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REVIEW ARTICLE

Equipment–process–strategy integration for sustainable machining: a review

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ABSTRACT Although the manufacturing industry has improved the quality of processing, optimization and upgrading must be performed to meet the requirements of global sustainable development. Sustainable production is considered to be a favorable strategy for achieving machining upgrades characterized by high quality, high efficiency, energy savings, and emission reduction. Sustainable production has aroused widespread interest, but only a few scholars have studied the sustainability of machining from multiple dimensions. The sustainability of machining must be investigated multidimensionally and accurately. Thus, this study explores the sustainability of machining from the aspects of equipment, process, and strategy. In particular, the equipment, process, and strategy of sustainable machining are systematically analyzed and integrated into a research framework. Then, this study analyzes sustainable machining-oriented machining equipment from the aspects of machine tools, cutting tools, and materials such as cutting fluid. Machining processes are explored as important links of sustainable machining from the aspects of dry cutting, microlubrication, microcutting, low-temperature cutting, and multidirectional cutting. The strategies for sustainable machining are also analyzed from the aspects of energy-saving control, machining simulation, and process optimization of machine tools. Finally, opportunities and challenges, including policies and regulations toward sustainable machining, are discussed. This study is expected to offer prospects for sustainable machining development and strategies for implementing sustainable machining.

KEYWORDS sustainable machining, equipment, process, strategy, manufacturing

1 Introduction

Environmental problems are increasingly threatening the survival and development of human society. Addressing global climate change and environmental pollution has become a broad consensus of the international community [1]. The manufacturing industry is a pillar industry that creates abundant human wealth and promotes societal and economic development. However, manufacturing is beset by many problems, including low environmental protection awareness, heavy waste in production processes, low rates of product recycling, and high energy consumption [2]. The global share of China's manufacturing industry (CMI) exceeded 28% in 2019, but the manufacturing industry has contributed to nearly 30% of carbon emissions [3]. In 2010, the total energy consumption values of manufacturing industries in Japan, the UK, Germany, and France were 713.00, 289.30, 467.69, and 373.09 million tons of coal equivalent (Mtce), respectively (Fig. 1(a)); by contrast, the total energy consumption of CMI was 1884.98 Mtce, exceeding the sum of the four countries [4]. Figure 1(b) shows the distribution of various sectors in total energy consumption in the USA, in which industry accounts for 31% of all energy consumption, and manufacturing

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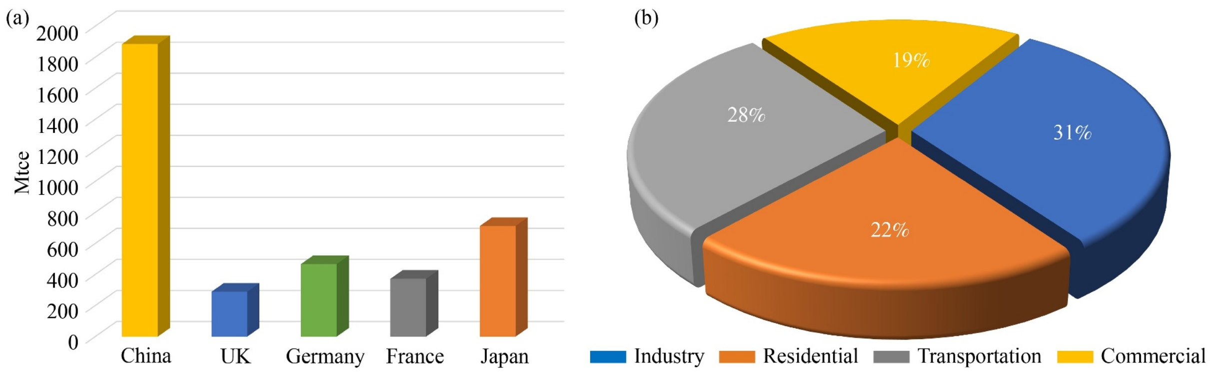

Fig. 1 (a) Comparison of energy consumption between China's manufacturing industry (CMI) and developed countries and (b) distribution of various sectors in total energy consumption in the USA.

accounts for approximately 60% of total industrial energy consumption [5]. Advanced manufacturing can widely reduce greenhouse gas emissions and pollution, further suggesting the need to transform and upgrade the manufacturing industry [6]. With resource shortages, environmental pressures, and the emphasis of the government on sustainable development, the sustainable upgrading of the manufacturing industry is imminent [7]. Both the Industry 4.0 plan of Germany and the "Made in China 2025" plan of China are aimed at ensuring a more energy-efficient and environmentally friendly manufacturing industry [8]. Sustainable machining is considered to be one of the most effective approaches for achieving energy conservation and environmental protection in manufacturing. The potential for energy savings and emission reduction in the traditional manufacturing industry is huge [9–11]. Therefore, on the basis of the characteristics of manufacturing systems, this study investigates sustainable machining from the aspects of machine tools, machining processes, and control strategies. Then, suggestions on the sustainable transformation and upgrading of the manufacturing industry are proposed.

As the research on sustainable manufacturing is still scattered, this study summarizes the literature on the sustainability of manufacturing systems from different levels. The direction, specific processes, policies, and regulations of the sustainable upgrading of the manufacturing industry are discussed in detail, aiming to provide suggestions for enterprises and governments on how to implement the sustainable upgrading of the manufacturing industry while providing a reference for subsequent research. The literature presented herein was carefully selected on the basis of content evaluation analysis. The literature was searched using standard journal databases and search engines such as Science Direct, Google Scholar, and Web of Science. Then, on the basis of the search terms selected from the concept analysis, those related to sustainable machining were added. "Topic, title, keywords" was used for searching. The search terms included "life cycle assessment" OR "solid lubricants" OR "gas-cooling machining" OR "nanoparticles" OR "biological lubricants" OR "energy-saving machine tool" OR "cutting tools" OR "cutting fluid" OR "dry cutting" OR "minimal quantity lubrication" OR "cryogenic cutting" OR "sustainable machining" OR "processing simulation" OR "process optimization" OR "policies and regulations of sustainable machining".

• Sustainability of machining equipment

As the carrier of the manufacturing industry, manufacturing equipment is a vital approach for realizing a circular economy, energy savings, emission reduction, and sustainable development. Sustainable machine tools not only save energy but also cause minimal to no pollution to the environment. For machine hardware, such as spindles and motors, performance improvement is beneficial to energy savings. In addition, although traditional cutting tools are not designed for energy savings at the beginning, by changing the base material of cutting tools or adding coatings on their surface, the energy efficiency and processing effect of these cutting tools can be optimized without significantly increasing the cost. Although the use of cutting fluid improves the machining conditions, it also pollutes the environment. Therefore, improving the tool coating and cutting fluid materials should aim to achieve sustainable machining. Sustainable materials are expected to effectively solve the abovementioned problems because they have the characteristics of low energy consumption and low pollution [12,13]. Moreover, the aforementioned plans would not significantly increase the cost of sustainable upgrading of the current manufacturing industry, which is quite attractive for today's manufacturing enterprises.

• Sustainability of machining processes

A process corresponds to a specific method for machining specific parts. Various processes adapted to different processing scenarios offer different energy consumption performances. Processes characterized by energy savings and emission reduction are called sustainable processes; by contrast, traditional processes usually do not have these advantages. From another perspective, the sustainable upgrading of the manufacturing industry cannot be immediately realized. For its current upgrading, the sustainable potential of traditional technology as a desirable solution must be explored and optimized. Many efforts have been considered for sustainable machining processes, such as improvements in cutting methods, lubrication methods, and optimization, to achieve energy savings. For instance, compared with the traditional process, microcutting has excellent performance in energy consumption and machining quality. Regardless of whether cutting fluid is needed, dry cutting, microlubrication, and cryogenic cutting provide excellent technological solutions for avoiding negative impacts on the environment. The innovation in this field has also attained some achievements in multidirectional cutting.

• Strategies of sustainable machining

In addition to the equipment and process levels, other strategies can be executed to achieve sustainable manufacturing systems. Take the control of machine tools as an example in which traditional machine tools ignore the energy-saving potential of this part. The energy consumption of machine tools can be reduced by optimizing their start and stop components. Furthermore, other potential schemes can be explored in the energy-saving control of machine tools. Energy-saving and emission reduction strategies at the process level mainly include process simulation and optimization, which have been proven to be complementary. Process simulation is similar to the digital twin mode in the machining field, as it simulates processes in advance and improves energy efficiency. Process optimization is evaluated using different parameters with the aim of achieving the best processing quality and energy efficiency.

