstrated the feasibility and observed mechanical degradation in recycled materials. Understanding the root cause for quality variation in recycled materials will be the key to enhancing the quality of recycling. The majority of current studies are based on experimental methods, highlighting the need for a systematic framework to standardize the process for effective and efficient plastic recycling. Furthermore, efforts in thermoset recycling are still in their early stages, indicating a necessity for future endeavors to overcome technical barriers to enable and facilitate the de-crosslinking reaction. Currently, most AM metal powder recycling is limited to sieving and sometimes powder cleaning, which tackles the issue of particle size and shape without considering the chemical composition such as oxygen and hydrogen contents. More efforts are needed to characterize the material properties of virgin powder and unused powder to design innovative and effective methods of recycling and reusing metal powders. In regards to AM composite (including polymer-fiber composites and polymer-metal composite) recycling, many studies have been carried out to examine the recyclability of different composites and evaluate the mechanical properties of the recycled materials. The current approaches are focused on specific types of composites and fail to be applied to a variety of material complexities. Exploring the future of composite recycling in AM could focus on the following innovative directions. (1) Developing efficient methods to separate and sort composite materials, enabling easier recycling and reuse of returned materials. (2) Designing new composite materials that have better recyclability and good quality in AM. (3) Conducting comprehensive environmental impacts assessment to advance sustainable recycling practices. (4) Exploring the quality of the recycled composites over multiple service cycles.

CRediT authorship contribution statement

Jing Zhao: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Yiran Yang:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Md Humaun Kobir:** Data curation, Methodology, Writing – original draft. **Jeremy Faludi:** Conceptualization, Investigation, Methodology. **Fu Zhao:** Conceptualization, Investigation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Stahel WR. The circular economy. Nature 2016;531:435–8.
[2] Kurilova-Palisaitiene J, Sundin E, Poksinska B. Remanufacturing challenges and possible lean improvements. J Clean Prod 2018. https://doi.org/10.1016/j.jclepro.2017.11.023.
[3] Cruz Sanchez FA, Boudaoud H, Camargo M, Pearce JM. Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy. J Clean Prod 2020. https://doi.org/10.1016/j.jclepro.2020.121602.
[4] Achterberg E, Hinfelaar J, Bocken N. Master circular business with the value hill. 2016.
[5] Lieder M, Rashid A. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J Clean Prod 2016;115:36–51. https://doi.org/10.1016/J.JCLEPRO.2015.12.042.
[6] Hirsch P, Schempp C. Categorisation system for the circular economy. 2020.
[7] Kirchherr J, Reike D, Hekkert M. Conceptualizing the circular economy: an analysis of 114 definitions. Resour Conserv Recycl 2017:127. https://doi.org/10.1016/j.resconrec.2017.09.005.
[8] Hettiarachchi BD, Sudusinghe JI, Seuring S, Brandenburg M. Challenges and opportunities for implementing additive manufacturing supply chains in circular economy. IFAC-PapersOnLine 2022;55:1153–8.
[9] Shanmugam V, Das O, Neisiany RE, Babu K, Singh S, Hedenqvist MS, et al. Polymer recycling in additive manufacturing: an opportunity for the circular economy. Mater Circ Econ 2020:2. https://doi.org/10.1007/s42824-020-00012-0.
[10] Rahito, Wahab DA, Azman AH. Additive manufacturing for repair and restoration in remanufacturing: an overview from object design and systems perspectives. Processes 2019:7. https://doi.org/10.3390/pr7110802.
[11] Li X, Mao H, Pan Y, Chen Y. Mask video projection-based stereolithography with continuous resin flow. J Manuf Sci E T ASME 2019:141. https://doi.org/10.1115/1.4043765.
[12] Shi Y, Faludi J. Using life cycle assessment to determine if high utilization is the dominant force for sustainable polymer additive manufacturing. Addit Manuf 2020:35. https://doi.org/10.1016/j.addma.2020.101307.
[13] Kanishka K, Acherjee B. Revolutionizing manufacturing: a comprehensive overview of additive manufacturing processes, materials, developments, and

challenges. J Manuf Process 2023:107. https://doi.org/10.1016/j.jmapro.2023.10.024.
