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CRITICAL REVIEW

Current state and emerging trends in advanced manufacturing: process technologies

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Abstract

Advanced manufacturing is challenging engineering perceptions of how to innovate and compete. The need for manufacturers to rapidly respond to changing requirements and demands; obtain, store, and interpret large volumes of data and information; and positively impact society and our environment requires engineers to investigate and develop new ways of making products for flexible and competitive production. In addition to the associated operational, technological, and strategic advantages for industry, advanced manufacturing creates educational, workforce, and market opportunities. Thus, this literature review is aimed at investigating the current state and emerging trends in advanced manufacturing. Specifically, this study addresses advances in manufacturing process technologies, focusing on shaping processes (mass reducing, mass conserving, and joining) as well as non-shaping processes (heat treatment and surface finishing), and metal-based additive manufacturing. This literature review finds myriad efforts have been undertaken by researchers in industry, academia, and government labs from around the world, which have supported the development and implementation of new process technologies to improve manufacturing systems extending from unit process and shop floor operations to facility and supply chain management activities. However, as evidenced by recent and emerging global challenges in energy, critical materials, and health care, the manufacturing industry must continue the innovative development of advanced materials, manufacturing processes, and systems that ensure cost-efficient, rapidly flexible, high-quality, and responsible production of goods and services.

Keywords Advanced manufacturing · Conventional processes · Additive manufacturing · Manufacturing systems · Smart manufacturing

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1 Introduction

The term *advanced manufacturing* is used to describe the ever-changing suite of technologies, processes, skills, and strategies used to fabricate much of what we use as a society [1]. Countries invest in advanced manufacturing research to improve their competitive advantages and leadership across global markets [2, 3]. Recent national efforts highlight the importance of advanced manufacturing industries across the globe. In Japan, for instance, advanced manufacturing has been identified as one of four primary economic sectors, influencing one-third of its economic potential, and comprised of automotive, industrial machinery, and electronics industries [4]. In 2014, the U.S. Advanced Manufacturing Partnership (AMP) was formed to identify emerging technologies for sustaining its manufacturing leadership [1], while the European Commission highlighted advanced manufacturing as an enabler of industry process accuracy improvement, reduction of energy and materials consumption, and enhanced waste management [5]. These national efforts have noted the significant benefits that advanced manufacturing technologies and a skilled workforce provide in producing industrial and consumer products, e.g., quality improvement, market share growth, lower cost and process time, and higher productivity. These benefits are enabled by cutting-edge developments at the manufacturing process and systems levels [6–8].

Sustainable development has received increasing attention from society, academia, and industry for the past half century due to global warming, growing public awareness, corporate social responsibility, stricter regulations, and resource scarcity [9]. Advanced manufacturing provides opportunity for engineers and researchers to imagine new ways of making products for sustainable manufacturing as well as smart, rapid, flexible, and competitive production. Thus, the objective of this literature review is to investigate recent operational, technical, and strategic developments as well as open challenges and future trends in advanced manufacturing processes from sustainability perspective. Advanced manufacturing technologies incorporate numerous unit manufacturing processes (UMPs) to convert raw materials into a final product utilizing energy, labor, equipment and tools, and supporting systems. This review focuses on several shaping processes (mass reducing, mass conserving, and joining) and non-shaping processes (heat treatment and surface finishing). In addition, metal-based additive manufacturing processes are reviewed to elucidate recent advances impacting their performance in terms of cost, resource use, and worker health and safety. Section 2 addresses advances in manufacturing processes, focusing on shaping processes, non-shaping processes, and metal-based additive manufacturing processes. Section 3 presents challenges, future trends, and recommendations identified through the review.

2 Advances in manufacturing process technologies

By synthesizing definitions reported in research literature, Garretson et al. [10] defined a unit manufacturing process (UMP) as "the smallest elementary manufacturing activity required for a specific taxonomological transformation and composed of machines, devices, or equipment." This review paper leverages the taxonomy reported by Todd et al. [11] to categorize the UMPs reviewed. The first category in the taxonomy covers shaping processes (Sects. 2.1–2.3) and includes mass reducing, mass conserving, and joining processes. The second category encompasses non-shaping processes (Sects. 2.4–2.5) and includes heat treatment and surface finishing processes. Finally, advances in metal-based additive manufacturing processes are reviewed in Sect. 2.6. It should be noted that additive manufacturing technologies were developed and became commercially viable for production after the taxonomy was published.

2.1 Mass reducing processes

In mass reducing processes, the desired geometry of the final product is achieved by removing the extra material from the workpiece [12]. Todd et al. [11] defined three branches of mass reducing processes: mechanical, thermal, and chemical. The most widely used processes in this category, machining processes, underlie mechanical reducing [12]. This section focuses on single-point, multi-point, and abrasive machining processes. In single- and multi-point cutting, a tool with one and multiple cutting edge(s) are used respectively to remove material from the workpiece. Abrasive machining utilizes a pattern of randomly-oriented cutting points (grits) applied to a belt, disk, wheel, or other substrate. These grits range widely in materials and sizes.

2.1.1 Single-point material removal

Single-point material removal is a foundational industrial manufacturing process. Small, medium, and large manufacturers leverage single-point machining processes (e.g., turning, boring, and planning) to convert raw stock material to final product dimensions. Single-point machining processes can achieve high volume production, high quality finishes, and precise dimensional tolerances. Due to their prevalence in industry, relatively minor improvements in the sustainability performance of single-point material removal operations can have a significant impact industry-wide. Turning operations have been the focus of many studies that investigate how changes to cutting parameters can contribute to enhancing sustainability performance.

Bhanot et al. [13] presented an approach to perform sustainability assessment of turning processes in the automotive industry. Production cost, cutting quality, production rate, and process management were considered as a function of machining process attributes (e.g., material removal rate, surface roughness, cutting temperature, machine idle time, and machine cost) to quantify the economic aspect. Water intensity, energy intensity, materials, and waste management were considered as a function of water consumption per unit of output, energy per unit output, hazardous materials, and air and water emissions, respectively, to quantify the environmental aspect. Finally, worker health, worker safety, labor relations, and training/education had measures such as average number of hours of training per operator, skill level, noise levels, and exposure to high energy components to quantify the social aspect. These metrics were determined using a survey to obtain industry stakeholder perspectives. Economic and environmental metrics were determined as functions of turning process parameters (e.g., cutting speed, cutting force, and lubrication) using transformation equations. These metrics were then aggregated via grey relational analysis, a multi-criteria decision-making method, to evaluate the trade-offs between the three pillars of sustainability for wet machining, dry machining, and standard cutting parameter cases. Results indicated that wet machining aligns with the economic aspect more than the other two, requiring operating modifications (e.g., dry machining and minimum quantity lubrication, discussed later) to balance the environmental aspect. Additionally, the authors concluded that dry conditions (dry machining) can balance environmental and economic concerns; however, it was not indicated how tool wear or machining quality was affected. The approach presented by Bhanot and co-workers [13, 14] touches upon several key areas of study in single-point machining: (1) optimization and tuning of material removal parameters and tools, (2) advanced lubrication and cooling methods (discussed in Sect. 2.1.2), and (3) assisted turning and machining technologies.

Multiple approaches to optimizing single-point machining processes to balance trade-offs between sustainability aspects have been pursued in prior research. Helu et al. [15] determined that green machining of Ti-6Al-4 V for maximizing surface quality should target rough cut improvement strategies and feed rate optimization since finish cuts and feed rate most influence surface quality. However, their recommendations are not universal, since other cutting parameters can affect energy, tool wear, service costs, and finished part functionality. In general, they demonstrated how trade-offs in sustainability aspects are dependent on the functionality of the finished parts. Helu et al. [15] built on their prior work [16], which completed a total cost analysis of energy, tooling, service, and quality for single-point machining strategies that aim to reduce process times. The study was motivated by the realization that, while process time reduction strategies typically reduce machining energy costs, these strategies can increase stresses, forces, and heat on the tool, part, and machine, which in turn influence service, tooling, and quality costs. Results of the total cost analysis indicated a decrease in energy costs, an increase in tooling costs, and an increase or decrease in service costs, depending on specific process time reduction decisions.

These outcomes were limited because machine tool breakdown variability was not fully captured, reductions in other energy overheads (e.g., HVAC or lighting costs) were not considered, and part functionality as related to machining parameters was not incorporated. Single-point machining process research has investigated various modeling methods to characterize the relationship between turning parameters, desired turning outcomes (e.g., surface roughness), and sustainability metrics [15, 17]. Response surface methodology (modeling the relationships between cutting parameters and energy consumption), Taguchi analysis, analysis of variance (ANOVA), and evolutionary heuristics are methods that have been employed to quantify and to optimize these relationships for different materials (Table 1).

Since 2020, single point machining sustainable manufacturing research has expanded the types of sustainability metrics considered in cutting parameter decisions, investigated sustainability tradeoffs for different types of material, and analyzed additional turning strategies, such as multi-pass processes. Pujiyanto et al. [26] incorporated a total noise metric in assessment of multi-pass carbon steel C45 turning as a means to addressing the social pillar of sustainability. In addition to energy consumption of a turning process, Vukelic et al. [27] included four life cycle assessment indicators into their optimization of cutting parameters for dry turning of Inconel 601 based on environmental and economic considerations. In an investigation of AISI 1045 steel turning process parameter optimization, La Fé Perdomo et al. [24] utilized CO_2 emissions as a measure for environmental sustainability and defined social sustainability as operator safety which was a metric disaggregated into exposure to toxic chemicals, exposure to high temperature, and exposure to high-speed surfaces.