2 Equipment–process–strategy integration framework for sustainable machining

Sustainable machining embodies the sustainable development strategy for human society in modern manufacturing and promotes sustainable manufacturing and sustainable economies [14]. At present, research on the sustainable upgrading of the manufacturing industry is relatively scattered, and only a few scholars have proposed relevant suggestions at the system level. As the manufacturing industry is a complex system, it should be comprehensively investigated in terms of sustainable upgrading, indicating the necessity of establishing a framework that can demonstrate the sustainability of processing machining. The European Ecodesign Directive singled out machine tools as a key component of sustainability transition, and one of the main reasons for this initiative is the high energy consumption [15]. At present, sustainable transformation is not hindered by the lack of intelligent technology but by the slow introduction of sustainable machine tools. Therefore, the sustainable upgrading of machining equipment is the first issue that needs to be solved. Machining equipment is the carrier of the manufacturing industry, and various processes are developed on this basis to adapt to different processing scenarios. Although traditional processes neglect energy conservation, they have the potential for sustainable upgrading. Therefore, the second research aspect should be to identify sustainable processes. For a specific process, different processing parameters entail varying energy consumption performances, but demonstrating specific sustainable processes is a complex endeavor [16]. A sustainable control strategy based on machine tools and process parameters is also imperative. Figure 2 shows the framework adopted in this review to demonstrate the equipment used for sustainable machining. The main considerations are sustainable machine tools, sustainable cutting tools, and sustainable cutting fluid. The machining process, which includes dry cutting, minimal quantity lubrication, microcutting, cryogenic cutting, and multidirectional cutting, is also one of the most important measures to achieve sustainable machining. In contrast to the strategies for machining system hardware, strategies for achieving sustainable machining include three levels: control of machine tool, process, and parameter optimization. The development trend of sustainable machining and incentive policies are explored in this review.

3 Sustainability of machining equipment

Equipment is the component of the sustainable machining system that guarantees product quality while achieving high-quality, high-efficiency, low-consumption, and clean production [17–20]. Machine tools are the main equipment of the machining process and have the potential to achieve sustainable upgrading of machining.

3.1 Sustainability of machine tools

Machine tools are not only the main equipment of machining but also one of the main links of energy consumption in the manufacturing industry. Traditional machine tools only pay attention to the processing effect but ignore the energy consumption during processing and the negative impact on the environment, and traditional machine tools have the problem of low energy efficiency.

Strategies for sustainable machine tools are shown in Fig. 3 [21–23]. Research on sustainable machine tools focuses on three aspects: lightweight components, energy-saving optimization of motors, and energy-saving optimization of hydraulic components [24]. Some achievements have been attained on the single-level sustainable upgrading of machine tools, but research on

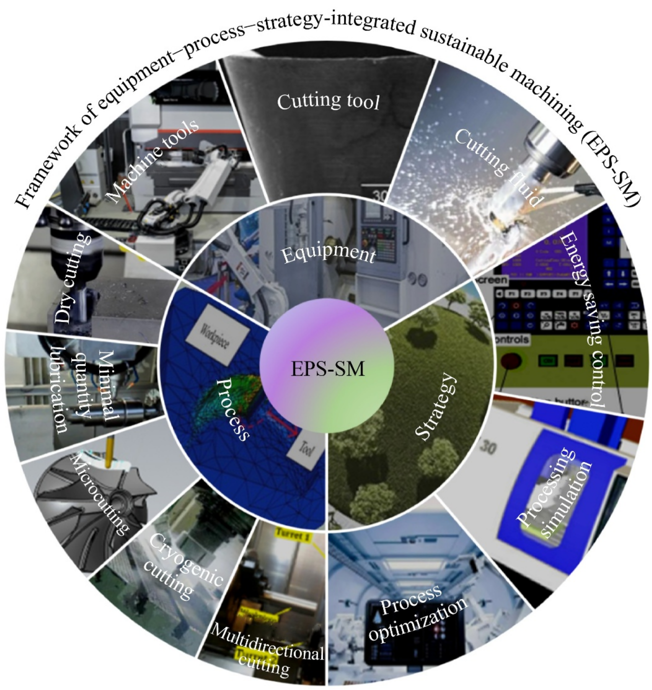

Fig. 2 Equipment–process–strategy integration framework for sustainable machining.

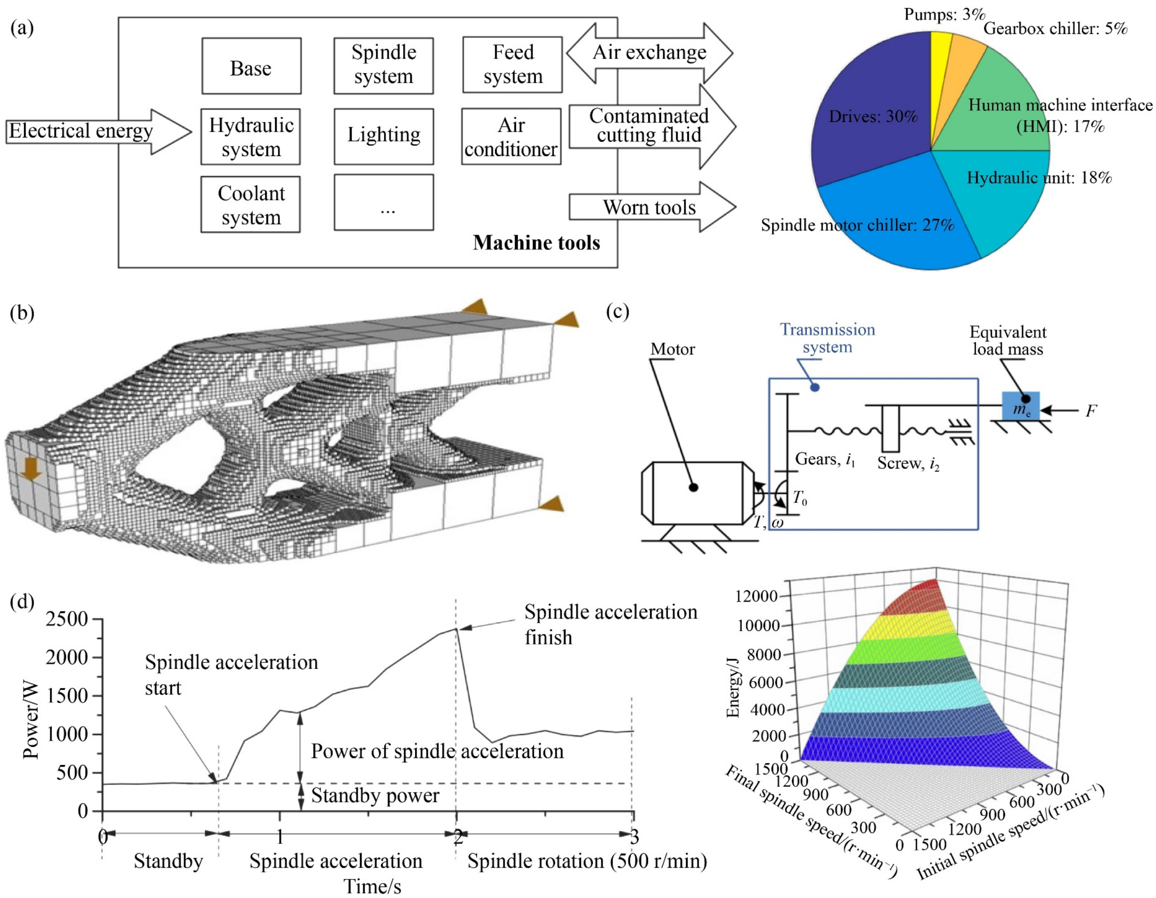

Fig. 3 Strategies for sustainable machine tools: (a) direct power consumption of machine tool systems [21], (b) lightweight machine tool components [22], (c) motor energy-saving optimization [21], and (d) spindle energy consumption optimization [23]. Reproduced with permissions from Refs. [21–23] from Elsevier.

the co-optimization of the hardware and software of machine tools needs to be further deepened. The motors, servo drives, hydraulic, and pneumatic systems equipped with machine tools are the main components consuming energy [25]. The spindle is one of the most energy-consuming components of machine tools. The improvement and optimization design of the spindle structure can not only achieve more accurate machining but also save much energy [26]. In addition to reducing energy consumption by controlling the start and stop components of spindles at the system level, learning algorithms (i.e., BP neural networks, improved cell multi-objective genetic algorithms, and genetic algorithms) can be used to optimize the energy consumption of machine tool spindles [27,28]. More energy is needed if the spindle is started to attain a much higher speed. The transmission system of machine tools also consumes a considerable amount of energy. A lightweight design method can reduce the weight of a ball bearing under the constraints of system eigenvalue and bearing fatigue life [29]. In addition, research on newly designed lightweight machine tool slide components provides solutions to reduce the energy consumption of machine tools [30]. To reduce the energy consumption of machine tool motors, many scholars have committed to improving motor performance and transforming power intensive systems. For example, a new type of variable speed-drive motor showed good energy performance. The experimental results showed that much energy consumption could be saved during processing [31]. In terms of machine tools, the optimization of hydraulic systems can greatly reduce energy consumption [32]. The cooling agent accounts for approximately 26% of the total energy consumption in the grinding process. Significant energy-saving potential can be achieved by adopting energy-efficient cooling systems for machining systems [33,34]. Furthermore, improving the lubrication system of machine tools can help to reduce energy consumption [35].

Lightweight machine tool components, including spindles, have become an important measure to reduce machine tool energy consumption. New energy-saving hydraulic devices, such as those that combine variable pumps, variable-speed control drive devices, and hydraulic boosters, also help to reduce energy consumption. The potential of the aforementioned measures in achieving energy savings and emission reduction of machine tools is gradually being explored by researchers. However, reducing the energy consumption of machine tools from the hardware perspective is hardly pursued.