[14] Sauerwein M, Doubrovski EL. Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. Mater Today Commun 2018:15. https://doi.org/10.1016/j.mtcomm.2018.02.028.
[15] Sauerwein M, Zlopasa J, Doubrovski Z, Bakker C, Balkenende R. Reprintable paste-based materials for additive manufacturing in a circular economy. Sustainability (Switzerland) 2020:12. https://doi.org/10.3390/su12198032.
[16] Kromoser B, Reichenbach S, Hellmayr R, Myna R, Wimmer R. Circular economy in wood construction – additive manufacturing of fully recyclable walls made from renewables: proof of concept and preliminary data. Construct Build Mater 2022:344. https://doi.org/10.1016/j.conbuildmat.2022.128219.
[17] Lamm ME, Wang L, Kishore V, Tekinalp H, Kunc V, Wang J, et al. Material extrusion additive manufacturing of wood and lignocellulosic filled composites. Polymers (Basel) 2022;12:2115. https://doi.org/10.3390/polym12092115.
[18] Rosenthal M, Rüggeberg M, Gerber C, Beyrich L, Faludi J. Physical properties of wood-based materials for liquid deposition modeling. Rapid Prototyp J 2023:29. https://doi.org/10.1108/RPJ-09-2022-0322.
[19] Krapez Tomec D, Kariz M. Use of wood in additive manufacturing: review and future prospects. Polymers (Basel) 2022;14:1174.
[20] Guo Y, Chen S, Sun L, Yang L, Zhang L, Lou J, et al. Degradable and fully recyclable dynamic thermoset elastomer for 3D-printed wearable electronics. Adv Funct Mater 2021:31. https://doi.org/10.1002/adfm.202009799.
[21] Yuan T, Zhang L, Li T, Tu R, Sodano HA. 3D printing of a self-healing, high strength, and reprocessable thermoset. Polym Chem 2020:11. https://doi.org/10.1039/d0py00819b.
[22] Zhu G, Hou Y, Xiang J, Xu J, Zhao N. Digital light processing 3D printing of healable and recyclable polymers with tailorable mechanical properties. ACS Appl Mater Interfaces 2021:13. https://doi.org/10.1021/acsami.1c08872.
[23] Krishnakumar B, Sanka RVSP, Binder WH, Parthasarthy V, Rana S, Karak N. Vitrimers: associative dynamic covalent adaptive networks in thermoset polymers. Chem Eng J 2020:385. https://doi.org/10.1016/j.cej.2019.123820.
[24] Niu W, Zhang Z, Chen Q, Cao PF, Advincula RC. Highly recyclable, mechanically isotropic and healable 3D-printed elastomers via polyurea vitrimers. ACS Mater Lett 2021:3. https://doi.org/10.1021/acsmaterialslett.1c00132.
[25] Kölsch JC, Berač CM, Lossada F, Stach OS, Seiffert S, Walther A, et al. Recyclable vitrimers from biogenic poly(itaconate) elastomers. Macromolecules 2022:55. https://doi.org/10.1021/acs.macromol.2c00825.
[26] Luo S, Ma Y, Wei X, Jin Y, Qiu L, Zhang W. Malleable and recyclable vitrimer-graphene aerogel composite with high electrical conductivity. ACS Appl Electron Mater 2021:3. https://doi.org/10.1021/acsaelm.0c01028.
[27] Wu J, Yu X, Zhang H, Guo J, Hu J, Li M-H. Fully biobased vitrimers from glycyrrhizic acid and soybean oil for self-healing, shape memory, weldable, and recyclable materials. ACS Sustain Chem Eng 2020:8. https://doi.org/10.1021/acssuschemeng.0c01047.
[28] Zhu J, Zhou H, Wang C, Zhou L, Yuan S, Weihong Zhang. A review of topology optimization for additive manufacturing: status and challenges. Chin J Aeronaut 2021:34. https://doi.org/10.1016/j.cja.2020.09.020.
[29] Fu YF. Recent advances and future trends in exploring Pareto-optimal topologies and additive manufacturing oriented topology optimization. Math Biosci Eng 2020:17. https://doi.org/10.3934/mbe.2020255.