Other recent single-point machining sustainability studies leveraged existing metrics for economic and environmental sustainability elements but for case studies of different turning process designs or materials. Pujiyanto et al. [26] not only incorporated the social sustainability metric of total noise but also considered multi-pass turning processes, and Li et al. [29] evaluated the environmental and economic aspects of multi-direction turning (as opposed to single-direction turning). Herwan et al. [30], Trifunović et al. [28], and Vukelic et al. [27] undertook sustainable single-point machining studies on grey cast iron, polyoxymethylene copolymer, and Inconel 601 materials that had not previously been studied from a sustainability perspective. Single-point machining sustainability analyses appear to have or be converging to a common framework as single-point machining sustainability studies have matured. This framework, typically, entails execution of experiments based on Design of Experiments methods (i.e., Taguchi methods), characterization of the relationships between cutting parameters and key sustainability metrics, identification of Pareto frontier(s) of non-dominated solutions, and selection of cutting parameters using a multi-criteria decision making (MCDM) approach. The framework is generally observable in the selected references in Table 1, where researchers have leveraged methods such as ANOVA and response surface analysis to evaluate the relationship between cutting parameters and sustainability metrics and then used evolutionary heuristics such as particle swarm and genetic algorithm

Table 1 Methods implemented to optimize single point machining parameters for sustainability metrics

Study goal	Methodology	Key findings	Reference
Review sustainability machining parameter optimization	Classify studies based on time published and scope of sustainable dimensions studied	Summarize future directions of sustainable machining research and general trends of prior literature around efficiency, consistency, and sufficiency strategies	[18]
Optimize machining parameters for power consumption, surface roughness, and tool wear for AISI 316 stainless steel	Response surface methodology and central composite design	Improvement of 14.94%, 4.71%, and 13.98% in power consumption, surface roughness, and tool wear, respectively	[19]
Optimize machining parameters for EN 353 alloy steel	Taguchi method and analysis of variance (ANOVA)	Improvement of 61.78%, 57.03%, and 7.49% in energy efficiency, active energy consumed, and power factor, respectively, compared to baseline parameters classified as common for rough turning	[20]
Optimize energy consumption and surface roughness for machining AISI 6061 T6 aluminum	Response surface methodology and analysis of variance (ANOVA)	Specific energy consumed reduced by 14.41%; and surface roughness enhanced by 360.47%	[21]
Effect of speed, feed, depth of cut, environment, dry/MQL/wet conditions, and cutting tool type on surface roughness, material removal rate, and energy in machining of AISI 1040 carbon steel	Response surface methodology and analysis of variance (ANOVA)	Surface roughness influenced by cutting environment and tool; material removal rate influenced by tool type, cutting velocity, feed, and depth of cut; and power dependent on cutting environment, tool type, cutting velocity, and depth of cut for cases evaluated	[22]
Demonstrate evolutionary heuristic for optimizing trade-offs in production cost, production time, and energy consumption by tuning cutting parameters	Particle swarm multi-objective optimization	Particle swarm method provided framework for multi-objective machining optimization with sustainability indicators	[23]
Optimize multi-pass cylindrical turning considering cost, CO_2 emissions, and operational safety	Non-sorting genetic algorithm (NSGA-II)	Non-sorting genetic algorithm (NSGA-II) capable of formulating a tri-dimensional Pareto front for selecting cutting conditions based on sustainability metrics and preferences	[24]
Minimize direct energy consumption during turning of GOST 4543 and BDS 4880 steels	Minimum energy criterion based on models for dependence of specific energy on material removal rate, and dependence of direct energy consumption on only cutting parameters	Less energy consumed with maximum feed rate and depth of cut. Lower energy consumption given a machining insert with higher wear resistance	[25]
Optimize cutting parameters for multi-pass turning of carbon steel C45 considering total energy, surface roughness, total noise, total cost, and total carbon emissions	Non-sorting genetic algorithm (NSGA-II) with elitism then Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) for decision making	Successful generation of Pareto fronts based on the five metrics considered and identification of a set of cutting parameters using TOPSIS that balanced tradeoffs of each metric	[26]
Optimize dry turning of Inconel 601 considering surface roughness, flank wear, cutting time, energy consumption, and four life cycle assessment indicators	Genetic algorithm	Dry turning of Inconel 601 can reduce energy consumption and impact on environment, while meeting quality requirements if larger radii turning inserts, higher cutting speeds, and smaller feeds/depths of cut are used	[27]
Characterize influence of cutting parameters on energy consumption and machinability of polyoxymethylene copolymer using a polycrystalline diamond tool	Multi-objective genetic algorithm and exhaustive iterative search algorithm	Depth of cut was the most important parameter in trade-offs between cutting energy and material removal rate	[28]
Optimize turning of AISI 1045 steel considering CO2 emissions, operator safety, and costs. Operator safety is based on exposure to toxic chemical, high temperature, and high speed surface	Non-sorting genetic algorithm (NSGA-II)	NSGA-II was able to generate and effective tri-dimensional Pareto front to help with decision making for multi-pass cylindrical turning of AISI 1045	[24]

Table 1 (continued)

Study goal	Methodology	Key findings	Reference
Multi-objective evaluation of forward and reverse multi-directional turning considering energy consumption, cutting time, production cost, surface roughness efficiency, cost, and quality	TOPSIS	TOPSIS provided framework for determining a multi-objective scheme for multi-directional turning	[29]
Optimize energy consumption, tool cost, and surface roughness for grey cast iron finish cutting by high speed dry turning	ANOVA and Taguchi based Bayesian optimization method	Higher cutting speeds demonstrated better surface roughness and a depth of cut of 0.1mm was best for all sustainability indexes	[30]

to generate a set of solutions on or near the Pareto frontier. MCDM methods, such as TOPSIS, are implemented to select a set of cutting parameters from non-dominated solutions.

From 2022 to 2024, three review papers emerged that summarize aspects of sustainable single-point machining. Pimenov et al. [31] reviewed resource savings from optimization of general machining for sustainable manufacturing with a focus on lubrication and cooling methods such as minimum quantity lubrication, nanofluids, and vegetable oils. Xu et al. [32] reviewed both the smart (Industrial Internet of Things—IIOT) and sustainable aspects of ultra-precision machining. Only ultra-precision machining processes were considered, and the outcome of the review was a six-layer IIOT framework for smart and sustainable ultra-precision machining that aimed to address low energy efficiency, lack of real-time monitoring data, and machining efficacy challenges of ultra-precision machining. Soori et al. [33] provided a broad review of sustainable CNC machining systems, resulting in a list of future sustainable machining research suggestions in major thrust areas such as material selection, energy efficiency, waste reduction, life cycle assessment, lean manufacturing, renewable energy, monitoring/machine utilization, supply chain, virtual simulation, and operator training/engagement.

Analysis of energy, cutting parameters, and surface roughness relationships have typically been the focus of improving the sustainability performance of turning. Studies have conducted life cycle assessment (LCA) to provide additional depth, but environmental and social metrics have not been fully integrated into existing optimization methods [13, 24, 34, 35]. Efforts to transition single-point material removal operations toward the use of environmental-friendly cutting fluids have followed the trend from conventional techniques (e.g., flood, high pressure, mist, and internal cooling) to new methods that reduce fluid use or use more environmental-friendly fluids (e.g., dry machining, minimum quantity lubrication, and cryogenic cooling) [36, 37]. Section 2.1.2 discusses detailed advancements in lubrication and cooling for sustainable machining that are relevant to single- and multi-point material removal.

Recent advancements in ultrasonic machining and laser-assisted machining (LAM) may provide new opportunities to explore sustainable methods of single-point material removal, particularly when combined with existing approaches to optimizing cutting parameters, minimum quantity lubrication, cryogenic machining, or dry machining [14, 38]. LAM is the use of an external heat source to soften a workpiece to enhance cutting. Ultrasonic vibration assisted machining (UVAM) or ultrasonic assisted turning (UAT) applies vibrations directly to the workpiece or cutting tool. Studies on the effect of these assistive methods have suggested that they provide enhancements to cutting force, tool life, and surface properties [14, 38, 39]. However, rigorous sustainability analyses and LCA studies are needed to make definitive conclusions on the impact of LAM and UVAM on single-point material removal sustainability metrics since reported studies have evaluated sustainability performance at a cursory level [39, 40].

2.1.2 Multi-point material removal and cutting fluid use

In a multi-point material removal process, a cutting tool removes material from the workpiece with multiple cutting edges, reducing production time and cost compared to single-point processes [41]. Multi-point material removal processes are ubiquitous in industry, especially for machining complex surfaces. Cutting fluids are widely used as lubricants and coolants while protecting the workpiece from corrosion. They are effective in improving the machinability, productivity, tool life (decreasing tool wear caused by diffusion and adhesion), and workpiece quality. However, cutting fluids can cause environmental, ecological, and human health problems during distribution, utilization, and disposal. The costs and environmental impacts of cutting fluids are two major factors influencing their current and future use [42]. Reducing fluid use and developing environmental-friendly alternatives have been explored to mitigate these problems while improving machining quality and productivity.

Dry machining and minimum quantity lubrication (MQL) Dry machining is a technology that obviates the need for cutting fluid during a machining process and can effectively alleviate the problems attendant with cutting fluid use. However, since cutting fluid serves several important functions, the application of dry machining is not a simple task of just turning off the cooling lubricant supply [43]. Several studies have investigated the effective use of dry machining and the impacts caused by the lack of cutting fluids. One approach has demonstrated the design of self-lubricating textured tools, which can reduce cutting force, cutting temperature, and tool wear [44–49]. Other research has explored how machining parameters affect the dry machining process [50–52]. Studies have shown that dry machining may reduce tool flank wear and burr formation, but the lack of cutting fluid may also cause larger surface roughness [53–55].

Another effective method to reduce the use of cutting fluids is minimum quantity lubrication (MQL), also called near dry machining or micro-lubrication. In this method, the cutting fluids are mixed with compressed air and fed directly to the cutting zone in minute quantities [43, 56]. Research has investigated MQL as a way to reduce the human health impacts of the lubricants [57], as well as the use of solvents other than water, such as CO_2 [58]. Individual components of MQL systems, such as feed technology, machine tools, and cutting tools, mutually affect each other [43]. Much research has been done to analyze the impact of MQL system parameters on the cutting fluid distribution and droplet size [56, 59–62]. Droplets with smaller diameters can penetrate the surface more easily and improve heat transfer and lubrication. Air flow and distance between the cutting zone and nozzle have the strongest influence on the droplet diameter [42].

Machining parameters can also affect cutting fluid performance. As a starting point, simulation or experiment-based research has attempted to quantify these process impacts. Jiang et al. [63] provided a model to optimize the machining parameters. Their model treats cutting fluid consumption and process cost as two objectives and uses a genetic algorithm to solve the resulting multi-objective optimization problem. Iqbal et al. [64] provided an experimental approach to quantify the impacts of flank wear as a tool replacement criterion for milling process sustainability metrics, including energy use, process cost, work surface roughness, and material removal rate. During the machining process, the cutting tool can wear due to abrasion, adhesion, and oxidation [65]. Effective use of MQL can improve the quality of the workpiece and can reduce tool wear and cost [66–70]. In some cases, such as milling with large cutting depth, cutting fluid reaches the chip-tool interface hardly. New techniques have been designed to effectively use a cutting fluid in those cases. Huang et al. [71] reported a contact-charged electrostatic spray lubrication technique, which improved the tribological and lubrication performance compared to traditional MQL. This method can create droplets of smaller size, which enhance oxygen penetration, providing a protective oxide layer for the workpiece (sometimes such layers are not desirable). Nadolny et al. [72] developed a system for centrifugal supply of oil mist during grinding. They demonstrated improved wheel life and reduced roughness of the machined surface.