3.2 Sustainability of cutting tools

As one of the components of machine tools, cutting tools have the potential for energy-saving upgrading of machine tools. At present, the machining economy, machining quality, and additional environmental impact of machine tools need to be improved. Some achievements have been attained in the research of machine tools that encounter problems in cutting metal. However, further studies are needed on the aspects of economy and environmental protection.

The correct selection of tool materials not only improves the efficiency of mechanical processing but also further realizes sustainable manufacturing. Figure 4 [36] shows how coatings can be added to a tool and its effect on tool wear and chip morphology. A strategy for the selection usually entails two steps: (i) an analysis of the development and trend of critical raw materials (CRMs) in cutting tools used in machining [37] and (ii) using the rule-based reasoning (RBR) method and gray complex proportional assessment method to select the cutting tool materials [38]. First, for some difficult-to-machine

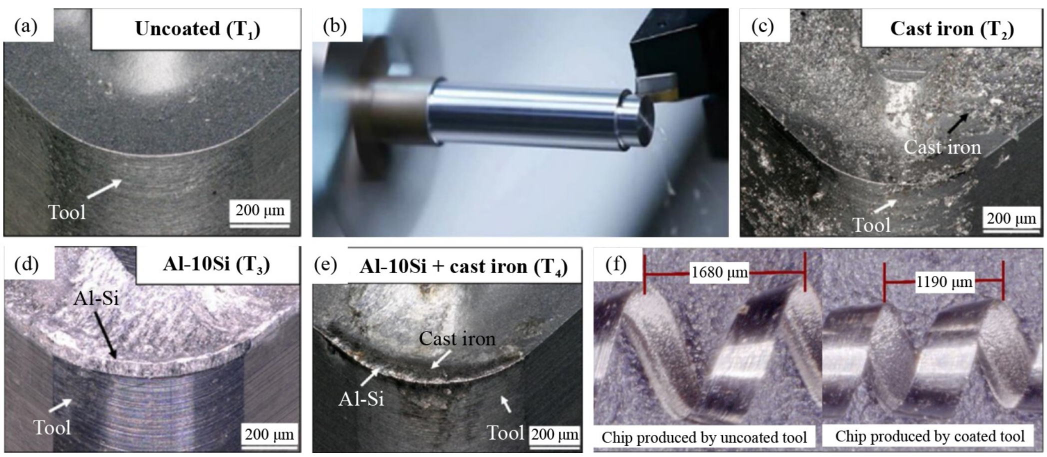

Fig. 4 Effect of coating on tool wear and chip [36]: (a) uncoated tool, (b) premachining of tool, (c) cast iron-coated tool, (d) Al-10Si-coated tool, (e) Al-10Si- and cast iron-coated tool, and (f) chip morphology. T_1: uncoated tungsten carbide, T_2: tool pre-machined with cast iron, T_3: tool pre-machined with Al-10%Si, T_4: tool pre-machined with both Al-10%Si and cast iron. Reproduced with permission from Ref. [36] from Elsevier.

materials, alloy cutting tools offer good cutting performance while ensuring low environmental pollution. For example, the effect of a physical vapor deposition (PVD) TiAlN-coated polycrystalline cubic boron nitride (PCBN) brazing-cemented carbide blade on the cutting performance of Inconel 718 was studied to solve the effective machining problem of the aerospace superalloy Inconel 718 [39]. Depositing special materials on the tools in the machining Inconel 718 process helped to improve the surface quality of workpieces and save energy [36]. Functionally graded cemented carbide (FGCC) is also a suitable material and has good hardness performance, and it has potential in machine tool applications [40]. Turning experiments were also performed using different tools under dry and minimal quantity of lubricants conditions, and the results showed that compared with coated cemented carbide, cermet tools perform effectively in reducing cutting force at low speed [41]. Second, ceramic materials can be applied to cutting tools because of their excellent performance. For the preparation of ceramic materials, TiC whiskers were used as the toughening phase to prepare TiB_2-based ceramic cutting tool materials [42]. The nanocomposite ceramic tool material with graphene nanosheets as the reinforcing phase showed friction reduction and wear resistance during the cutting process [43]. In addition, the advantages and disadvantages of the technologies and processes involved in manufacturing ceramic tools were analyzed and compared to determine the most appropriate method of manufacturing ceramic tools [44]. A new ceramic matrix composite based on cubic boron nitride and the TaC binder phase was prepared by sintering the specimen under high-pressure and high-temperature conditions, and the result showed high resistance to mechanochemical wear [45]. Optimization based on ceramic tools can also improve machining results; for instance, for the first time, porous space in cutting tool ceramics was used to influence the performance of diamond machining of such ceramics and improve their machinability by water absorption [46].

Recent research on cemented carbide cutting tools has mainly focused on three aspects: cemented carbide grain refinement, the binder phase of cemented carbide tool materials, and other additives of cemented carbide tool materials. The machining characteristics of these tools are related not only to their own materials and microshapes but also to the material and cutting parameters of the parts to be processed. However, finding a machine tool that is suitable for various machining scenarios is unrealistic. Research on this aspect remains scattered and complex, which is also one of the challenges facing this work.

3.3 Sustainability of cutting fluids

Cutting fluid is a kind of fluid used for cooling and lubrication in metal processing. Traditional cutting fluids pollute the environment; by contrast, components of the sustainable cutting fluid are harmless to people and the environment [47]. Recycled wastewater can also be safely discharged.

The application of nanotechnology in the manufacturing industry provides new ideas for research on sustainable cutting fluids. A new cutting fluid was created by incorporating WS_2 nanoparticles into the cutting fluid and then used to explore its effect on the friction of the cutting process [48]. The turning process of AISI 4340 alloy steel was studied to analyze the influence of various fluid characteristics (e.g., surface tension) of nanofluids on machinability [49]. Research on how to improve the conversion performance of single-point diamond-turned optical polymers showed the good application potential of a novel nano-droplet cutting fluid composed of emulsified water and oil nanodroplets [50]. A carbon nanotube-based cutting fluid was applied in the machining process and achieved a good machining effect on hardened steel [51]. The machining characteristics of different cutting fluids are shown in Fig. 5. The influence of the cutting fluid on the broaching process is also being studied. Water-based cutting fluids not only have good lubrication and cooling effects but also pollute the environment less, especially when green additives are added to water-based cutting fluids [52]. Research results indicate that aqueous solutions of surfactants have great potential as green cutting fluids for manufacturing systems because of their good cooling and lubrication performance [53]. Compared with traditional environmentally damaging mineral oil, vegetable oil has less impact on the environment. Therefore, green cutting fluid based on vegetable oil is commonly used in the manufacturing industry. The effectiveness of vegetable oil-based cutting fluid was evaluated from different aspects, such as cutting force, tool wear, and temperature of the cutting area [54]. The experimental outcome showed that the use of super olein as a cutting fluid in the machining process was conducive to improving the surface quality of the workpiece [55]. Under the same circumstances, the effects of jatropha oil emulsion and mineral oil were almost the same, but the former was more environmentally friendly [56]. Vegetable oil-based green cutting fluid also has the potential for optimization. For example, the cutting performance of AISI 321 stainless steel was studied to determine the optimal lubrication strategy [57].

In recent years, an increasing number of scholars and enterprise players have paid attention to sustainable cutting fluids. China’s research in the field of sustainable cutting fluid is in the laboratory stage. However, problems such as low sustainability are still common. Future development will likely be concentrated on oil-based or water-based cutting fluids.