[30] Liu J, Gaynor AT, Chen S, Kang Z, Suresh K, Takezawa A, et al. Current and future trends in topology optimization for additive manufacturing. Struct Multidiscip Optim 2018:57. https://doi.org/10.1007/s00158-018-1994-3.
[31] Xiong Y, Yao S, Zhao ZL, Xie YM. A new approach to eliminating enclosed voids in topology optimization for additive manufacturing. Addit Manuf 2020:32. https://doi.org/10.1016/j.addma.2019.101006.
[32] Sabiston G, Kim IY. Void region restriction for additive manufacturing via a diffusion physics approach. Int J Numer Methods Eng 2020:121. https://doi.org/10.1002/nme.6434.
[33] Yamada T, Noguchi Y. Topology optimization with a closed cavity exclusion constraint for additive manufacturing based on the fictitious physical model approach. Addit Manuf 2022:52. https://doi.org/10.1016/j.addma.2022.102630.
[34] Wang W, Xia Y. Topology optimization based channel design for powder-bed additive manufacturing. Addit Manuf 2022:54. https://doi.org/10.1016/j.addma.2022.102717.
[35] van de Ven E, Maas R, Ayas C, Langelaar M, van Keulen F. Overhang control based on front propagation in 3D topology optimization for additive manufacturing. Comput Methods Appl Mech Eng 2020:369. https://doi.org/10.1016/j.cma.2020.113169.
[36] Liu J, Yu H. Self-support topology optimization with horizontal overhangs for additive manufacturing. J Manuf Sci E T ASME 2020:142. https://doi.org/10.1115/1.4047352.
[37] Luo Y, Sigmund O, Li Q, Liu S. Additive manufacturing oriented topology optimization of structures with self-supported enclosed voids. Comput Methods Appl Mech Eng 2020:372. https://doi.org/10.1016/j.cma.2020.113385.
[38] Dobrzyńska E, Kondej D, Kowalska J, Szewczyńska M. State of the art in additive manufacturing and its possible chemical and particle hazards—review. Indoor Air 2021:31. https://doi.org/10.1111/ina.12853.
[39] Zhang J, Chen DR, Chen SC. A review of emission characteristics and control strategies for particles emitted from 3D fused deposition modeling (FDM) printing. Build Environ 2022;221:109348. https://doi.org/10.1016/J.BUILDENV.2022.109348.
[40] Khalid M, Peng Q. Sustainability and environmental impact of additive manufacturing: a literature review. Comput Aided Des Appl 2021:18. https://doi.org/10.14733/cadaps.2021.1210-1232.
[41] Peng T, Kellens K, Tang R, Chen C, Chen G. Sustainability of additive manufacturing: an overview on its energy demand and environmental impact. Addit Manuf 2018:21. https://doi.org/10.1016/j.addma.2018.04.022.
[42] Di L, Yang Y. Greenhouse gas emission analysis of integrated production-inventory-transportation supply chain enabled by additive manufacturing. J Manuf Sci E T ASME 2022:144. https://doi.org/10.1115/1.4051887.
[43] Gutowski T, Jiang S, Cooper D, Corman G, Hausmann M, Manson JA, et al. Note on the rate and energy efficiency limits for additive manufacturing. J Ind Ecol 2017:21. https://doi.org/10.1111/jiec.12664.
[44] Paul R, Anand S. Process energy analysis and optimization in selective laser sintering. J Manuf Syst 2012:31. https://doi.org/10.1016/j.jmsy.2012.07.004.
[45] Paul R, Anand S. A combined energy and error optimization method for metal powder based additive manufacturing processes. Rapid Prototyp J 2015:21. https://doi.org/10.1108/RPJ-07-2013-0065.
[46] Xu X, Meteyer S, Perry N, Zhao YF. Energy consumption model of Binder-jetting additive manufacturing processes. Int J Prod Res 2015:53. https://doi.org/10.1080/00207543.2014.937013.
[47] Griffiths CA, Howarth J, De Almeida-Rowbotham G, Rees A, Kerton R. A design of experiments approach for the optimisation of energy and waste during the production of parts manufactured by 3D printing. J Clean Prod 2016:139. https://doi.org/10.1016/j.jclepro.2016.07.182.