A concern with some MQL techniques is the generation of mists, which can impact worker health. Another limitation of MQL techniques is that not enough lubrication may be provided when they are used in the machining of materials such as titanium alloy. Recent work has focused on using micro-flood techniques [73] or nanofluids that improve the efficacy of the fluid and can be used more selectively [74]. Shen et al. [75] provided an experimental study of high-speed, near-dry electrical discharge machining (EDM), which is suitable for difficult-to-machine materials. They analyzed the effects of machining parameters, such as current, droplet size, and electrode rotation speed, on quality metrics (e.g., surface roughness). Pan et al. [76] compared cutting force and cutting temperature in milling of titanium alloy when different types of lubrication are deployed. Results show that nanofluid MQL significantly reduced friction coefficient and cutting forces. Bai et al. [77] studied the impacts of adding Al_2O_3 nanoparticles into cottonseed oil-based cutting fluids. Experiments are carried out to find the optimal concentration of Al_2O_3 nanoparticles that lead to the best performance. Cutting force, specific energy, and surface roughness are analyzed.

Environmental-friendly cutting fluids Gas-based coolant/lubricants may be an environmental-friendly substitute for cutting fluids. In machining, both gas and cooled-pressured fluids can be referred to as gas-based coolant/lubricants [57]. Commonly used gas-based coolant/lubricants are air, nitrogen, argon, helium, and carbon dioxide, which can prevent the cutting tool and workpiece from being oxidized at high cutting temperatures [57, 78]. Gas-based coolant can be used to form mist or droplets, improving the lubrication capability of traditional cutting fluids [57, 79]. Under some machining conditions (e.g., heavy-duty cutting), the cutting fluid may fail to reach the cutting zone using conventional cooling methods, and pressurized gas-based coolants can be applied to overcome this challenge. A pressurized gas stream with fluid droplets may reduce built-up edge and tool wear [78]. However, one major problem of gas-based cutting fluids is that they have poor cooling capacity. Research has demonstrated that the application of cryogenic cooling, or refrigerated air, in a variety of machining operations can reduce temperatures in the cutting zone and reduce tool wear [80–83]. Pereira et al. [81] concluded that one approach to balance technical and environmental issues in machining is to combine the cryogenic and MQL techniques. In addition, it has been reported that bio-based cutting fluids can have similar or improved performance than mineral oil-based fluids while also being more readily degradable [57, 84–86]. However, some bio-based coolants such as vegetable oils have the disadvantage of low thermal and oxidative stability, high freezing points, and poor corrosion protection. Additives may be used to solve these issues [87, 88].

2.1.3 Abrasive machining

Abrasive machining is the process where material is removed from the workpiece surface by multiple randomly-oriented hard grains that each function much like a small cutting tool. Grinding is the most representative and widely used abrasive machining method and is the focus of this section, though polishing, honing, and grinding are used to refine dimensions or to finish surfaces. The specific energy consumption (SEC, energy per unit volume of cutting material) of grinding [89] is greater than the SEC of other standard machining operations [90, 91] and has been a focus of recent manufacturing research. The specific energy, e, for grinding can be determined from the cutting force, F, wheel speed, v, and volumetric material removal rate, Q, as shown in Eq. 1 [92]:

$$e = Fv/Q \tag{1}$$

The cutting force, F, is composed of three components, i.e., the chip removal force, F_c, sliding force, F_s, and ploughing force, F_p, as shown in Eq. 2 [90].

$$F = F_c + F_s + F_p \tag{2}$$

During grinding, F_s and F_p do not contribute to shearing of the material but generate heat and deform the material. If wheel speed is held constant, the issue to consider in reducing energy use is how to balance F and Q to achieve a reduction in e (Eq. 1). One solution is to add texture to the grinding wheel [93]. Textured grinding wheels possess active and passive grinding areas on the wheel surface [94]. Active grinding areas perform material removal (presence of abrasive grains), while passive grinding areas mark the absence of abrasive grains on the grinding wheel surface. This arrangement on the grinding wheel surface reduces the number of active cutting edges and suppresses sliding, F_s, and ploughing, F_p, forces [93]. Consequently, the overall cutting force, F, will be reduced. Azarhoushang et al. [95] provided a detailed theoretical model (Eq. 3) to demonstrate that texturing (wheel structuring) significantly reduces the specific grinding energy when compared to conventional non-textured wheels of the same dimension.

$$\left(\frac{h_{\mathrm{cu,max-con}}}{h_{\mathrm{cu,max-tex}}}\right)^m = (1-\chi)^{\frac{3\eta m}{4}} = \frac{e_{c-\mathrm{tex}}}{e_{c-\mathrm{con}}} \tag{3}$$

In this equation, $h_{\mathrm{cu,max\text{-}con}}$ and $h_{\mathrm{cu,max\text{-}tex}}$ are the maximum uncut chip thicknesses associated with conventional and textured grinding wheel, respectively; χ indicates the ratio of surface area of active grinding to total grinding; $e_{c\text{-con}}$ and $e_{c\text{-tex}}$ are the SEC by the conventional and textured wheel, respectively; m is a constant determined by the roughness of the ground surface (equal to 0.3 for roughing operations and in the range of 0.8–1.0 for finishing operations); and η is a constant representing the abrasive grain density, which can generally be determined experimentally. In addition to reducing specific grinding energy, textured grinding wheels improve spacing for chip accommodation [89, 93] and, thus, mitigate wheel loading and frequent dressing. Dry machining conditions are also attainable with textured grinding wheels [89, 95] facilitating more coolant flow into the grinding zone than conventional wheels [96–99]. Thus, texturing enables minimization of coolant use and reduces associated environmental and social concerns [100]. Textured grinding wheels are classified into three categories based on the width of the minimal repeated geometrical unit of the grinding passive area: microtexture, macrotexture, and megatexture [94]. Table 2 summarizes the major differences of the three types on the aspects of passive area width, the method for texture generation, and the major applications.

Grinding wheels with microtextures Microtextures of less than 100 µm are generally produced by laser ablation to directly cut the textures into a piece of hard material, e.g., cubic boron nitride (CBN), while megatextures and macrotextures are made by bonding abrasive grains on the grinding wheel base and mechanically cutting the textures. The fabrication accuracy in laser ablation generates homogenous cutting edges with uniform protrusion and preferential crystallographic orientation [101, 102]. The advantage is passive, and active grinding areas are cut on the solid abrasive eliminating the need for bonding material and reduces the environmental impacts associated with the bonding material [102].

Grinding wheels with macrotextures Grinding wheels with macrotextures (engineered wheels) are characterized by controlled arrangement of abrasive grains on the grinding wheel surface, such that the texture dimension is between 100 and 500 µm [94]. Patterns inspired by nature, such as phyllotactic patterns, have been investigated for arranging the abrasive grains on the grinding wheel [103–106]. The effectiveness and efficiency of such patterns with varying divergence angles, phyllotactic coefficients, and abrasive grain cluster radii have been experimentally observed [104]. An analytical approach to model the temperature fields in grinding with a phyllotactic-patterned wheel was studied by Lyu et al. [105]. The model was based on the moving heat source theory developed by Jaeger [60]. It was established and experimentally verified that a phyllotactic-patterned wheel can reduce grinding temperatures more effectively than a grinding wheel with a random arrangement of abrasive grains.

Grinding wheel with megatextures Megatexture generally includes textures with a passive area width larger than 500 µm, e.g., segmented, grooved, and slotted grinding wheels. To study thermal damage to the workpiece, Fang et al. [107] developed an analytical model to predict the temperature profile in surface grinded with a segmented wheel. The magnitude of fluctuations in wheel temperature profile was estimated by using several wheel segments. They measured different temperature profiles, which varied based on wheel-workpiece engagement state using identical grinding parameters. They found that the peak and valley temperatures along the profiles remained consistent under the same grinding parameters, even when varying the wheel-segment engaging states. Xiaorui et al. [108] undertook a semi-analytical approach in establishing a force model for grinding with a segmented wheel by considering the function of instantaneous material removal rate (MRR). Thus, the analytical approach was used to express instantaneous MRR as a function of segment geometry.

2.2 Mass conserving processes

Mass conserving processes refer to making products through consolidation (e.g., casting and molding) and deformation (e.g., forging, extrusion, drawing, rolling, bending, and stamping); the material weight remains essentially the same before and after processing. It is important to regard manufacturing processes not only as obligatory steps to generate a product but also to consider technology as an enabler for more environmentally benign products [109]. This view has also been taken in recent developments of mass conserving processes by including considerations of energy efficiency, cost reduction, productivity, and material efficiency.

2.2.1 Consolidation

In consolidation processes, a liquid material is poured into a mold that contains a cavity of the desired shape and is then allowed to solidify (e.g., casting and molding). Reducing energy consumption and CO_2 emissions have been considered for improving consolidation processes [110, 111]. Green sand molds are still the most popular tooling for discrete part casting processes and are prone to emitting carbon

Table 2 Categorization of textured grinding wheels [94]

	Microtexture	Macrotexture	Megatexture
Passive area width	< 100 µm	100–500 µm	> 500 µm
Texture generation	Laser ablation	Single-point dressing tool, masking, fly cutting, milling, and electroplating	Single-point dressing tool and segmented dressing
Applications	Micro-grinding tool	Surface grinding and external cylindrical grinding	Surface grinding and creep-feed grinding

and other compounds [112]. Casting energy consumption and CO_2 emissions can be reduced by implementing continuous casting-heat treatment processes [113] and vacuum-assisted molding processes [114]. Meanwhile, sustainability performance of casting can be improved through modeling and simulation of the production system [115, 116]. Die casting, a typical casting process, is energy-intensive, material-wasting, and emissions-causing [117]. Recently, computer-aided technologies have been adopted in die casting to improve sustainability for process planning [118] and design optimization [119]. Similarly, in polymer injection molding, energy consumption modeling has been shown to be effective in reducing the energy consumption [120–124] and handling the uncertainty and complexity [125]. When calculating the energy consumption, the idle or baseline energy consumption of the machine tool is non-negligible [122]. With broader, integrated consideration, sensitivity analysis in LCA and life cycle inventory (LCI) activities is necessary to assess the environmental impacts of the injection molding processes in further detail [126, 127]. This aspect allows researchers to identify priority areas systematic metrics, thereby actions to develop more sustainable practices [127]. In addition, approaches such as the Taguchi method, the NSGA-II algorithm [128], and cloud energy management systems [129] have been useful in optimizing injection molding energy consumption.