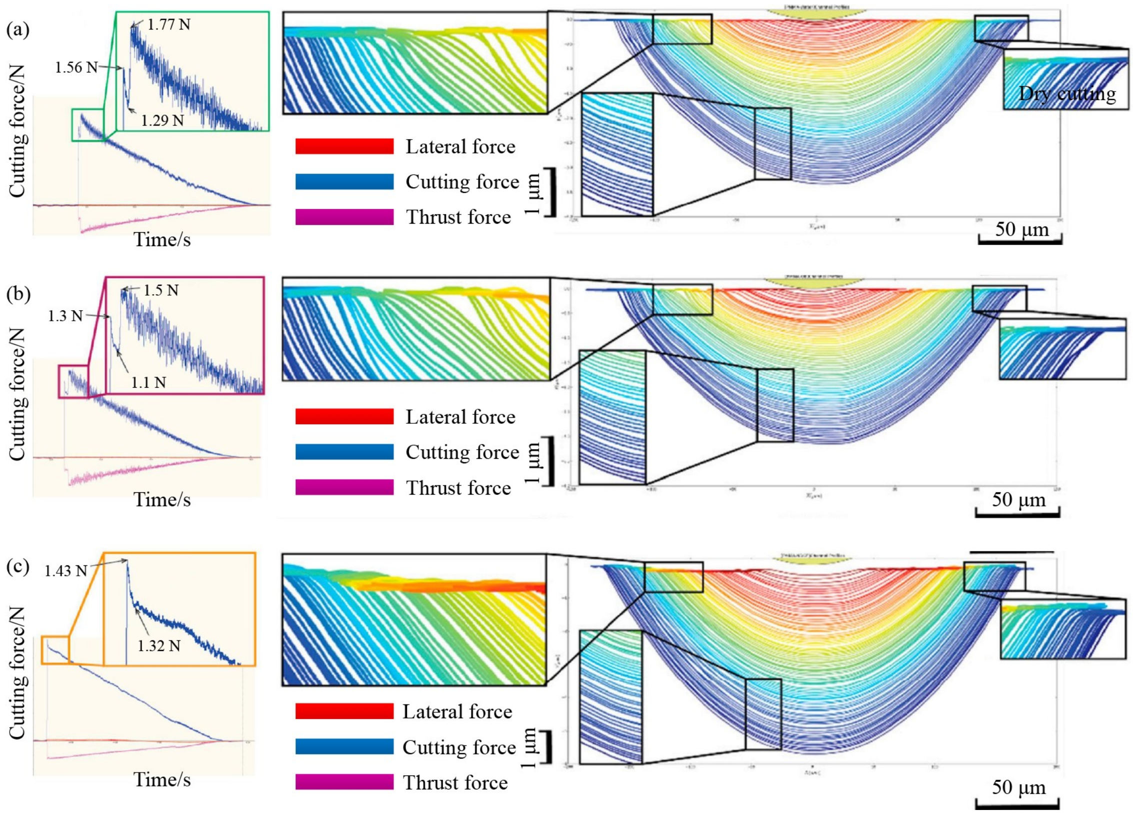

Fig. 5 Machining characteristics of different cutting fluids [50]: (a) water-based cutting fluid, (b) oil-based cutting fluid, and (c) nanodroplet cutting fluid. Reproduced with permission from Ref. [50] from MDPI.

4 Sustainability of machining processes

Sustainable machining processes are crucial in machining systems and an important symbol of modern industrialization; hence, they have received increasing attention from countries and research institutions around the world. Sustainable processes not only use environmentally friendly materials in the machining process but also realize the efficient use of resources and reduce environmental pollution. A sustainable process was used to predict the safety parameters of organic peroxides, optimize reactor design, and correct other chemical process errors [58]. In addition, sustainable processes are beneficial for improving the performance of low-carbon steel and optimizing the component efficiency of large carbon refractories [59,60]. This section mainly introduces sustainable processes such as dry machining, process simulation, microlubrication, and microcutting.

4.1 Dry cutting

Dry cutting is a kind of sustainable process technology that does not use cutting fluid in the cutting process, thus reducing both the costs and the negative impact on the environment. Figure 6 [61,62] shows a schematic diagram of dry cutting and the characteristics of the cutting parameters. In the traditional cutting process, the use of cutting fluid affects the surface quality of products and pollutes the environment. The adoption of sustainable process technology can help promote the development of green manufacturing technology [62].

First, investigating the turning process in near-dry conditions can promote the development of dry cutting technology [63]. Take cBN-coated tools as an example. The dry-turning process of hardened ductile iron was analyzed to explore the change in tool performance under dry-cutting conditions. The results showed that the cutting force increased with increasing cutting depth. When the cutting speed increased, the cutting force decreased, and the cutting temperature increased [64]. Second, the material of the turning is vital to dry cutting. The 7055 aluminum alloy has excellent performance, such as high specific strength and superior corrosion resistance, hence its wide application in the aerospace field. In a study of the machinability of 7055 aluminum alloy under dry-cutting conditions, the degree and depth of work hardening were significantly and positively correlated with the cutting depth [65]. In general, compared with other traditional materials, aluminum alloys have considerable advantages in terms of strength, oxidation resistance, and corrosion resistance, hence their wide use in the electronics, weapon, and aerospace

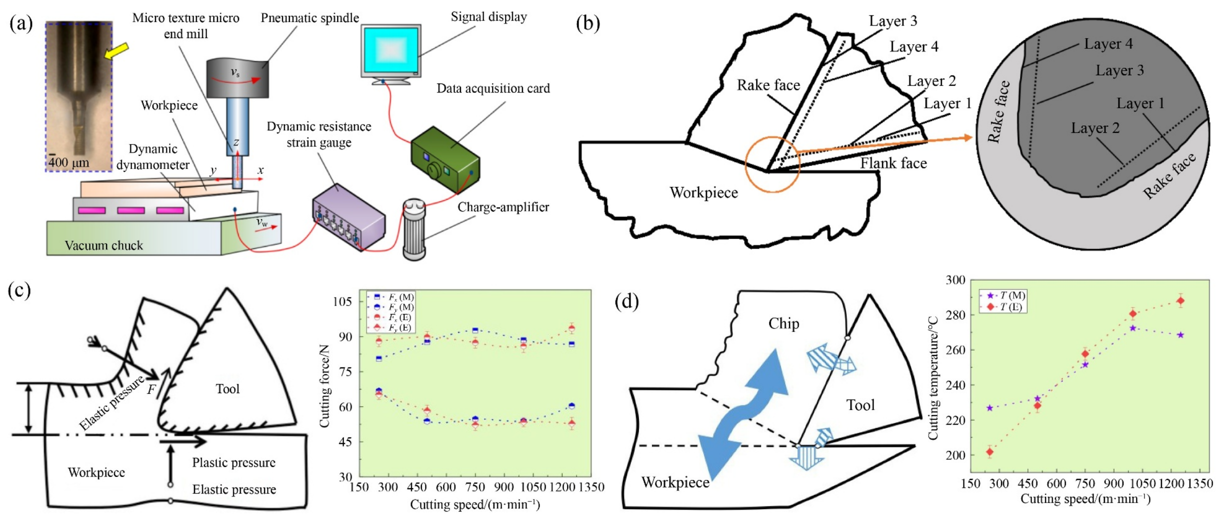

Fig. 6 Dry cutting: (a) dry microcutting experiment and detection process [61], (b) schematic diagram of dry cutting, (c) influence of cutting speed on cutting force [62], and (d) influence of cutting speed on cutting temperature [62]. M: measured, E: experimental. Reproduced with permissions from Refs. [61,62] from Elsevier.

industries. Finally, dry cutting can affect the surface quality of products. The surface quality and tool wear of dry microcutting were investigated by using a microtextured spiral micro-end mill and performing dry microcutting experiments on aluminum alloy materials. Research on the surface quality of aluminum alloy workpieces under dry-cutting conditions showed that the implantation of microtextures would not reduce the surface quality of the workpiece but rather improve the consistency of the machined surface [61]. In the research of self-lubricating FGCC, the design and composition optimization methods of tool materials corresponding to dry machining were proposed, eventually providing a basis for dry machining to realize clean and green manufacturing [40].

Research on dry-cutting technology has also started in China, and some research results are promising. However, the application scenarios of dry-cutting technology are somewhat limited, and reforming technologies to broaden the application scenarios is somewhat difficult. With the in-depth study of related processes, dry-cutting technology will likely be an important sustainable machining technology.

4.2 Minimal quantity lubrication

The minimal quantity lubrication (MQL) technique is used in the machining process to overcome the environmental pollution caused by the extensive use of cutting fluid. Past results showed that compared with the traditional cooling strategy, the MQL cooling strategy has better performance in terms of machining quality, environmental protection, and tool life [66–68]. However, the technology needs to solve the problem of harsh application conditions and few usage scenarios.

An experiment involving MQL technology on the rake and flank of a tool to turn at two feed rates and two cutting lengths was developed to investigate the performance of MQL technology in reducing tool wear. The results showed that when MQL is applied to the tool front tool holder, the tool life is usually the same as drying conditions, but the tool life is increased when MQL is applied to the tool side. In addition, MQL improves the grinding surface quality of workpieces while reducing the grinding temperature and grinding force (Fig. 7) [69,70]. Research on MQL deep-hole drills showed that the working state of cutting fluid can be accurately grasped by establishing a mathematical model for the nonlinear distribution of cutting fluid pressure with respect to time in the machining process. This model can greatly reduce the amount of computation and converges much faster [71]. Second, the lubrication parameter design helps to reveal the functions and mechanisms in MQL [72]. Under the condition of intermittent turning, the function and mechanism of MQL were studied. The results showed that the cutting fluid should not be extremely small. Furthermore, appropriate lubricants are required to maintain the strength of the boundary film to achieve good MQL cutting performance [73]. Research on cutting tools has also promoted the development of technology in this field. For example, in the grinding process of grinding wheels, the use of a mathematical model of grinding wheels can positively affect the grinding parameters, including the lubricating fluid factor [74]. In the machining process, the centrifugal force generated by the high-speed rotation of the machine tool spindle leads to the separation of oil mist, which eventually weakens the effect of the lubricating fluid. A new microlubricant supply strategy was proposed to solve this problem [75]. Finally, the diversity of lubricants differentiated the performances in minimal quantity lubrication. Vegetable oil and synthetic ester oil were