[48] Zhao J, Yang Y, Li L. Efficiency-aware process planning for mask image projection stereolithography: leveraging dynamic time of exposure. Addit Manuf 2020:36. https://doi.org/10.1016/j.addma.2020.101407.
[49] Yang Y, Li L. Cost modeling and analysis for mask image projection stereolithography additive manufacturing: simultaneous production with mixed geometries. Int J Prod Econ 2018;206:146–58. https://doi.org/10.1016/J.IJPE.2018.09.023.
[50] Ma Z, Gao M, Wang Q, Wang N, Li L, Liu C, et al. Energy consumption distribution and optimization of additive manufacturing. Int J Adv Manuf Technol 2021:116. https://doi.org/10.1007/s00170-021-07653-8.
[51] Baumers M, Tuck C, Wildman R, Ashcroft I, Hague R. Energy inputs to additive manufacturing: does capacity utilization matter?. In: 22nd annual international solid freeform fabrication symposium - an additive manufacturing conference. 2011. SFF; 2011.
[52] Baumers M, Tuck C, Wildman R, Ashcroft I, Rosamond E, Hague R. Transparency built-in: energy consumption and cost estimation for additive manufacturing. J Ind Ecol 2013:17. https://doi.org/10.1111/j.1530-9290.2012.00512.x.
[53] Baumers M, Holweg M. On the economics of additive manufacturing: experimental findings. J Operat Manag 2019:65. https://doi.org/10.1002/joom.1053.
[54] Faludi J, Baumers M, Maskery I, Hague R. Environmental impacts of selective laser melting: do printer, powder, or power dominate? J Ind Ecol 2017:21. https://doi.org/10.1111/jiec.12528.
[55] Afshar-Mohajer N, Wu CY, Ladun T, Rajon DA, Huang Y. Characterization of particulate matters and total VOC emissions from a binder jetting 3D printer. Build Environ 2015:93. https://doi.org/10.1016/j.buildenv.2015.07.013.
[56] Yang Y, Li L. Total volatile organic compound emission evaluation and control for stereolithography additive manufacturing process. J Clean Prod 2018:170. https://doi.org/10.1016/j.jclepro.2017.09.193.
[57] Han M, Li L, Zhao J. Volatile organic compound emissions from 4D printing: effects of material composition and external stimulus. Addit Manuf 2022;56:102894. https://doi.org/10.1016/J.ADDMA.2022.102894.
[58] Kwon O, Yoon C, Ham S, Park J, Lee J, Yoo D, et al. Characterization and control of nanoparticle emission during 3D printing. Environ Sci Technol 2017:51. https://doi.org/10.1021/acs.est.7b01454.
[59] Jeon H, Park J, Kim S, Park K, Yoon C. Effect of nozzle temperature on the emission rate of ultrafine particles during 3D printing. Indoor Air 2019. https://doi.org/10.1111/ina.12624.
[60] Sittichompoo S, Kanagalingam S, Thomas-Seale LEJ, Tsolakis A, Herreros JM. Characterization of particle emission from thermoplastic additive manufacturing. Atmos Environ 2020:239. https://doi.org/10.1016/j.atmosenv.2020.117765.
[61] Oskui SM, Diamante G, Liao C, Shi W, Gan J, Schlenk D, et al. Assessing and reducing the toxicity of 3D-printed parts. Environ Sci Technol Lett 2016:3. https://doi.org/10.1021/acs.estlett.5b00249.
[62] Coupek D, Friedrich J, Battran D, Riedel O. Reduction of support structures and building time by optimized path planning algorithms in multi-axis additive manufacturing. Proc CIRP 2018;67. https://doi.org/10.1016/j.procir.2017.12.203.
[63] Jiang J, Stringer J, Xu X. Support optimization for flat features via path planning in additive manufacturing. 3D Print Addit Manuf 2019:6. https://doi.org/10.1089/3dp.2017.0124.