2.2.2 Deformation

Deformation processes refer to methods that apply pressure to plastically deform a blank and, thus, obtain a desired shape and size of workpiece. These processes include bulk forming (e.g., forging and extrusion) and sheet metal forming (e.g., drawing, rolling, bending, and stamping). Forging can improve the mechanical properties of metal components, but the process requires high loads and energy consumption. Current research has concentrated on forging specifications, management models, and auxiliary tools with little guidance given for energy-saving design of forged products. Prior research has demonstrated improved forging quality and energy savings by optimizing process parameters [130–134]. Importantly, energy-saving forging scheduling and production planning with intelligent algorithms can increase process utilization with high energy efficiency and low carbon emissions [135, 136]. Recent research focusing on the extrusion process has sought to quantify and to optimize energy consumption through process modeling [137] and numerical simulation [138]. Other work has pursued quantifying energy consumption, solid waste generation, and carbon emissions to optimize extrusion process sustainability performance [139].

In addition, a body of work has investigated energy-efficient sheet metal forming. Research investigating energy consumption of deep drawing focused on optimization of process parameters and friction reduction [140–143]. Gao et al. [141] introduced a process partition concept to energy consumption analysis in deep drawing, which could provide the basis for significant energy reduction. Further, for the purpose of cost reduction and productivity and material efficiency improvement, a novel process technology, micro deep drawing has been advocated, due to its excellent characteristics, such as high throughput, high efficiency, high accuracy, high denseness, short cycle time, and low cost [144–146]. From the machine level viewpoint, Lohse et al. [147, 148] conducted energy efficiency analysis of several industrial presses, which led to the development of a system model that is able to analyze energy efficiency in detail for electrical, mechanical, and hydraulic energy losses during the deep drawing process.

In the rolling process, recent research on energy efficiency has focused on process parameter optimization through simulation and experiments [149–153], energy efficient approaches without sacrificing the robustness and performance [154, 155], and production scheduling optimization through different algorithms [156, 157]. Little work has been done to investigate the environmental impacts of the bending process. The main focus has been on process development and numerical simulation to improve formability [158–163]. Similarly, while sheet metal stamping is a high-cost, energy-intensive process, little work has been done to quantify the environmental impacts of the process. Gao et al. [164] proposed a comprehensive model of the stamping process chain for tracing carbon footprint, which would lead to the related energy and carbon emission reduction. Few researchers have taken an energy perspective as an objective in the planning and scheduling of stamping processes [165]. Several have studied the energy required to operate a stamping press [166] and developed energy-saving and energy efficiency-improving methods for the press [167–170]. New insight and a novel approach for integrating energy consumption estimation with LCI has been proposed by Cooper et al. [171], which was demonstrated for several forming processes. They concluded that researchers interested in reducing the environmental impacts of sheet metal forming should concentrate on innovations that would reduce sheet metal blanking and post-forming trimming losses, in addition to reducing die production impacts.

Single point incremental forming (SPIF) is a recent development in forming technology based on the modification of computer numerically controlled (CNC) machine tools. SPFI offers significant opportunities for forming operations, including improvements in machine efficiency, forming tool production, and forming system lubrication [172]. Energy saving approaches have also been studied in SPIF. For example, comparative analysis of CO_2 emissions [173, 174], modeling of energy consumption [175, 176], and an analysis of the parameter impacts [177] for SPIF has been demonstrated under specific frameworks. Such approaches can enable further process improvements that will enable minimization of manufacturing energy consumption.

Besides the contributions in saving energy, the trade-off between sustainability indicators in deformation processes is receiving more attention [178]. Hussain and Al-Ghamdi [179] analyzed energy, cost, and productivity as functions of process parameters for incremental sheet forming. Li et al. [180] proposed an operation scheduling method for a multi-hydraulic press system, which obtained a significant trade-off between process duration and average energy consumption. Gong et al. [181] investigated the trade-off between energy and labor costs in blow molding production through multi-objective optimization. Efforts discussed above are summarized in Fig. 1.

2.3 Joining processes

Since joining processes are essential for manufacturing complex products [182] and often consume significant amounts of energy, it is necessary to investigate opportunities to improve their energy efficiency. Some researchers have previously analyzed joining processes from energy and sustainability perspectives; for example, Borsato [183] developed a semantic information model as a formal ontology, which facilitates computer-aided calculations of an energy efficiency indicator (degree-of-perfection) for joining processes. This section introduces recent energy and sustainability research developments for mechanical and thermal joining processes.

2.3.1 Mechanical joining

In mechanical joining, the joint is created by placing two or more components under elevated pressure and temperature [184]. These processes are divided to four categories: cold welding, explosive welding, friction welding, and ultrasonic welding [11] as investigated in this section.

Cold welding Cold welding, or cold pressure welding, is a solid-state welding process that occurs when two clean contacting metal surfaces are brought together under high pressure at room temperature [12]. Since cold pressure welding has no thermal impact, it offers advantages over fusion welding and warm pressure welding [185]. Fusion welding requires heat energy to melt the base metals, while warm pressure welding uses heat and pressure to deform the base metals [12]. Cold welding has not been specifically investigated from a sustainability perspective, but studies have explored the development of new processes and the improvement of existing processes. While weld quality is diminished when a surface oxide layer exists, cold welding during the divergent extrusion process has demonstrated removal of surface oxides by upset collar formation, which led to higher bond strength [186]. Ebbert et al. [187] developed the electrochemical support (ECUF) process for inline electrochemical removal of surface oxides during cold welding to overcome the challenge of preparing the joining surface. ECUF needs lower applied forces and enables higher tool flexibility.

Explosive welding In explosive welding, metal plates are placed in parallel and joined as a result of deformation processes induced by high pressure in the collision area [188]. Lysak and Kuzmin [188] developed an energy balance method to evaluate the energy losses of

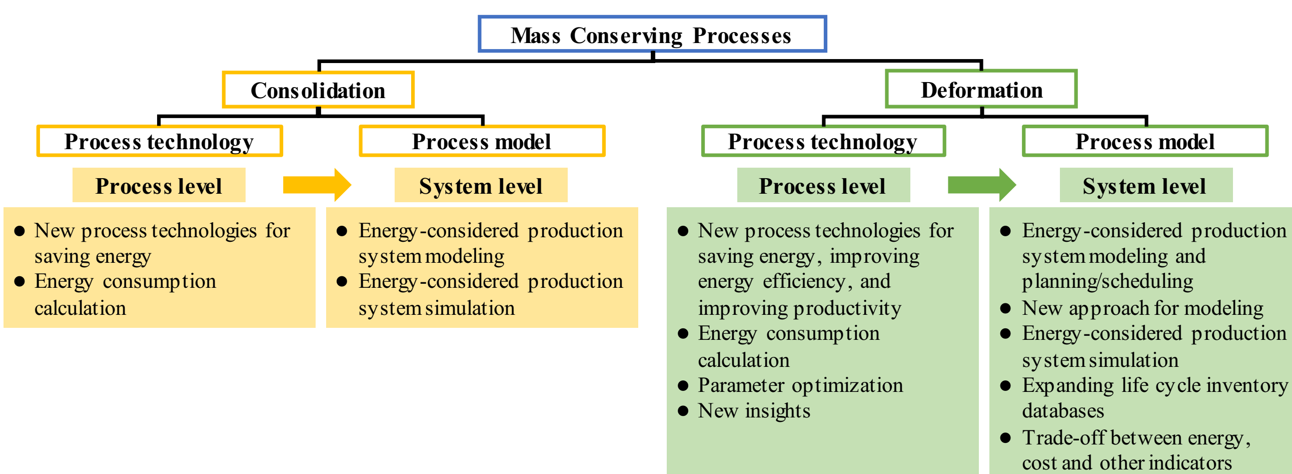

Fig. 1 Recent research on mass conserving processes

colliding plates in explosive welding. They considered deformation of the plates and jet formation to improve the welding efficiency and the strength of the joint and to minimize energy losses. They found that welding parameters such as impact velocity and impact pressure can considerably impact each of the energy balance items.

Friction welding Friction welding is a solid state joining process that creates the joint by combining frictional heat (mechanical rubbing between the two surfaces) and pressure (sufficient force to make a metallurgical bond) [12]. Garretson et al. [189] developed a unit process based analysis method to evaluate the sustainability performance of friction-welded metal aircraft assemblies for a cradle-to-gate life cycle scope. They utilized eight metrics to investigate the environmental, economic, and social impacts (e.g., energy consumption, cost, and acute injuries) of inertial (linear and rotational) friction welding of metal plate, bar, and tube. They found that compared to a bolted assembly, the friction welded assembly requires less total cycle time. This reduces the metrics that are directly proportional to cycle time and, ultimately, results in better sustainability performance. Recently, another friction welding process, friction stir welding (FSW), has gained popularity for joining metal sheet and plate [190]. FSW utilizes a rotating tool, which moves along the joint between the two components to create the frictional heat and make the weld seam. Few studies have investigated FSW from energy and material efficiency perspectives, however. Hamilton et al. [190] applied a heat input model of FSW for developing a characteristic temperature curve to define an energy-based slip factor to anticipate maximum welding temperature. The model considers temperature data, welding conditions based upon the solidus temperature, and the energy per unit length of weld. Vilaça et al. [191] developed an analytical model for 2D and 3D cases to predict the thermal field during FSW. They defined an FSW thermal efficiency coefficient based on the mechanical power of the tool and the point power source producing the thermal field.

Ultrasonic welding To create a joint, oscillatory shear stresses of ultrasonic frequency are generated at the interface of two workpieces, usually less than 3 mm in thickness, placed together under a relatively moderate clamping force [12]. Ultrasonic spot welding has been shown to reduce process time and energy consumption compared to conventional spot welding processes, e.g., resistance spot welding (RSW) [192, 193]. In RSW, two workpieces, usually steel sheet metal, are placed together under pressure. A current is then applied to generate electrical resistance heating, forming the joint [12].