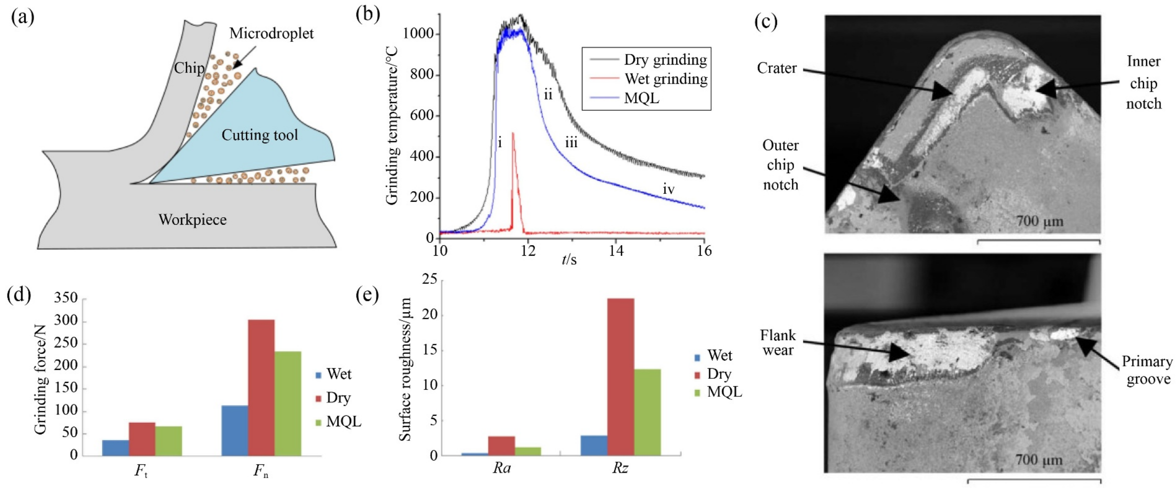

Fig. 7 Minimal quantity lubrication (MQL): (a) schematic diagram of MQL, (b) influence of lubrication conditions on cutting temperature [70], (c) effect of MQL on tool wear [69], (d) influence of lubrication conditions on grinding force [70], and (e) influence of lubrication conditions on surface roughness [70]. Reproduced with permissions from Refs. [69,70] from Springer Nature and Elsevier.

compared on the basis of the surface quality characteristics suitable for MQL applications, and the latter was found to be better for MQL in the grinding of Ti–6Al–4V [76]. The cutting performances of vegetable esters were also studied on the basis of the physical characteristics of MQL applications. Compared with synthetic esters, biodegradable synthetic esters were found to be the optimal cutting fluid for MQL processing [77]. In addition, experiments have shown that hybrid nanoparticles have better lubrication properties than pure nanoparticles [78].

Minimal quantity lubrication is a new type of cooling lubrication technology and an effective alternative to the existing cooling method of cutting fluids. This aspect comprises the research direction of integrating minimal quantity lubrication into the machine tool remanufacturing process.

4.3 Microcutting

Figure 8 [79,80] shows microcutting as a fast and low-cost machining process for small parts; it mainly includes micromilling, microlinear cutting, and laser microcutting [81]. Compared with traditional cutting, microcutting has the advantages of low cost, low energy consumption, and high efficiency [82]. In addition, given the limitations of traditional cutting, microcutting is considered a sustainable processing technology in the field of micropart processing, and most of the research results are concentrated in this area. The cutting tool and microscopic geometry of the cutting edge can not only stabilize the cutting edge but also positively affect the cutting force, surface roughness, and burr formation during micromilling [83,84]. However, this feature also leads to faster tool wear, which is a problem that needs to be solved in the field of microcutting technology.

Microslit cutting of aluminum foil is challenging because of the low hardness and deformability of aluminum foil. A novel machining strategy that used a tungsten microwire as a nonmoving or nonrotating cutting tool was proposed [85]. Grinding is also a traditional microcutting method. For example, grinding is considered to be an efficient and high-quality method to form fine groove textures on cutting tools with diamond grinding wheels [86]. Experiments showed that the negative rake angle of tools is an important parameter in microcutting. Machining with the optimal negative rake angle helps to achieve the optimal surface quality of the workpiece and tool wear [87]. Second, given the unique advantages of laser cutting, it is also considered a cost-effective green manufacturing and rapid processing technology [88]. Take the Ti–6Al–4V alloy as an example. A laser-assisted machining experiment was conducted, and the findings showed that laser power and cutting speed are important parameters in laser cutting, either expanding or reducing the heat-affected zone of workpieces, further affecting the machining quality [80]. A new method was subsequently proposed to solve the problem in which overheating during laser irradiation leads to the formation of microcut edge melting after laser quenching [89]. Additionally, microcutting simulation technology has begun to be applied in the microcutting process, and the widely used cutting simulation methods include finite element analysis and molecular dynamics [90,91]. Given the size effect of micromilling, the current constitutive model needs to be further improved to reduce the parameter error. A study on the improved constitutive model showed that the error of the relevant results could be reduced to an acceptable range, and its convergence could be verified [92]. A single-particle microcutting model was established to simplify the operation of the

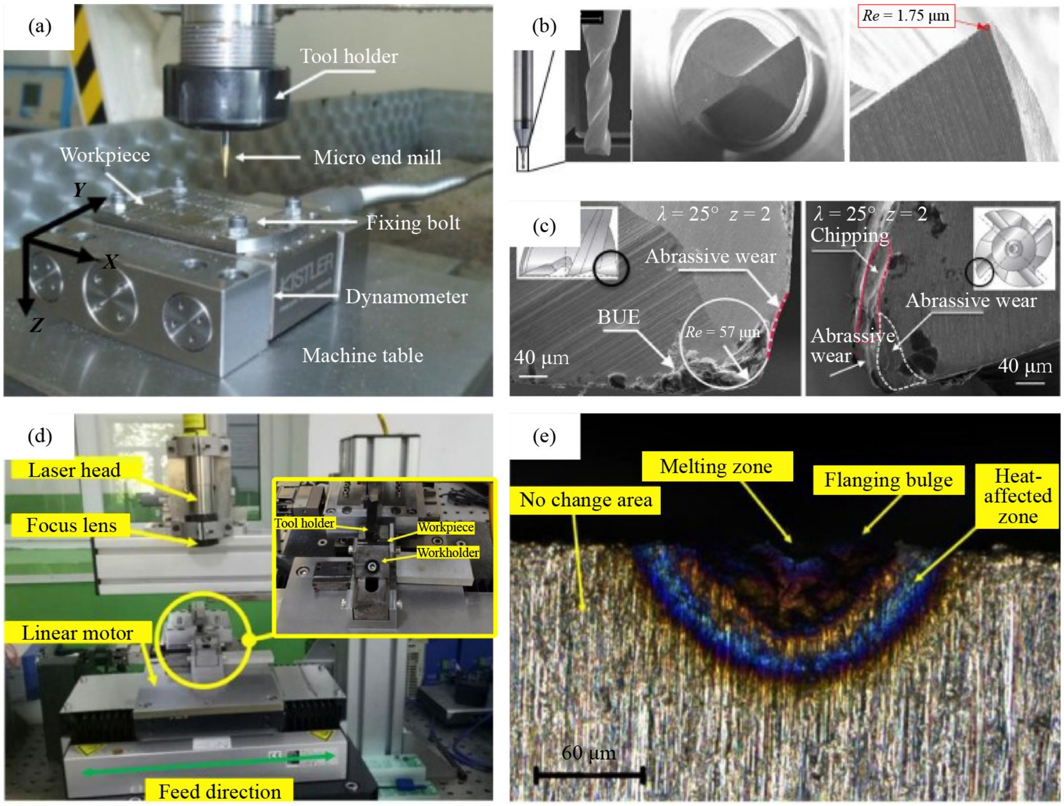

Fig. 8 Microcutting: (a) micromilling tests [79], (b) an example scanning electron microscope (SEM) image of the micro end mill [79], (c) SEM images of cutting tool damages [79], (d) laser-assisted cutting device [80], and (e) topographical view of the heat-affected zone for laser sawing [80]. BUE: built-up edge. Reproduced with permissions from Refs. [79,80] from Springer Nature.

reaming process of abrasive particles [93], and an energy optimization model for micromachining was established [94]. A device for measuring the linear cutting force in the vacuum chamber of an electron microscope was developed to determine the cutting feeds and cutting processes with tool tip radii as low as 200 nm [95]. As a method for reducing the influence of tool wear on the surface quality of the workpiece during microcutting, a new measurement system was designed to evaluate the profile of the microcutting edge to ensure the quality of products [96].

The main challenges of microcutting technology include the influence of the cutting-edge radius on machining and the influence of the workpiece material on the cutting process. Incidentally, the development of traditional machining strategies cannot ensure a breakthrough in the field of microcutting technology.

4.4 Cryogenic cutting

As an advanced sustainable manufacturing process, cryogenic cutting refers to the use of a low-temperature medium in the cutting process to cool the tool and workpiece, eventually improving the processing effect and reducing energy consumption. Some achievements have been achieved in the use of low-temperature carbon dioxide, low-temperature liquid nitrogen, and low-temperature compressed air as cooling media. Nonetheless, one of the problems to be solved at present is the presence of harsh working conditions of low-temperature cutting.