[64] Jiang J, Xu X, Stringer J. Optimisation of multi-part production in additive manufacturing for reducing support waste. Virtual Phys Prototyp 2019:14. https://doi.org/10.1080/17452759.2019.1585555.
[65] Jiang J, Xu X, Stringer J. Optimization of process planning for reducing material waste in extrusion based additive manufacturing. Robot Comput Integr Manuf 2019:59. https://doi.org/10.1016/j.rcim.2019.05.007.
[66] Arriola B, Oudheusden Van. 3D printing for repair guide n.d. doi:https://doi.org/10.5074/t.2022.003.
[67] Saboori A, Aversa A, Marchese G, Biamino S, Lombardi M, Fino P. Application of directed energy deposition-based additive manufacturing in repair. Appl Sci (Switzerland) 2019:9. https://doi.org/10.3390/app9163316.

[68] Gottwald RB, Griffiths RJ, Petersen DT, Perry MEJ, Yu HZ. Solid-state metal additive manufacturing for structural repair. Acc Mater Res 2021:2. https://doi.org/10.1021/accountsmr.1c00098.
[69] Yin S, Cavaliere P, Aldwell B, Jenkins R, Liao H, Li W, et al. Cold spray additive manufacturing and repair: fundamentals and applications. Addit Manuf 2018:21. https://doi.org/10.1016/j.addma.2018.04.017.
[70] Gouveia JR, Pinto SM, Campos S, Matos JR, Sobral J, Esteves S, et al. Life cycle assessment and cost analysis of additive manufacturing repair processes in the mold industry. Sustainability (Switzerland) 2022:14. https://doi.org/10.3390/su14042105.
[71] Onuike B, Bandyopadhyay A. Additive manufacturing in repair: influence of processing parameters on properties of Inconel 718. Mater Lett 2019:252. https://doi.org/10.1016/j.matlet.2019.05.114.
[72] Shuai C, Cheng Y, Yang Y, Peng S, Yang W, Qi F. Laser additive manufacturing of Zn-2Al part for bone repair: formability, microstructure and properties. J Alloys Compd 2019:798. https://doi.org/10.1016/j.jallcom.2019.05.278.
[73] Rauch M, Hascoët J-Y, Mallaiah M. Repairing Ti-6Al-4V aeronautical components with DED additive manufacturing. MATEC Web Conf 2020:321. https://doi.org/10.1051/matecconf/202032103017.
[74] Kistler NA, Corbin DJ, Nassar AR, Reutzel EW, Beese AM. Effect of processing conditions on the microstructure, porosity, and mechanical properties of Ti-6Al-4V repair fabricated by directed energy deposition. J Mater Process Technol 2019:264. https://doi.org/10.1016/j.jmatprotec.2018.08.041.
[75] Perini M, Bosetti P, Balc N. Additive manufacturing for repairing: from damage identification and modeling to DLD. Rapid Prototyp J 2020:26. https://doi.org/10.1108/RPJ-03-2019-0090.
[76] Li L, Zhang X, Pan T, Liou F. Component repair using additive manufacturing: experiments and thermal modeling. Int J Adv Manuf Technol 2022:119. https://doi.org/10.1007/s00170-021-08265-y.
[77] Wanjara P, Watanabe K, De Formanoir C, Yang Q, Bescond C, Godet S, et al. Titanium alloy repair with wire-feed Electron beam additive manufacturing technology. Adv Mater Sci Eng 2019;2019. https://doi.org/10.1155/2019/3979471.
[78] Lee JH, Lee CM, Kim DH. Repair of damaged parts using wire arc additive manufacturing in machine tools. J Mater Res Technol 2022;16. https://doi.org/10.1016/j.jmrt.2021.11.156.
[79] Marenych OO, Kostryzhev AG, Pan Z, Li H, van Duin S. Application of wire arc additive manufacturing for repair of Monel alloy components. Austr J Mech Eng 2021:19. https://doi.org/10.1080/14484846.2021.1981528.
[80] Zhuo Y, Yang C, Fan C, Lin S. Effects of trace Sn and Cr addition on microstructure and mechanical properties of TC17 titanium alloy repaired by wire arc additive manufacturing. J Alloys Compd 2021:888. https://doi.org/10.1016/j.jallcom.2021.161473.