2.3.2 Thermal joining

Another set of processes for making permanent joints is thermal joining. A heating source, filler material, and shielding of the melt pool are three key requirements of these processes [184]. They have been classified under three categories: brazing, soldering, and thermal welding [11]. Each of these categories is comprised of several UMPs and investigated in this section.

Brazing Brazing joins metals by melting a filler metal (also called brazing metal) and distributing it between the surface of the workpieces [12]. Sekulic et al. [194] evaluated the use of brazing in the assembly of compact aluminum heat exchangers. They developed and applied an energy metric that considers the actual and theoretical minimum process energy use and found that actual energy use in controlled atmosphere brazing (CAB) is five orders of magnitude greater than the theoretical minimum. CAB is commonly used in the automotive, aerospace, and process industries. Sekulic [195] had earlier developed an entropy-based evaluation metric and demonstrated its application for the CAB process and found that the metric could be used to elucidate other aspects of resource consumption, energy system optimization, and sustainability optimization.

As opposed to heating the filler material, torch brazing heats the workpiece faying surfaces to a proper temperature, and then, filler in the form of rod or wire is added to the joint [12]. However, drawbacks of torch brazing include non-uniform distribution of temperature, high energy consumption, and a long cycle time [196]. To avoid these drawbacks, Nicoara et al. [196] investigated the joining of aluminum tubes using inductive brazing, a process in which filler metal is preloaded between the workpieces. Electrical resistance is then generated between the workpieces using a high-frequency AC field [12]. They found that inductive brazing has significantly lower energy consumption and carbon footprint compared to torch brazing.

Soldering Similar to brazing, soldering applies a melted filler metal and distributes it between the surfaces of the workpieces being joined [12]. The melting temperature of the filler metal is typically defined below 450 °C (840 °F) for soldering, while it is above 450 °C (840 °F) for brazing [12]. The main environmental challenge of developing new solders is mitigating the toxicity of lead [197]. University and industry researchers are working to improve the sustainability performance of soldering processes. For instance, Lanin [197] investigated ultrasonic soldering to mitigate flux formation of lead-free solders, which improved the environmental performance of electronic component manufacturing.

To avoid oxidization and tarnishing of lead-free solder, Hewlett-Packard created a mixture of tin, silver, and copper for use in electronics packaging [198].

Thermal welding The third and final group of thermal joining processes is thermal welding, which includes several UMPs (e.g., braze welding, diffusion bonding, and electric arc welding) [11]. Haapala et al. [199] evaluated the environmental impacts of bonding and brazing processes for the production of stainless steel arrayed microchannel devices using a cradle-to-gate scope. By investigating nickel nanoparticle-assisted diffusion brazing and conventional diffusion bonding utilizing nickel phosphorus electroplating, they concluded that the health, safety, and environmental impacts of the production and use of metal nanoparticles are uncertain in many applications and must be better understood. Building on this work, Brown et al. [200] conducted a cradle-to-gate LCA to investigate the relative environmental impacts of nickel nanoparticle synthesis techniques, i.e., synthesis in ethylene glycol, in aqueous surfactant solution, and in microemulsions, for use in diffusion bonding of the microfluidic devices. Since the solvent is merely water, they found that synthesis in aqueous surfactant solution has better environmental performance compared to the other synthesis techniques. Brown et al. [201] next conducted a cradle-to-gate LCA to investigate the relative environmental impacts of patterning (photochemical machining and laser cutting) and bonding (i.e., nano-assisted diffusion brazing and diffusion bonding) for making a stainless steel microchannel air preheater. They found no significant difference in the overall impacts of the patterning techniques; however, compared to diffusion bonding, diffusion brazing caused impacts of the two process flows to increase by greater than 20%. This increase was due to the production of nickel nanoparticles (mainly the use of nickel chloride and associated electricity).

Electric arc welding is a thermal welding process encompassing several fusion (liquid-state) processes, which melt the weld material and the workpieces. DuPont and Marder [202] investigated the arc efficiency and melting efficiency of plasma arc welding (PAW), gas tungsten arc welding (GTAW), gas metal arc welding (GMAW), and submerged arc welding (SAW). They were able to semi-empirically predict process thermal efficiency using welding process parameters. Mose and Weinert [182] developed an analysis methodology to assess the energy profile and energy efficiency of process chains, which they applied to FSW and GMAW. They aimed to estimate product embodied energy, to enhance factory energy efficiency, and to optimize process energy consumption. They found that the ventilation system has a significant impact on the energy demand for GMAW. Although FSW needs an additional milling process to achieve higher surface quality, the energy demand compared to GMAW is lower. To determine the thermal efficiency of laser beam welding of materials with a high thermal conductivity, Ganser et al. [203] developed a numerical model based on computational fluid dynamics (CFD) simulation to estimate the molten pool isotherms. They determined the thermal efficiency for various geometries and welding velocities; they defined thermal efficiency as the ratio between the required energy for melting the volume of metal in the fusion zone and the absorbed laser beam energy. The model enables investigating the impacts of welding speed, laser beam power, and beam focus diameter on thermal efficiency during laser beam welding.

Yan et al. [204] developed a multi-objective optimization model of arc welding to minimize energy consumption and maximize thermal efficiency of the process. The welding model considers current, voltage, and velocity as the variables subject to machine, heat input, and quality constraints. DuPont et al. [205] previously conducted a literature review to identify manufacturing challenges, approaches, and achievements in fusion welding for energy applications. They found that computational modeling can play a key role in (1) developing fusion welding technology simultaneously with alloy development, (2) investigating the mechanical properties of welds based on the microstructural modeling, and (3) defining long-term creep properties from short-term tests.

2.4 Heat treatment processes

Sections 2.1–2.3 have presented advancements in manufacturing processes classified as shaping processes. Next, Sects. 2.4–2.5 will present advancements in non-shaping processes, including heat treatment and surface finishing processes. Heat treatment describes a number of processes, including annealing, hardening, and sintering [11]. These processes involve heating and cooling of the material to improve the mechanical properties through microstructural changes [12]. Mendikoa et al. [206] developed a methodology to optimize heat treatment process energy efficiency and maintenance cost based on temperature–time curve for cast steel parts. In the methodology, an expert provides the process design using intervals instead of specific values for each manufacturing process parameter. The process parameter values are then selected from within the intervals to optimize the energy efficiency and maintenance cost.

2.4.1 Annealing

Annealing enables grain recrystallization and stress relief, improving machinability through reduced hardness. Annealing follows three steps: heating the workpiece to a proper temperature, maintaining that temperature for a specified time, and cooling at a slow rate [12]. Garretson [207] modeled the annealing process for sustainability performance evaluation by treating the workpiece as the process information carrier. Given information about the incoming workpiece and the desired annealing process output, he calculated the energy consumed by recrystallization annealing (complete return of the grain structure to its pre-coldworked state) and recovery annealing (partial return of the cold-worked workpiece to its original grain structure).

2.4.2 Hardening

Heat treatment processes include surface hardening and through hardening [11]. In surface hardening, a local area or the entire workpiece surface is heated [12], while in through hardening, the hardness of the entire part or section of a part is increased. Under surface hardening, induction hardening and laser surface hardening processes have been investigated from the sustainability perspective. These processes are thermal treatments; thus, no chemical changes occur during the process. Eastwood and Haapala [208] applied a physics-based mathematical model for induction hardening to estimate energy use in evaluating product economic, environmental, and social performance. They demonstrated the approach for induction hardening the teeth of a steel bevel gear, which enables engineers to make design and production decisions informed by principles of sustainability. Orazi et al. [209] developed a laser process for surface hardening of large cylindrical components mounted in a machine spindle and demonstrated a significant reduction in energy use compared to induction hardening. The new process also did not exhibit softening phenomena typical of induction hardening and had greater flexibility. The authors presented a physical model-based simulation to aid in setting appropriate process parameters (e.g., laser beam speed). In addition, research has investigated energy performance improvement resulting from the integration of heat treatment with other manufacturing processes. Göschel et al. [210] studied press hardening, which combines forming and heat treatment processes. They developed a procedure for energy and material balancing (PEMB) to identify approaches for more energy- and resource-efficient processes and process chains. To calculate the total energy consumption, idle energy (the product of basic cycle time and basic load) and process energy were summed. Process energy was calculated based on force–displacement measurements or a mathematical function of shear strength, sheet thickness, length of the cutting line, and displacement of the punch.

2.4.3 Sintering

Sintering is accomplished as the last step of traditional powder metallurgy, a process to produce components by pressing and sintering metallic powders [12]. After blending and pressing the powders, sintering heats the metal compact to a temperature between 70 and 90% of its melting point to enhance strength and hardness. Spark sintering and hot pressing are two UMPs used to perform compaction and sintering in one step. Hot pressing applies heat during compaction, while the rest of the process is similar to conventional powder metallurgy pressing. Spark sintering overcomes some of the drawbacks of hot pressing, such as proper mold material selection and long process cycle time. Spark sintering involves two steps: first, powder is located in a die and then the workpiece is compressed by upper and lower punches, while a high-energy electrical current sinters the powder. Spark plasma sintering (SPS) utilizes low sintering temperature and provides more conductivity in composite ceramics manufacturing [211]. Moreover, the heating rate in SPS is fast, while the soaking time is short. Musa et al. [212] quantitatively compared the hot pressing and SPS processes considering end-product characteristics, operation conditions (i.e., holding temperature, process time, and applied pressure), and specific energy consumption (kJ/gram) of the product obtained from consolidating Ti-Al_2O_3-TiC powders. They found SPS has a significantly shorter cycle time than hot pressing, resulting in better environmental and economic performance. Sahakian et al. [213] investigated the functional, cost, and environmental impacts of three different processes. The first two involved micro powder injection molding (PIM) of silicon carbide (SiC) and aluminum nitride (AlN), while the third involved an epoxy process. Their goal was to determine the most appropriate material for electronics packaging of power semiconductors. They found epoxy would be the most cost efficient and environmental-friendly option on a per-part basis (due to the elimination of sintering); SiC ranked as the last option.

2.5 Surface finishing processes

Surfaces have a disproportionately large impact on the energy use and environmental burden of products. Shaping operations are inherently energy-intensive and typically require lubricants, which are resource-intensive and can have significant health impacts. The resulting move toward dry or near-dry machining has consequences on surface finishes and tolerances [214]. Following these shaping steps, surface finishing processes, which include cleaning, coating, and/or surface modification, have an outsized impact on the chemical and energy demands of production [215]. Thus, surface finishing has been a major focus of research seeking to identify more benign technologies. This section discusses recent technology and model development for sustainability performance improvement in the areas of surface preparation, coating, and modification.