First, cryogenic cutting has more advantages than traditional dry and wet machining [97,98]. In contrast to dry cutting, the increase in cutting force in cryogenic cutting under low-temperature compressed air is smaller after long-distance cutting [99]. Finite element simulations and experiments of dry and liquid nitrogen cryogenic cutting processes proved that liquid nitrogen could significantly reduce cutting temperatures [100]. Second, cryogenic cutting can not only improve the machinability of materials but also improve the service life of tools [101–103]. After low-temperature treatment, such as low-temperature liquid nitrogen or liquid carbon dioxide treatment, coated tools can replace the traditional cemented carbide tool [104,105]. In addition, cryogenic cutting can improve chip fragmentation [106] while reducing processing costs [107]. Figure 9 [108–110] shows a comparison of the chip morphology and tool wear under dry and liquid nitrogen cooling conditions. Third, in an experimental study on the milling process of AISI 304 stainless steel, low-temperature cooling somewhat influenced the cutting force [111]. Research

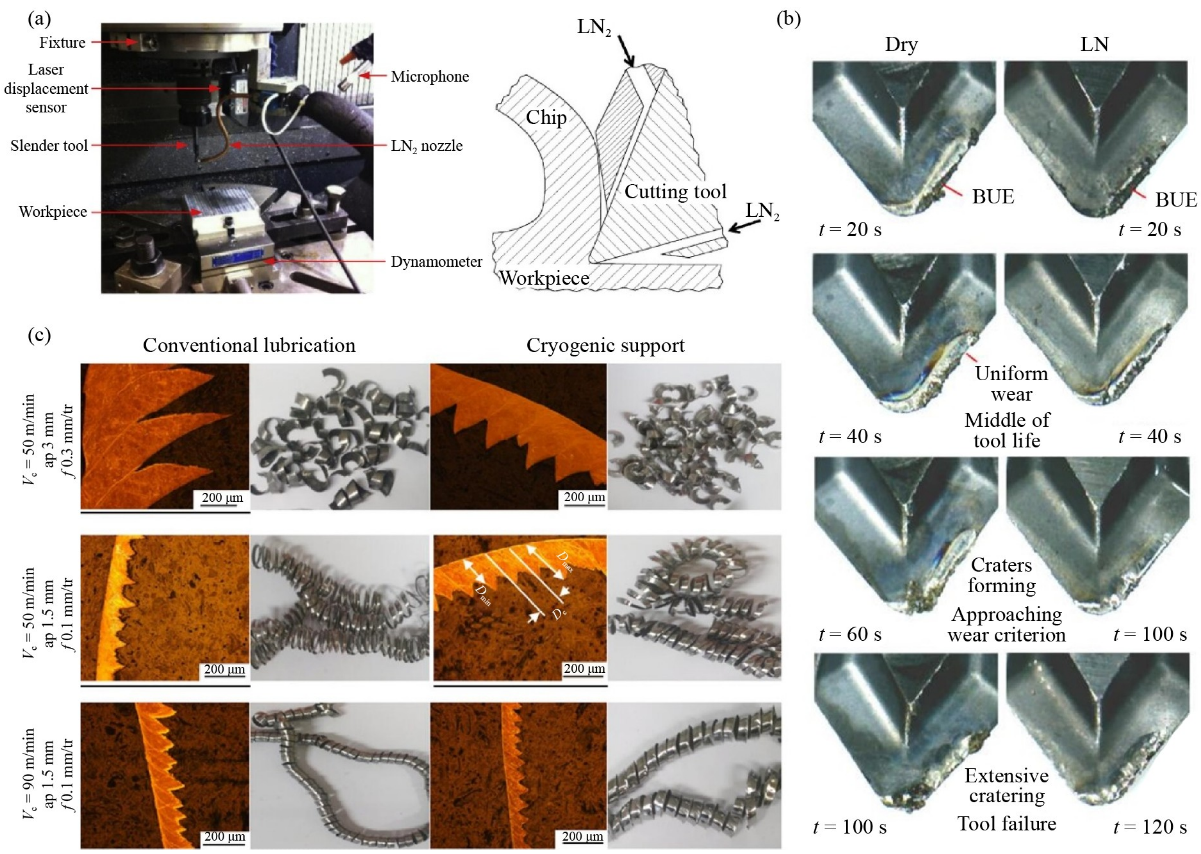

Fig. 9 Cryogenic cutting: (a) cryogenic cutting test [108], (b) comparison of tool wear [109], and (c) comparison of chip morphology [110]. BUE: built-up edge. Reproduced with permissions from Refs. [108–110] from Elsevier and Springer Nature.

has shown that different cutting parameters have varying effects regardless of whether they are in the same cooling medium [112]. For example, a mechanical processing test of hardened steel showed that the effectiveness of low-temperature coolant to improve the machinability of the steel was dependent on the cutting parameters [113]. Therefore, appropriate cooling media and parameters should be selected for different conditions. Under the combination of high-feed speed and low-cutting depth, the use of low-temperature liquid nitrogen can maximize the tool life [114]. Research on the end milling of Al 6082-T6 alloys showed that the cooling effect of low-temperature liquid nitrogen is better than that of low-temperature CO_2, but the machined surface quality is reduced [109]. The processing of titanium alloy Ti–6Al–4V is a challenging task. Compared with low-temperature liquid nitrogen processing, the application of CO_2 can reduce the cutting force by 24% and improve the surface finish by 48% [115]. When TiAlN-coated tools were used to end-mill a SKT4 die steel, the surface of the die steel cooled by low-temperature CO_2 had a better surface morphology than that cooled by wet cooling [116]. Finally, the working form of the cooling medium can also greatly influence the cooling effect. For example, a special low-temperature cooling system was used to apply a liquid nitrogen jet to the cutting area, and a better cooling effect and machining efficiency were eventually obtained [117]. An investigation on the turning process of AISI 304 stainless steel showed that low-temperature cooling with liquid nitrogen spraying is conducive to improving the surface roughness of a workpiece [118].

Cryogenic cutting is widely used in materials that are relatively difficult to process, such as steel with high manganese content and titanium alloy. Most studies have shown that low-temperature treatment can significantly improve tool life and material machinability. Most importantly, cryogenic cutting is an important technology to achieve energy conservation and emission reduction of machine tools. The research and development (R&D) of low-temperature cutting systems is necessary to further develop this technology [119].

4.5 Multidirectional cutting

Multidirectional cutting is a new cutting technology in which reverse cutting is conducted immediately after completing the traditional forward cutting process, and there is no zero return, which can save turning time, improve production efficiency, and contribute to a flexible and diverse turning path [120]. Traditional cutting is in a nonmachining state for a part of the time in a cutting process, resulting in a waste of energy, which is a huge obstacle when the aim is to improve the energy efficiency of cutting and reduce the processing time [121]. With the emphasis of the manufacturing industry on environmental problems, traditional machining is facing a situation that has to be improved. At present, research on multidirectional cutting is still in its infancy. Some achievements have been attained in the theoretical and experimental stages, but practicality is another issue. For example, parallel cutting presented great potential to solve the problems of high energy consumption and low efficiency in traditional cutting. Parallel cutting uses multiple cutting tools to act on an ordinary workpiece, eventually improving production efficiency and reducing energy consumption [122,123]. How to solve the chatter problem caused by the interaction between the tool and workpiece is the main challenge of parallel cutting [124,125]. Modeling the dynamics and stability of the parallel-cutting process, solving it, and optimizing its parameters are regarded as effective strategies to solve the tremor problem [126,127]. In addition, some scholars have developed other tremor suppression techniques and achieved good results [128–130].

At present, research on multidirectional cutting is still in its infancy. In view of further improving the multidirectional cutting method and its evaluation index, a series of evaluations of energy consumption, economy, and machining quality of multidirectional cutting will likely be the focus of future research.

5 Strategies of sustainable machining

5.1 Energy-saving control of machine tools

Traditional machine tools ignore the requirements of energy conservation and emission reduction during control. Research on the energy-saving control of machine tools has reached a certain level of achievement in the field of intelligent algorithms, but energy savings and machining quality improvement are difficult to balance.

Figure 10 [131–133] shows the energy-saving control strategies of the machine tool. Cutting is a widely used traditional process that consumes most of the energy in manufacturing [134]. First, green machine tools improve processing performance, and the tool radius compensation (TRC) function is important for milling machines. A new TRC was proposed to achieve high accuracy in machining complex surfaces [135]. After building an adaptive optimization algorithm, models were established to determine the optimal specific cutting energy heat of the machine tool spindle, and the experimental results