[81] Pagone E, Antonissen J, Martina F. Life cycle sustainability assessment of repair through wire and arc additive manufacturing. Miner, Metals Mater Ser 2022. https://doi.org/10.1007/978-3-030-92563-5_39.
[82] Priarone PC, Campatelli G, Catalano AR, Baffa F. Life-cycle energy and carbon saving potential of wire arc additive manufacturing for the repair of mold inserts. CIRP J Manuf Sci Technol 2021:35. https://doi.org/10.1016/j.cirpj.2021.10.007.
[83] Huang CJ, Wu HJ, Xie YC, Li WY, Verdy C, Planche MP, et al. Advanced brass-based composites via cold-spray additive-manufacturing and its potential in component repairing. Surf Coat Technol 2019:371. https://doi.org/10.1016/j.surfcoat.2019.02.034.
[84] Joey Griffiths R, Petersen DT, Garcia D, Yu HZ. Additive friction stir-enabled solid-state additive manufacturing for the repair of 7075 aluminum alloy. Appl Sci (Switzerland) 2019:9. https://doi.org/10.3390/app9173486.
[85] Williams MB, Robinson TW, Williamson CJ, Kinser RP, Ashmore NA, Allison PG, et al. Elucidating the effect of additive friction stir deposition on the resulting microstructure and mechanical properties of magnesium alloy we43. Metals (Basel) 2021:11. https://doi.org/10.3390/met11111739.
[86] Oyesola MO, Mpofu K, Mathe NR, Daniyan IA. Hybrid-additive manufacturing cost model: a sustainable through-life engineering support for maintenance repair overhaul in the aerospace. Proc Manuf 2020;49. https://doi.org/10.1016/j.promfg.2020.07.019.
[87] Al-Badour F, Zainelabdeen IH, Suleiman RK, Adesina A. Crack repair using hybrid additive manufacturing and friction stir processing. In: American Society of Mechanical Engineers, Pressure Vessels and Piping Division (Publication) PVP. vol. 6A-2019; 2019. https://doi.org/10.1115/pvp2019-93688.
[88] Chadha C, Patterson AE, Allison JT, James KA, Jasiuk IM. Repair of high-value plastic components using fused deposition modeling. In: Solid Freeform Fabrication 2019: Proceedings of the 30th Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference. 2019. SFF; 2019.
[89] Gide KM, Islam S, Bagheri ZS. Polymer-based materials built with additive manufacturing methods for orthopedic applications: a review. J Compos Sci 2022:6. https://doi.org/10.3390/jcs6090262.
[90] Liu Z, Ge Y, Zhang L, Wang Y, Guo C, Feng K, et al. The effect of induced membranes combined with enhanced bone marrow and 3D PLA-HA on repairing long bone defects in vivo. J Tissue Eng Regen Med 2020:14. https://doi.org/10.1002/term.3106.
[91] Yao CH, Lai YH, Chen YW, Cheng CH. Bone morphogenetic protein-2-activated 3D-printed polylactic acid scaffolds to promote bone regrowth and repair. Macromol Biosci 2020:20. https://doi.org/10.1002/mabi.202000161.
[92] Xu H, Wang C, Liu C, Li J, Peng Z, Guo J, et al. Stem cell-seeded 3D-printed scaffolds combined with self-assembling peptides for bone defect repair. Tissue Eng Part A 2022:28. https://doi.org/10.1089/ten.tea.2021.0055.
[93] Han R, Buchanan F, Ford L, Julius M, Walsh PJ. A comparison of the degradation behaviour of 3D printed PDLGA scaffolds incorporating bioglass or biosilica. Mater Sci Eng C 2021:120. https://doi.org/10.1016/j.msec.2020.111755.
[94] Kanishka K, Acherjee B. A systematic review of additive manufacturing-based remanufacturing techniques for component repair and restoration. J Manuf Process 2023:89. https://doi.org/10.1016/j.jmapro.2023.01.034.