2.5.1 Surface preparation

After a part is shaped, a broad suite of mechanical, thermal, or chemical techniques can be used to remove burrs and polish a surface. Many of these processes have environmental implications (Sect. 2.1). Mechanical techniques (e.g., abrasive grinding) generate significant amounts of heat and require grinding fluids; for example, burnishing might require lubricants that have human health impacts [216]. In response, a great deal of research has focused on MQL (Sect. 2.1.1). Thermal techniques include controlled heating and cooling cycles that often result in hardening of the surface, and quenching fluids are often used to cool the workpiece. Water-based quenchant has historically been effective. However, one of its most concerning health impacts is the use of biocides as they produce more recalcitrant wastewaters. Recent work suggests careful control of nutrient levels in the fluids may be effective to limit bacterial growth [217].

Cryogenic machining processes are becoming popular as they do not require water; however, there is a major energy penalty generally translated into higher costs [218]. Chemical processes often include degreasing and cleaning steps that prepare a metal part for coating, which can be material-intensive if organic solvents are used [219]. Recent work has explored the formulation of ionic-liquid based solvents (molten salts with extremely high vapor pressures) for surface preparation [220]. Environmental impacts and costs vary greatly and are determined by the molecules organic structure. More research is needed to understand whether ionic liquids will be a preferable alternative to existing organic or aqueous-based solvents. Finally, recent work using extremophile bacteria to etch certain metals (e.g., copper) could be pioneering in developing microbiological methods for surface modification without the use of organic or pH modified solvents [221].

2.5.2 Surface coating

Manufactured surfaces are often coated to achieve corrosion or wear resistance or to achieve a desired tribological or optical behavior. Many of the most common coating technologies (e.g., electrochemical deposition and chemical vapor deposition) result in hazardous waste streams that are expensive to treat. Recent alternatives emerged from efforts in nano-scale science have been centered on creating nano-scale textures on the surface of metals that can achieve a range of functions, extreme hydrophobicity in particular, which are desirable alternatives to conventional coating techniques [222]. These nano-textures are often designed to mimic the morphology of lotus leaves and are being deployed on a growing range of metal surfaces [223]. Chemical processes (e.g., electroplating) are historically among the more environmentally impactful manufacturing operations as the aqueous waste solutions contain high concentrations of dissolved metals, e.g., hexavalent chromium [224]. A great deal of recent research has focused on developing novel methods for treating this waste [225], while other work has focused on using deep eutectic solvents that can more efficiently transfer the dissolved metals to the part surface [226].

2.5.3 Surface modification

Surface modification processes are typically carried out to harden or otherwise enhance the properties of the workpiece surface. Thermal or chemical diffusion processes are effective, though generally slow, processes for hardening metal surfaces [227]. Most of the surface modification literature has focused on steel, but growing interest has focused on light metals, which are being increasingly used in different energy efficiency applications, but which are much harder to treat at the surface using thermal or chemical techniques [228]. Mechanical hardening processes (e.g., shot peening or rolling) are widespread but can result in toxic industrial waste streams [229]. Recent work has focused on developing shot-free peening by using a cavitating water jet to improve the fatigue strength of the workpiece surface [230]. Similarly, nanoparticle-enabled rolling fluids are being explored to improve the efficacy and reduce the impact of rolling operations [231].

2.6 Metal-based additive manufacturing

Several metal-based additive manufacturing (AM) processes and systems have been developed that build up parts by joining successive layers of material using metal powder, wire, or foil. Research on these novel processes has been primarily focused on improving productivity and quality while reducing cost. AM technologies have enabled the production of complex geometries (e.g., hollow structures and cavity-containing components) which use less material. This enhanced capability allows a designer to create more environmentally optimized designs without compromising functional performance [232]. In addition, lightweight structures achieved via AM processes could bring further environmental benefits by reducing use phase energy consumption [233]. However, it has been pointed out that AM processes may have their own environmental challenges [234, 235], e.g., high energy consumption and air emissions during printing and feedstock production. Whether or not AM processes are more environmentally friendly than traditional methods largely depend on production volume and part geometry [236]. Therefore, improving the sustainability performance of AM is critical to expanding its application in various industries, including aerospace, automotive, and healthcare. In this section, prior AM research addressing sustainability performance is introduced. The focus here is on metal-based AM processes, which have gained broad application in industry. Following to the ASTM F2792-12a classification, three technologies are selected i.e., powder bed fusion, direct energy deposition, and binder jetting, which are the most intensively studied to date.

2.6.1 Powder bed fusion

Powder bed fusion (PBF) covers a range of processes, e.g., direct metal laser sintering (DMLS), selective laser melting (SLM), and electron beam melting (EBM), and they can be classified based on energy source [237–239]. The common energy sources used in PBF are lasers, electron beams, ultrasonic vibration, plasma, explosion, and hot ionized gases. In these processes, the energy source selectively consolidates the powder material to form each layer. Liao and Cooper [240] analyzed published studies on cumulative energy demand of parts made via PBF over different stages, i.e., manufacturing of AM machines, powder production, direct energy consumption, product use, and end of life. It was pointed out that life cycle energy consumption is dominated by direct energy usage during production, due to slow processing rate. There are many studies that focused on improving the understanding of PBF's energy consumption. For example, Kellens et al. [241] reported the power profile of the major subsystems for an SLM machine during the preheating, melting, recoating, and cooling phases when making an ANSI 316 stainless steel part. The experimental results showed that melting required the highest average power (3.25 kW), followed by recoating, preheating, and cooling. Baumers et al. [242] investigated whether shape complexity impacts process energy use. They computed a voxel-based shape complexity metric and measured the power consumption of an electron beam process in making a titanium part. They found that while the process energy consumption does not have a strong correlation with the shape complexity, it is mainly impacted by the product cross-sectional area. In addition to manufacturing energy consumption, several research studies incorporated a comprehensive LCA to evaluate the environmental impacts (e.g., energy consumption [233, 243–245], material consumption [244, 246], and CO_2 emissions [233, 243, 245]) of AM. Several of these studies also compared the associated environmental impacts with the impacts of machined components using analytical models [233, 243–245, 247]. The common life cycle stages for additive and machined components are shown in Fig. 2.

Huang et al. [233] are one of the first to compare AM vs. conventional manufacturing process chain while considering use phase energy saving. For metallic aircraft components, the study quantifies the net changes in life cycle primary energy and greenhouse gas (GHG) emissions. The authors developed cradle-to-gate LCI models to estimate energy and GHG reductions when additively manufactured (PBF process) aircraft components (optimized design) are adopted in place of machined parts. In the study, five steps were implemented: (1) identify candidates for the adoption of AM components in the aircraft system, (2) estimate replaceable mass by AM components, (3) quantify the energy and GHG reduction associated with the component replacement using LCI models, (4) develop a temporal adoption model (until the year 2050) under different adoption scenarios (e.g., adoption rate), and (5) report potential energy savings and GHG reductions due to AM component adoption using the fuel use model over the period 2014–2015. They estimated fleet-wide life cycle energy savings and associated cumulative GHG emission reductions as 70–173 million GJ/year and 92–215 million metric tons, respectively, from 2014 to 2050. Raoufi et al. [248–250] investigated the economic and environmental performance of laser powder bed fusion (LPBF) at low and high production volumes for making a 316 l stainless steel microscale product. Moreover, they compared LPBF with another AM process (binder jetting) and a powder metallurgy process (metal injection molding). They found that LPBF would lead to higher unit cost than binder jetting and metal injection molding for the range of annual production volumes explored due to the capital tooling cost as well as the labor cost associated with the powder removal step. Moreover, LCA results indicated LPBF and binder jetting have lower environmental impacts compared

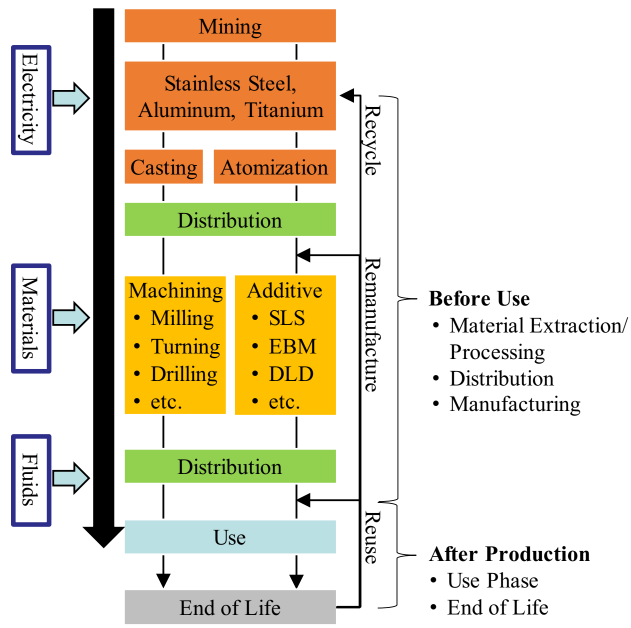

Fig. 2 Life cycle of machined and additive components

to metal injection molding at low production volumes. However, the environmental impacts of the selected additive manufacturing processes do not reduce significantly as production volume increases since the main environmental impact drivers for both additive manufacturing processes are raw material and utilities.

Priarone et al. [243] proposed analytical models to estimate life cycle energy demand and CO_2 emissions when manufacturing a Ti-6Al-4 V- or stainless steel-based metal component via PBF or conventional machining. They found that additive manufacturing led to greater energy savings and CO_2 emissions reductions than production using conventional machining processes. Further, they noted that greatest environmental benefits were achieved by lightweighting, enabled by design optimization. Obeidi et al. [251] studied the optimization of the powder bed fusion (PBF) process by reducing build time through adjustments to the build layer thickness of deposited metal powder and the input volumetric energy density. They adjusted the layer thickness from 30 microns to 60 and 90 microns, which resulted in build time savings of around 50% and 66.4%, respectively; this adjustment reduced energy consumption from 36.5 to 18.4 kW and 12.25 kW, while only observing minor reductions in AM part quality. This optimization leads to a direct reduction in the total cost of production by decreasing factors such as electric energy usage, inert gas consumption, and labor, all while maintaining the chemical and mechanical properties of the parts.