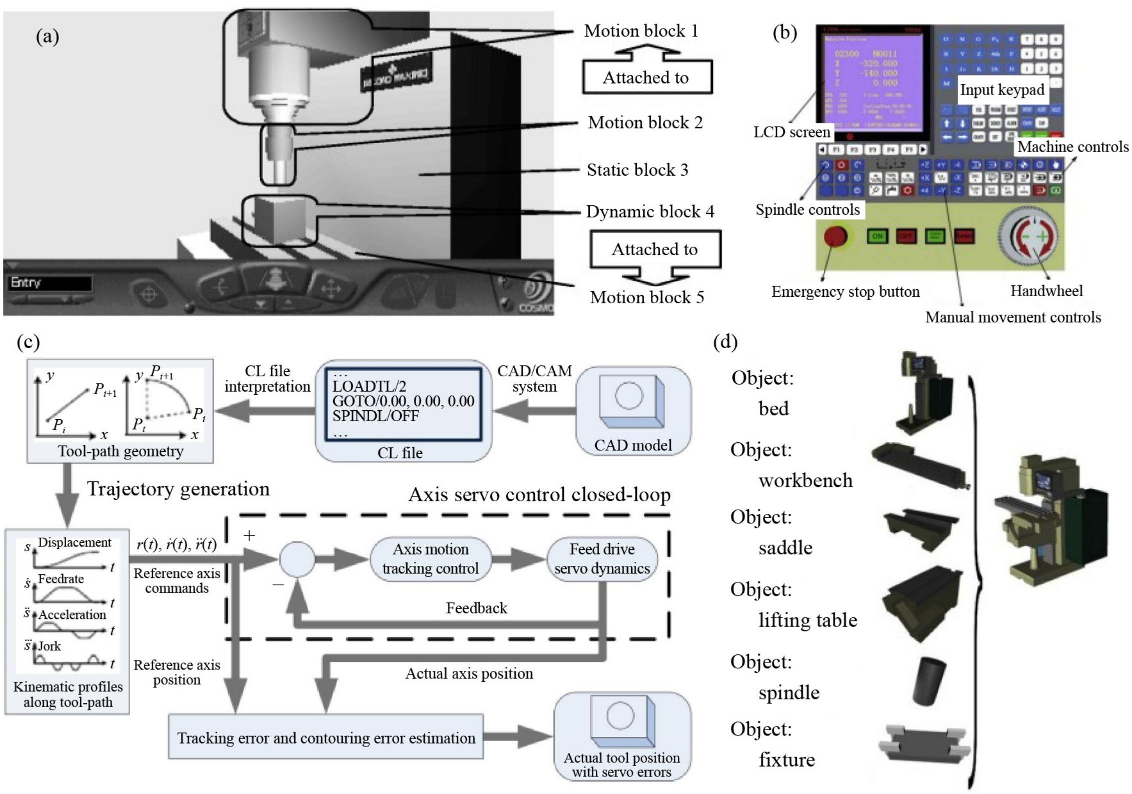

Fig. 10 Energy-saving control of machine tools: (a) virtual structure of machine tool [131], (b) virtual computer numerical control panel [132], (c) composition of virtual machine tool [133], and (d) control system of machine tool [132]. Reproduced with permissions from Refs. [131–133] from Taylor & Francis and Elsevier.

showed that the model has application potential in engineering [136]. Second, green machine tools contribute to the innovation of optimization algorithms and control methods. On the basis of the data of machine tools and workpieces, a method to evaluate machine tool performance was proposed. The potential of this method was consequently confirmed by a study on milling [137]. The optimization of the control system is a good approach for optimizing the energy consumption of machine tools. For example, a method was proposed to optimize the control of a six-axis milling machine [138]. Third, green machine tools improve product quality. Compared with traditional machine tools, hybrid turning–milling machine tools are more advanced in terms of process and structure. Determining the factors affecting the machining accuracy is the premise of optimization. Subsequently, a geometric error sensitivity analysis method was proposed to identify the sensitive error items that could affect the machining accuracy due to multiple error items [139]. A better choice is to classify the influencing factors when investigating which among the parameters have the greatest impact on machine tool precision [140]. Finally, green machine tools aim to reduce energy consumption. In the machining process, with the goal of reducing energy consumption, the acceleration of the machine tool spindle is adjusted to synchronize with the feed system [141]. The monitoring of machine tool energy consumption is helpful in identifying the energy loss and adjusting the energy-saving strategy. Most traditional energy consumption monitoring methods, such as the use of torque sensors and dynamometers, can no longer meet the requirements of green manufacturing. An approach different from the conventional energy consumption monitoring method was proposed to reduce the cost [142].

Many technologically backward and seriously aging machine tools still abound. These technologies not only have low manufacturing efficiency but are also beset by problems such as pollution and high energy consumption. With the implementation of relevant systems and the active response of the Machine Tool Industry Association, China has eliminated energy-consuming and high-polluting machinery products, strictly abiding by relevant environmental protection systems.

5.2 Processing simulation

Process simulation technology is a virtualization technology supported by computer-aided technology and virtual reality technology, helping to establish virtual processing scenarios for the research and optimization of product processing methods [143,144]. The traditional manufacturing mode cannot predict the process in advance; virtual manufacturing technology represented by the digital twin mode can solve this problem and help to optimize energy consumption. Many researchers and enterprise players have contributed to the development of the manufacturing industry in virtual environments in the past few decades by providing cases for follow-up research and application [145,146].

Virtual manufacturing services have received increasing attention, and they are expected to be one of the fields contributing to the future competitiveness of industrialized countries [147]. Figure 11 [148,149] shows a flowchart of a process simulation. Process simulation technology is widely used in fixture design, sheet metal design, and ultraprecise diamond turning processes [150,151]. The first scheme is to establish a virtual model, including the construction of virtual systems and processing objects. The advantage of using simulation machining systems is that they can reveal or simulate the machining process as accurately as possible. A high-fidelity machining simulation solution was used to obtain more accurate results [149]. The controller is one of the

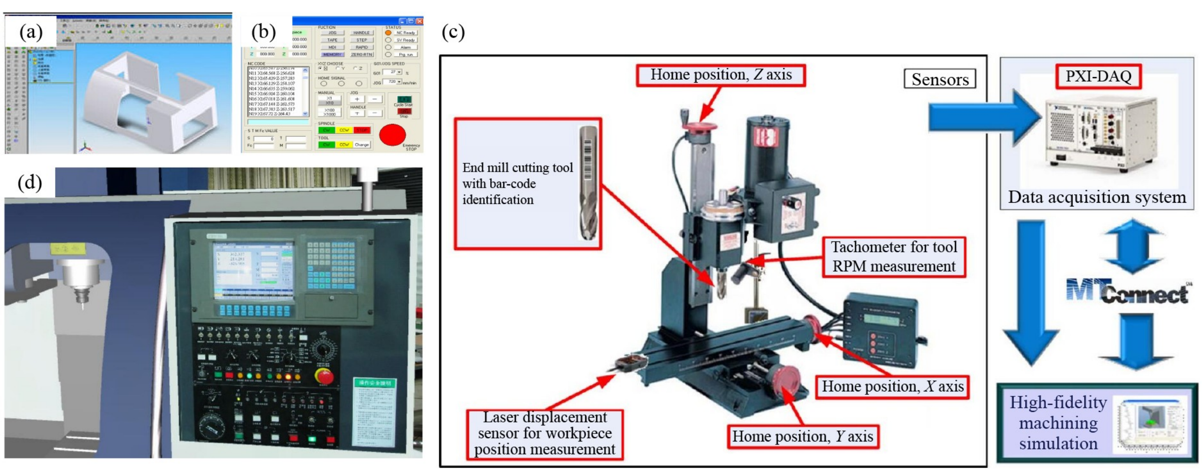

Fig. 11 Processing simulation: (a) modeling [148], (b) parameter adjustment [148], (c) process monitoring [149], and (d) process simulation [148]. Reproduced with permissions from Refs. [148,149] from Elsevier.

components of the machine tool, forming the hardware foundation of the machine tool control strategy. Some achievements have been attained in the research of virtual computer numerical control (CNC) controllers [148]. At present, the development of Internet of Things technology is a new development for green manufacturing. For example, the online virtual NC milling system is used to control the machining process in real time by using the Internet. This approach not only provides convenience for operators but also reduces the energy consumption commonly associated with manufacturing systems [152]. The second aspect represents studies regarding specific processing plans of the model. In the manufacturing system, the machining accuracy and efficiency of assembly production need to be improved given its potential for energy savings. On the basis of virtual manufacturing technology and manufacturing methods, a precision machining scheme model was established to solve the aforementioned problem [153]. The algorithm of material removal simulation based on the VRML achieved a much lower memory requirement and faster computation speed [154]. The last aspect corresponds to the optimization of the overall simulation processing plan. A numerical simulation method of the aluminum composite casting process was proposed. This method can show the state of aluminum alloy in the composite casting process by simulation, allowing the casting process to be accurately controlled [155]. Process simulation technology is also used for simulation analysis. For example, a complex spiral network structure was analyzed using the virtual manufacturing method. The modified method can improve the performance of metal rubber [156]. A generalized simulation and optimization strategy of the 2 1/2 axis milling process was also used to improve the material removal rate, and no machining error was observed [157].

Process simulation technology is a virtualization technology supported by computer-aided technology and virtual reality technology. It not only improves the processing efficiency but also optimizes the mechanical production structure. Subsequently, information technology related to the implementation of “virtual product development” was studied on the basis of a systematic literature review spanning the last 40 years. In the future, processing simulation will likely be widely used in green manufacturing.

5.3 Process optimization

Different processes vary in energy consumption performance, but the energy consumption of the same process is also expected to change with the parameter modifications. If process parameters are properly selected, then the energy consumption can be reduced [158]. Researchers have conducted extensive research on turning and milling and the corresponding parameter optimizations. However, optimization algorithms need to be further investigated.