[95] Barragan De Los Rios GA, Ferreira R, Mariani FE, da Silva EJ, Coelho RT. Study of the surface roughness of a remanufactured bimetallic AISI 1045 and 316L SS part obtained by hybrid manufacturing (DED/HSM). Int J Adv Manuf Technol 2023:124. https://doi.org/10.1007/s00170-022-09179-z.
[96] Kandukuri S, Günay EE, Al-Araidah O, Okudan Kremer GE. Inventive solutions for remanufacturing using additive manufacturing: ETRIZ. J Clean Prod 2021:305. https://doi.org/10.1016/j.jclepro.2021.126992.
[97] Liu J, Zheng Y, Ma Y, Qureshi A, Ahmad R. A topology optimization method for hybrid subtractive–additive remanufacturing. Int J Precis Eng Manuf Green Technol 2020:7. https://doi.org/10.1007/s40684-019-00075-8.
[98] Zheng Y, Ahmad R. Feature extraction and process planning of integrated hybrid additive-subtractive system for remanufacturing. Math Biosci Eng 2020:17. https://doi.org/10.3934/MBE.2020373.
[99] Strong D, Kay M, Wakefield T, Sirichakwal I, Conner B, Manogharan G. Rethinking reverse logistics: role of additive manufacturing technology in metal remanufacturing. J Manuf Technol Manag 2020:31. https://doi.org/10.1108/JMTM-04-2018-0119.
[100] Kuenstler AS, Hernandez JJ, Trujillo-Lemon M, Osterbaan A, Bowman CN. Vat photopolymerization additive manufacturing of tough, fully recyclable thermosets. ACS Appl Mater Interfaces 2023:15. https://doi.org/10.1021/acsami.2c22081.
[101] European Commission. Communication from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions: youth opportunities initiative. Off J Eur Union 2022: COM(2022).
[102] Beaumont NJ, Aanesen M, Austen MC, Börger T, Clark JR, Cole M, et al. Global ecological, social and economic impacts of marine plastic. Mar Pollut Bull 2019:142. https://doi.org/10.1016/j.marpolbul.2019.03.022.
[103] Okunola AA, Kehinde IO, Oluwaseun A, Olufiropo EA. Public and environmental health effects of plastic wastes disposal: a review. J Toxicol Risk Assess 2019:5. https://doi.org/10.23937/2572-4061.1510021.
[104] Gomes TE, Cadete MS, Dias-de-Oliveira J, Neto V. Controlling the properties of parts 3D printed from recycled thermoplastics: a review of current practices. Polym Degrad Stab 2022;196. https://doi.org/10.1016/j.polymdegradstab.2022.109850.
[105] Voet VSD, Guit J, Loos K. Sustainable photopolymers in 3D printing: a review on biobased, biodegradable, and recyclable alternatives. Macromol Rapid Commun 2021:42. https://doi.org/10.1002/marc.202000475.
[106] Yao B, Li Z, Zhu F. Effect of powder recycling on anisotropic tensile properties of selective laser sintered PA2200 polyamide. Eur Polym J 2020:141. https://doi.org/10.1016/j.eurpolymj.2020.110093.
[107] Weinmann S, Bonten C. Recycling of pa12 powder for selective laser sintering. AIP Conf Proc 2020;2289. https://doi.org/10.1063/5.0029945.
[108] Riedelbauch J, Rietzel D, Witt G. Analysis of material aging and the influence on the mechanical properties of polyamide 12 in the multi jet fusion process. Addit Manuf 2019:27. https://doi.org/10.1016/j.addma.2019.03.002.
[109] Dotchev K, Yusoff W. Recycling of polyamide 12 based powders in the laser sintering process. Rapid Prototyp J 2009:15. https://doi.org/10.1108/13552540910960299.
[110] Kumar S, Czekanski A. Development of filaments using selective laser sintering waste powder. J Clean Prod 2017:165. https://doi.org/10.1016/j.jclepro.2017.07.202.
[111] Yang F, Jiang T, Lalier G, Bartolone J, Chen X. Process control of surface quality and part microstructure in selective laser sintering involving highly degraded polyamide 12 materials. Polym Test 2021:93. https://doi.org/10.1016/j.polymertesting.2020.106920.