Another method to improve sustainability performance in AM processes is to reuse and recycle powder material as powder production is the 2nd largest contributor to cumulative energy demand [240]. The powders are commonly produced via atomization (e.g., water, gas, plasma, and centrifugal atomization), which is an energy-intensive process. From cost and material/energy efficiency standpoints, it is desired to reuse/recycle the unused powder from the process. Several extensive studies have been done on the powder reuse/recycling for EBM. Tang et al. [252] studied the influence of powder reuse on the characteristics of Ti-6Al-4 V powder and found that the tensile strength of the built parts is not affected for up to 20 reuse cycles. The oxygen and nitrogen content of the powder increases slightly after each cycle, which puts a limit on the maximum number of reuses. These results are in agreement with other studies [253–256]. When a more stable alloy is used (e.g., Inconel 718), no negative effects are observed, and the powders can be used many more times. The physical properties (e.g., flowability) then limit the number of reuse cycles. Meier et al. [257] also studied the feasibility of reusing Ti-6Al-4 V powder in PBF. They found that Ti6Al4V powder can be reused up to 18 times without compromising tensile strength but observed the impact strength decreased by 30% for vertical and 12% for horizontal stress-relieved specimens. The study also found that changes in particle size distribution (PDS) and powder morphology do not negatively impact the processability of PBF and argued that it is essential to adequately mix and compact the feed powder to ensure consistent quality. Recently, Warner et al. [258] reviewed strategies to enable powder reuse in PBF. Three most commonly adopted reuse methods are single batch (no new powder addition until the current batch runs out while sieving is done to remove agglomerates), collective aging (multiple batches are used but powder of the same age are mixed for reuse), top up method (place sieved powders on top of the bed), and refreshing method (mix sieved powders after one or several prints with virgin ones for next batch). One of the key areas of interest is powder characterization. A wide range of properties are measured, e.g., particle size, shape, fluidity, composition, and microstructure, but more comprehensive method is needed. Eventually successful power reuse relies on the quality of the parts built. Similar to particle characterization, many mechanical properties are measured but there is no universal approach or standard that has been reached.

For powder-based AM processes, concerns also have been raised about occupational exposure to nanoparticles (between 1 and 100 nm), especially when alloys containing chromium, nickel, and cobalt are used. Graff et al. [259] evaluated three common technologies used to measure the concentration, size, and composition of particles emitted from the selected laser melting of IN939 powder. They suggested that better measurement techniques for nanoparticles are needed, and clinical trials are needed to determine the health effects. Karlsson et al. [260] evaluate potential health hazards of particles released from PBF of two nickel-based alloys. Limited particle releases were found, and minimal effects on the cultured lung cells were observed up to 100 µg/ml level. At PBF facility, background particle concentration is low, but peaks of nanoparticles were observed when sieving and post-print grinding occur. It was pointed out that further studies are needed to understand the toxicity of nanoparticles. Occupational health studies at Swedish companies suggest that based blood and urine samples impacted kidney function and respiratory system inflammation are possible, but long-term studies are needed [261].

2.6.2 Binder jetting

Binder jetting (BJ) printing offers higher production efficiency and lower costs compared to the powder metallurgy method while also being capable of fabricating complex metal parts [262]. During the BJ process, two materials are used: a liquid bonding agent and a metal powder. The bonding agent (binder) is selectively deposited on the power bed to bind the metal powder in a specific area to form a layer. A comparative LCA study indicates that production of metal powder is the largest contributor to the cumulative energy demand, followed by direct energy consumption during printing [263]. As mentioned in the LPBF section, Raoufi et al. [248–250] characterized the economic and environmental performance of metal additive manufacturing (LPBF and BJ) and powder metallurgy (metal injection molding) processes for producing components of a 316 l stainless steel microscale product. They found that the main cost drivers in BJ are the capital tooling cost as well as the labor cost associated with the depowdering steps. From the environmental aspect, their LCA results indicated that the main environmental impact drivers for both additive manufacturing processes were raw material and utilities—process inputs more directly tied to the number of parts produced. Zhou et al. [264] proposed a framework connecting design, process optimization and planning, energy and material consumption, and production to describe making a part using BJ. The feedback from the modeling framework facilitates part design and process planning. From the experimental and simulation results, the authors concluded there are opportunities to enhance BJ sustainability performance through design optimization and proper process parameter selection. Also, the limitations of BJ include the need for post-processing due to curing and densification, lower resolution, high surface roughness, and the potential for part distortion, which can result in defective products [265].

Avoiding the production of defective parts is important for industrial sustainability as this reduces powder consumption. To investigate the factors affecting a part quality in BJ, for example, Miyanaji et al. [266] provided a perspective of the process principles and characteristics by investigating the process design considerations. They found that process parameters (e.g., binder saturation, feedstock flowability, powder spreading, and drying) could significantly impact the geometric accuracy and integrity of the green parts. Chen and Zhao [267] focused on four key process parameters (i.e., layer thickens, saturation, power ratio, and drying time) and two quality properties (i.e., surface quality and dimensional accuracy) to find the optimal process parameters. Experimental results showed that layer thickness and drying time were the most significant factors affecting surface roughness and shrinkage rate, respectively. Using the optimal settings, the surface roughness was reduced by 39.88% and shrinkage decreased by 85.85% on average from the initial process parameters. Tang et al. [244] proposed a new framework to minimize the impacts of energy and material consumption of BJ through part design optimization. To take advantage of the design freedom offered by AM, the authors suggest the product functional description (i.e., functional surfaces and functional volumes) should be used as an input to evaluate the environmental impacts of BJ. The results of applying the proposed method to evaluate an aircraft engine bracket show that BJ consumed significantly less energy when fabricating the topologically optimized product than the original design. BJ, however, usually requires post-processing for better surface quality. Further study incorporating the environmental impacts of different post-processes should be conducted. Reuse of powder BJ is another way of reducing environmental impacts. Bidare et al. [268] investigated the reusability of two stainless steel powders. It was found that high humidity in the printing chamber leads to packing density decrease due to even slightly increased moisture content of the powder. Degradation also occurs due to loss of fine particles and binder residue. It is also possible to recycle green part wastes, but more research is needed.

2.6.3 Directed energy deposition

Common directed energy deposition (DED) technologies are laser metal deposition, laser engineering net shaping, and direct metal deposition (DMD). In DED processes, metal powder or wire is fed through a nozzle; the material is then melted onto the specific surface of the part using a concentrated energy source such as a laser or electron beam [269]. Typically, a DED machine is equipped with a multi-axis arm, so the feeding nozzle can move in multiple directions to deposit the material from any angle. Due to this functionality, DED can repair an existing part by depositing additional material, in addition to printing new parts [270]. Several efforts have been found to model the resource consumption in laser metal deposition processes to evaluate environmental impacts [271, 272]. Le Bourhis et al. [271] proposed a global method to estimate the life cycle environmental impacts of a part manufactured using the laser melt deposition process. They developed predictive models for material, fluid, and electricity consumption defined from a CAD model and manufacturing path. This approach intended to integrate the environmental models (for material, fluid, and electricity use) into the design loop for design optimization. For the method to quantify environmental impacts, a damage-oriented method, Eco-Indicator 99 [273], was used. The authors showed that the manufacturing path is a key factor affecting environmental impact when printing a part. Further study for optimizing tool paths is needed to improve resource efficiency in the process.

Kerbrat et al. [274] proposed a methodology to evaluate the environmental impacts of parts produced using different feeding nozzle sizes in the laser melting deposition process. In the study, the consumption of three resources (i.e., powder, gas, and electricity) was considered to quantify environmental impacts using Eco-Indicator 99; two different nozzle sizes (4 mm and 0.8 mm) were tested. To quantify the environmental impact, both analytic and empirical models were developed as functions of process parameters, machine knowledge (e.g., nozzle efficiency and the ratio of lost/fused powder), and several other factors. The proposed methodology was used to evaluate the environmental impact of a given part. Experimental results showed that higher environmental impact was observed when the smaller nozzle size was used, mainly due to the extended manufacturing time. The manufacturing time was significantly decreased when the larger nozzle was used (74 min and 1315 min, respectively, when 4 mm and 0.8 mm nozzles were used). As noted by the authors, however, the environmental impact due to the nozzle size can be dependent on part design. Also, when the larger nozzle was used, powder consumption (193 mPts) was the most predominant factor contributing to environmental impact rather than electricity (131 mPts) and gas (6 mPts) consumption. Efforts for improving the energy and material efficiency of the metal-based AM processes have largely been limited to understanding how energy is consumed and how process conditions affect material reusability. For DED processes, it has been suggested that powder utilization efficiency could be improved by changing nozzle design [275, 276]. Further research is needed to use the gained knowledge from past studies to improve the sustainability performance of AM processes and machines.

The powders are commonly produced via water or gas atomization which is an energy-intensive process. From both a cost and material/energy efficiency standpoint, it is desired to reuse/recycle the unused powder from the process. This is particularly true for the laser direct deposition process, where more than 60% of powders are wasted and disposed [275]. It is known that the unused powders degrade due to exposure to elevated temperatures, thus using recycled powders may cause part quality issues. Slotwinski et al. [277] analyzed how recycling could affect the characteristics of stainless steel (17-4SS) and cobalt chrome (CoCr) powders used in the direct metal laser sintering process. They found that the powder size distribution increases after recycling. Besides these efforts on escalating energy and material efficiency, productivity, and reducing manufacturing cost, it is important to take all resource streams into account, not only energy and GHG emissions. Researchers have to understand the complete life cycle of the products and emphasize resource efficiency in addition to energy efficiency. For instance, embodied energy has to be included into manufacturing planning and monitoring and into supply chain considerations [110]. Therefore, future research needs to aim at reducing impacts of resource uses in addition to minimizing energy use. In the meantime, the research direction should be gradually shifted to the production system level such as process planning/scheduling and production system development based on high-fidelity simulation and experiments with expanding LCI database. Details are presented in Fig. 3.