[112] Romani A, Perusin L, Ciurnelli M, Levi M. Characterization of PLA feedstock after multiple recycling processes for large-format material extrusion additive manufacturing. Mater Today Sustain 2024:25. https://doi.org/10.1016/j.mtsust.2023.100636.
[113] van Sice C, Faludi J. Comparing environmental impacts of metal additive manufacturing to conventional manufacturing. In: Proceedings of the Design Society. vol. 1; 2021. https://doi.org/10.1017/pds.2021.67.
[114] Powell D, Rennie AEW, Geekie L, Burns N. Understanding powder degradation in metal additive manufacturing to allow the upcycling of recycled powders. J Clean Prod 2020:268. https://doi.org/10.1016/j.jclepro.2020.122077.
[115] Maamoun AH, Elbestawi M, Dosbaeva GK, Veldhuis SC. Thermal post-processing of AlSi10Mg parts produced by selective laser melting using recycled powder. Addit Manuf 2018:21. https://doi.org/10.1016/j.addma.2018.03.014.
[116] Garboczi EJ, Brooks AJ, Kerwin L, Samant R. Inductively coupled plasma process for reconditioning Ti and Ni alloy powders for additive manufacturing. Metall Mater Trans A Phys Metall Mater Sci 2021:52. https://doi.org/10.1007/s11661-021-06198-5.
[117] Weiss C, Haefner CL, Munk J. On the influence of AlSi10Mg powder recycling behavior in the LPBF process and consequences for mechanical properties. JOM 2022:74. https://doi.org/10.1007/s11837-021-05080-4.
[118] Smythe SA, Thomas BM, Jackson M. Recycling of titanium alloy powders and swarf through continuous extrusion (Conformtm) into affordable wire for additive manufacturing. Metals (Basel) 2020:10. https://doi.org/10.3390/met10060843.

[119] Ujeniya PS, Rachchh NV. A review on manufacturing, machining, and recycling of 3D printed composite materials. IOP Conf Ser Mater Sci Eng 2019;653. https://doi.org/10.1088/1757-899X/653/1/012024.
[120] Singh N, Singh R, Ahuja IPS, Farina I, Fraternali F. Metal matrix composite from recycled materials by using additive manufacturing assisted investment casting. Compos Struct 2019:207. https://doi.org/10.1016/j.compstruct.2018.09.072.
[121] Rahimizadeh A, Kalman J, Fayazbakhsh K, Lessard L. Recycling of fiberglass wind turbine blades into reinforced filaments for use in additive manufacturing. Compos B Eng 2019:175. https://doi.org/10.1016/j.compositesb.2019.107101.
[122] Huang H, Liu W, Liu Z. An additive manufacturing-based approach for carbon fiber reinforced polymer recycling. CIRP Ann 2020:69. https://doi.org/10.1016/j.cirp.2020.04.085.
[123] Ding S, Zou B, Wang P, Huang C, Liu J, Li L. Geometric modeling and recycling of 3D printed fiber reinforced thermoplastic composite plain weft knitted structures. Compos Part A Appl Sci Manuf 2021:149. https://doi.org/10.1016/j.compositesa.2021.106528.
[124] Liu W, Huang H, Zhu L, Liu Z. Integrating carbon fiber reclamation and additive manufacturing for recycling CFRP waste. Compos B Eng 2021:215. https://doi.org/10.1016/j.compositesb.2021.108808.
[125] Al-Mazrouei N, Al-Marzouqi AH, Ahmed W. Characterization and sustainability potential of recycling 3D-printed nylon composite wastes. Sustainability (Switzerland) 2022:14. https://doi.org/10.3390/su141710458.
[126] Chawla K, Singh R, Singh J, Mehta H. Investigations on mechanical properties of secondary recycled ABS reinforced with Fe powder for 3D printing applications. Mater Today Proc 2021;50. https://doi.org/10.1016/j.matpr.2021.10.291.
[127] Simon Ž, Stojcevski F, Dharmasiri B, Henderson LC, Amini N. Circular economy-driven additive manufacturing: a model for recycling PLA/copper composites through multi-extrusion processing. J Ind Eng Chem 2024:130. https://doi.org/10.1016/j.jiec.2023.09.044.