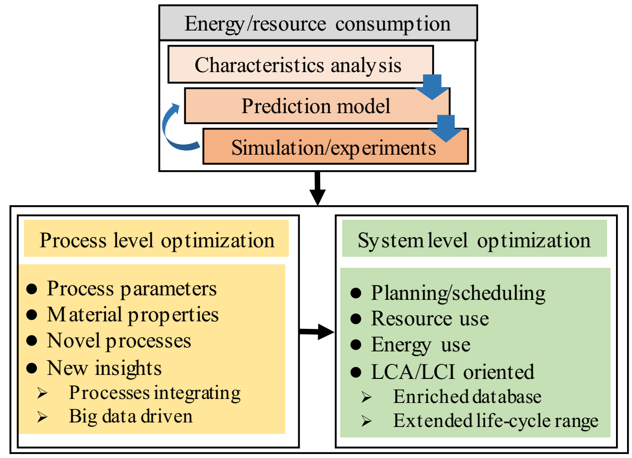

Fig. 3 Further study on mass conserving processes

3 Challenges, future trends, and recommendations

Production systems incorporate numerous UMPs to convert raw materials into a final product utilizing energy, labor, equipment and tools, and supporting systems. This review has focused on several shaping processes (mass reducing, mass conserving, and joining) and non-shaping processes (heat treatment and surface finishing). In addition, metal-based additive manufacturing processes were reviewed to elucidate recent advances impacting their performance in terms of cost, resource use, and worker health and safety. Each of these is summarized below, and opportunities for future research are highlighted.

3.1 Mass reducing processes

Mass reducing processes generate a desired part geometry by removing material from a workpiece, which can be accomplished through mechanical, thermal, and/or chemical reducing. Mechanical reducing is the most common and is the focus of this review. Future research opportunities for single point, multi-point, and abrasive machining processes are summarized as follows.

3.1.1 Single-point material removal

Single-point material removal represents a critical set of manufacturing processes utilized by a wide range of manufacturers. The single-point material removal has a rich history of research, and the literature review provided in this paper indicates that it will continue to address significant future research challenges. Three key advanced manufacturing trends were identified in sustainable research. First, multi-objective single-point material removal optimization models should continue to be enhanced to better understand the trade-offs between each pillar of sustainability across the machine tool and machined component life cycles. Enhancements need to target, specifically, the trade-offs of decisions in the manufacturing phase (e.g., high feed rate) with the impact on performance of machine tools and machined parts during their use phase. Second, while not unique to single-point material removal, social sustainability metrics should become more standardized across cases. Social sustainability metrics have been incorporated in recent single-point material removal studies, but further studies are needed. Third, detailed sustainable manufacturing studies should continue to be undertaken as new materials are developed and advancements are made to single-point material removal, e.g., laser-assisted machining and ultrasonic-assisted turning (UAT).

3.1.2 Multi-point material removal and cutting fluid use

Similar to single-point material removal, cutting fluids play an important role in multi-point removal machining—another broad set of operations widely used by all manufacturers. Reducing cutting fluid use while also improving the performance of environmentally-friendly alternatives are two major future research directions. With respect to reducing the use of cutting fluids, opportunities exist in dry machining, MQL, and design of new tools, optimizing machining parameters. Opportunities may exist in designing environmentally-friendly cutting fluids, such as gas-based coolants and bio-based coolants. Because of its better lubrication properties and environmental benefits, the demand for bio-based cutting fluids is expected to increase. Two major challenges should be solved to make bio-based cutting fluids even more applicable: First, the costs of bio-based cutting fluids are relatively high, and the scale of the production is low (since bio-based cutting fluids are mainly made from vegetable oils, efforts should be made to balance the needs for vegetable oils between manufacturing and food supply [278]); second, physical and chemical properties of vegetable oil tend to be less preferable than petroleum-based oils or mineral oil. Additives can improve the performance of bio-based cutting fluids but can introduce additional sustainability-related impacts.

3.1.3 Abrasive machining

Abrasive machining represents a broad set of technologies applied across industry—grinding is the most commonly used abrasive process. Due to the random cutting edges on the grinding wheel surface, the mathematical modeling of the grinding process is more complex than other cutting processes, such as milling and turning. Although some research has studied simplified models considering a single grit, building comprehensive models that reliably predict the behavior of grinding processes is still a challenge. A number of research studies have explored relevant sustainability impacts. On the system level, the effect of the life cycle of the grinding wheel and the associated tool design has been studied [92, 100]. On the component level, adding textures to the wheel surface helps reduce the specific grinding energy.

Textured grinding wheels are categorized into microtexture, macrotexture, and megatextures. Controlling crystallographic orientation through laser ablation has been applied for grinding wheel microtexturing [94]. However, other orientations and diamond crystallite specifications (i.e., sizes, shapes, and spacing) need further research for specific scenarios (materials, tool type, and size). With regard to the grinding wheels with macrotextures, a rigorous mathematical model able to calculate and prove an optimized pattern for a particular grinding operation is lacking.

3.2 Mass conserving processes

With advancements in materials science, novel materials with high strength, toughness, ductility, corrosion resistance, and low density, including high-strength steels, titanium alloys, and magnesium alloys, have seen wide use in manufacturing [279]. Mass conserving processes are facing the challenge of how to achieve the consolidation or deformation of these novel materials under normal conditions with high quality. High-pressure die casting [280] can be reliably applied with high efficiency. Multi-physical field-assisted processes, such as microwave-assisted injection molding [281], electromagnetics assisted drawing [282, 283], hot stamping [284], and rolling with inter-pass cooling [285], can effectively achieve higher speed and quality requirements. New processing techniques, with considerations of higher efficiency and reliability under complex application scenarios, have been emerging for traditional materials. For instance, advanced cold forming technology can alleviate difficulties of precision manufacturing for complex hollow components. Flexible bending [286] is capable of controlling the trajectory of the forming tool that directly interacts with the tube blank using numerical control. The tube blank experiences continuous bending deformation, overcoming some difficulties of forming three-dimensional complex metal bends. Incremental forming [287] has demonstrated the plastic forming of complex bend tubes with three-dimensional spatial axes and variable cross-sections. Its implementation combines a local spinning process with a multi-roll free bending forming process. Furthermore, reduction of tube wall thickness can be better controlled if incremental forming technology is integrated with the hydraulic bulging process. Improving the sustainability of mass conserving processes (especially consolidation) is worthy of further investigation. In particular, cleaner and more energy-efficient processes need to be developed.

3.3 Joining processes

Mechanical, thermal, and chemical joining processes typically have high energy consumption, which necessitates enhancement of their sustainability performance from an environmental perspective. Mechanical joining processes include cold welding, explosive welding, friction welding, and ultrasonic welding. While researchers have mainly focused on developing new cold welding processes or improving the existing cold welding processes for surface oxide removal, sustainability performance has not received much attention. Further research in explosive welding is needed to investigate the impacts of the collision parameters and conditions on the energy balance items to improve energy efficiency. Few studies have investigated the sustainability performance of friction welding and friction stir welding processes. It has been suggested that weighting schemes could be applied for a better comparison of the economic, environmental, and social metrics in friction welding. Moreover, a scaling factor(s) could be developed to consider the division of heat generation between plastic deformation and friction. Recently, researchers have focused on developing solid-state welding processes such as ultrasonic spot welding for improving environmental performance relative to conventional spot welding processes.

Thermal joining processes include brazing, soldering, and thermal welding. The main difference between brazing and soldering is the melting temperature of the filler material. Researchers have mainly focused on sustainability assessment of aluminum applications (e.g., heat exchangers) in brazing, while other materials and applications remain open to investigation. In soldering, mitigating the toxicity of lead is the main environmental challenge; lead-free solders have attracted attention from university and industry researchers. However, while lead-free solders improve the sustainability performance, they have drawbacks, such as flux formation. Thermal welding processes have experienced more scrutiny under sustainability assessments than brazing and soldering. Metal nanoparticles have been proposed to reduce energy use of diffusion brazing and diffusion bonding. However, it was found that production and use of metal nanoparticles need further investigation since they could increase systemic material and energy demands, as well as health and safety concerns.

3.4 Heat treatment processes

Heat treatment describes a set of non-shaping manufacturing processes including annealing, hardening, and sintering. Using a UMP-based mathematical model of the annealing process, it was found that influencing the material properties by changing the annealing profile (e.g., cooling rate) would impact the cycle time of follow-on machining processes for making the intended product. Collaboration with suppliers to provide the proper, or known, material properties could offer an opportunity to improve performance while reducing overall energy consumption and the associated environmental impacts. Also, providing a more-detailed mathematical model would assist applying optimization techniques to determine the optimal process parameters. Other reported work described a UMP-based mathematical model for induction hardening. The model utilizes design inputs and process parameters to quantify sustainability metrics. Verifying the model using experimental data (e.g., liquid flows, cycle time, and utilities) remains undone. With regard to the sintering process, three potential research directions were identified. First, to analyze the sensitivity of the sustainability metrics, process input uncertainty needs to be investigated. Second, the impact of heat treating on use and end-of-life phase sustainability metrics should be considered. Third, to provide more precise comparison studies for device applications, the impact of material properties on the product performance needs to be investigated.

3.5 Surface finishing processes

Shaping processes are typically energy and resource intensive. To improve their sustainability performance, dry or near-dry operations have been investigated, which impacts the surface finishes. Surface finishing processes, similar to shaping processes, have high energy and chemical consumption. Research on surface finishing processes is classified into surface preparation, surface coating, and surface modification. Since chemical processes in surface preparation are material intensive, using ionic-liquid–based solvents instead of existing organic or aqueous-based solvents needs more research. To avoid hazardous waste streams from typical surface coating processes, nanoscale texture coating has been introduced. Its application has been explored for magnesium alloys, which provides an opportunity to investigate other metals. Moreover, to improve the sustainability performance of chemical coating processes from environmental perspective, treating the waste needs further investigation. While surface finishing processes of steel have received much attention from researchers, light metals need further investigation. Also, considering the successful feasibility assessment of nanoparticle-based cooling-lubricating fluids, its commercial development is a motivation for further research.

3.6 Metal-based additive manufacturing

Metal-based additive manufacturing makes it possible to produce parts with complex geometry that cannot be made via traditional processes. Although metal-based additive manufacturing processes themselves tend to be energy intensive and the production of feedstock materials is also energy intensive, these processes can greatly reduce material consumption and achieve significant energy savings during use phase through more optimized part designs. Many studies have examined the environmental performance of a variety of metal-based additive manufacturing processes using LCA methodology. It has been pointed out that process parameters can be optimized and process monitoring techniques can be utilized to reduce energy consumption while increasing part quality. Future efforts are needed, however, to advance understandings on hybrid processes and at the production system level, including process planning, manufacturing scheduling, and supply chain management.

At the process-level, more investigation should be done to model and understand the performance of multi-material geometries, by especially focusing on multi-scale process modeling from the material (microstructural) level, both during manufacturing and product use. As these processes continue to evolve, including the use of new alloys and alloying methods (e.g., alloy jetting), the effects on worker safety and health must be better understood and mitigated.

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Declarations

Competing interests The authors declare no competing interests.

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