The process of determining appropriate parameters to achieve the best energy consumption performance is called process parameter optimization (a form of process optimization) [159]. Process optimization usually consists of two steps: modeling and solving. For example, an enhanced energy consumption analysis model was developed on the basis of the decomposition of the machine tool into multiple energy-related components. In particular, the model was optimized to achieve the best energy consumption performance in the cutting process of a CNC machining center, and the best cutting parameters were determined [160]. Aimed at achieving the maximum energy efficiency while minimizing the production cost, a multi-objective optimization model based on an adaptive multi-objective particle swarm optimization (MOPSO) algorithm was proposed to optimize the cutting parameters, in which the power consumption characteristics of multipass CNC surface milling were considered [161]. A multi-objective optimization model was also used to reduce the energy consumption and total completion time of NC machine tools, and the MOPSO algorithm of the crossover method was used to solve the model [162]. The development of virtual machine tool (VMT) technology provides more solutions for process optimization. For example, a VMT processing energy consumption evaluation model was established to adapt to the changing optimization objectives of machine tools [163]. Figure 12 [164–166] shows a flowchart of the proposed method for optimizing the machining condition, thereby reducing the energy consumption. A genetic algorithm was used to solve the model and subsequently optimize the processing conditions and reduce energy consumption. Many studies have also focused on optimization methods. For example, the response surface method (RSM) and genetic algorithm are helpful in building optimization models and can be used to predict energy consumption and the corresponding machining parameters in the turning process [166]. A complex optimization method for cutting parameters in which energy efficiency and machining time were taken as the research objectives was proposed by combining the Taguchi method, RSM, and MOPSO algorithm [167]. The results established the feasibility of simultaneously reducing energy consumption and processing time in using the model.

Process optimization includes single-objective optimization and multi-objective optimization. An increasing number of studies have shown that integrated multi-objective optimization models and methods contribute considerably to this field [168]. In addition to the parameter optimization of certain processes, the optimization between different processes (process planning optimization) is attracting the attention of researchers [169].

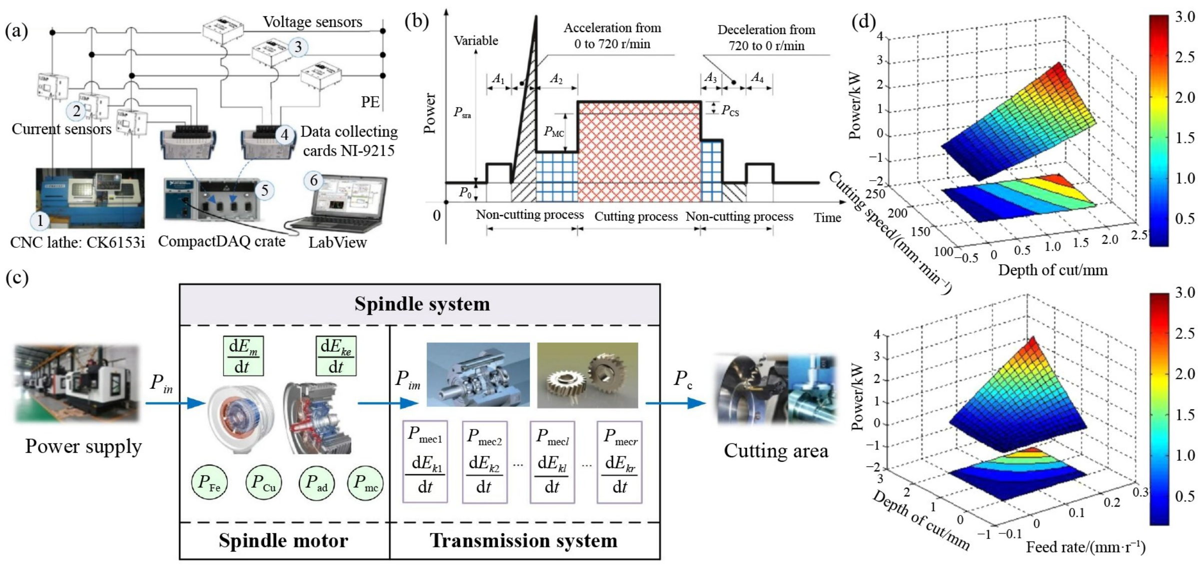

Fig. 12 Process optimization: (a) data acquisition [164], (b) power diagram [164], (c) energy flow of the lathe spindle system [165], and (d) optimization of process parameters [166]. Reproduced with permissions from Refs. [164–166] from Elsevier.

6 Outlook and the future

6.1 Sustainability of machining equipment

Traditional machine tools are still widely used by many small processing companies—a scenario that is more widespread in emerging economies [170]. Although the cost of optimizing the energy consumption performance of machine tools with respect to the software level is relatively low, traditional machine tools often cannot be optimized because they do not consider these performance factors at the beginning of their design. Many machine tools can hardly optimize energy consumption from a control system perspective. For the sustainable upgrading of machine tools, at the hardware level, the current research is mainly focused on the adoption of renewable materials of machine tool parts, lightweight designs, modular designs of machine tools, and recyclability of old machine tools [171,172]. Intelligent manufacturing and sustainable machine tools are of great significance in the context of Industry 4.0; hence, from the perspective of software utilization, the combination of machine tools and machine intelligence is the direction of future development [173]. The manufacturing industry has increasingly imposed much higher requirements to evaluate the environmental friendliness and performance of product components, further complicating the requirements for manufacturing systems in the machining of these parts, especially cutting tools. In sustainable machining, cutting tools need to be energy efficient and environmentally friendly while meeting processing requirements, with tools generating less heat while ensuring longer life, material recovery (especially remanufacturing properties), and low costs [174]. As it is a great challenge for single-alloy cutting tools to achieve excellent performance, scholars prefer to add specific layers on the base material to achieve excellent machining performance and environmental friendliness [175]. For example, PVD TiAlN-coated PCBN-brazed cemented carbide blades can help solve the problem of ineffective machining of the aerospace superalloy Inconel 718 [176]. In addition, metal–ceramic cutting tools and nanocomposite ceramic cutting tools with graphene nanoslices as the reinforcing phase have good environmental friendliness features and machining performance. Studies on cutting fluids for sustainability mainly focus on nanofluid cutting fluids, water-based cutting fluids, and oil-based cutting fluids [177]. Although cutting fluids with good performance in some scenarios have been studied, sustainable cutting fluids for more scenarios need further research. Moreover, the selection and optimization of sustainable cutting fluids are important and challenging tasks. In the context of sustainable machining, the analysis of the life cycle of cutting fluids established that the selection factors of cutting fluids mainly comprise four aspects: cost, cutting fluid quality, environmental pollution, and resource loss. Four factors are also used as the selection criteria for green cutting fluid, and the trapezoidal fuzzy evaluation model of the decision matrix of the analytic hierarchy process is used to select three commonly used cutting fluids.

6.2 Sustainability of machining processes

Dry-cutting technology has developed rapidly to meet increasing global environmental protection requirements and sustainable development strategies [178]. European countries, America, Japan, and other industrially developed countries all attach great importance to dry-cutting research, and dry-cutting technology has been successfully applied in the production field. With the gradual deepening of research, dry cutting is being divided into more refined technology types. For example, full dry cutting can achieve good results because of its fast running speed and short contact time between the tool and workpiece, and more cutting heat that can be taken away by chips [179]. In semidry cutting, 10–50 mL of cutting fluid can be used every hour and sprayed into contact surfaces by compressed air atomization, achieving a good environmental protection effect. In the field of precision machining of microparts, microcutting technology offers advantageous characteristics and the potential for sustainable development [180]. Given the small size of tools used for microcutting, the geometric shape and material of these tools are the key considerations in machining. The first aspect is the application of new materials, which currently include cermet, polycrystalline diamond, and cubic boron nitride. These materials offer different advantages in terms of impact resistance, high-temperature resistance, and wear resistance. In addition, the tool structures change, and the design of this aspect needs to be adjusted according to the change rule of the processing environment. In general, cryogenic cutting is widely used in materials that are more difficult to process, such as steel with high manganese content and titanium alloy [181]. With further research, ultralow-temperature cooling machining technology can contribute to machining performance and energy consumption. For example, a high-pressure liquid CO_2 gas supply system was applied to the processing of TC4 titanium alloy during liquid CO_2 cooling. Multidirectional cutting is another new cutting technology in which reverse cutting is conducted immediately after completing the traditional forward cutting process, and there is no zero return, which can save turning time, improve production efficiency, and contribute to a flexible and diverse turning path [182]. At present, research on multidirectional cutting is still in its infancy. With the goal of further improving the multidirectional cutting method and its evaluation index, the evaluation of energy consumption, economy, and machining quality of multidirectional cutting will likely be the focus of future research.

6.3 Strategies of sustainable machining

The intellectualization of machine tools has become a new power to promote sustainable processing [183]. The combination of artificial intelligence and machine tool control will bring great potential for the green upgrading of the manufacturing industry [184]. The energy consumption model of machine tools based on an adaptive optimization algorithm will help to improve the energy consumption performance of machine tools and realize sustainable development [185]. In addition, life cycle energy consumption evaluation based on process detection helps to optimize the energy consumption of machine tools. Process simulation technology is a virtualization technology supported by computer-aided technology and virtual reality technology, which helps establish virtual processing scenarios for research and optimization of product processing methods [186]. Process simulation, process optimization technology, and energy-saving control of machine tools are usually combined to exert the greatest impact, which is also the focus of future research, especially in multi-objective optimization algorithms [187]. In addition, the sustainable upgrading of the manufacturing industry depends not only on the specific equipment, technology, and process. In the long term, government policies and enterprise-level technological innovation are also important factors.

• Policies and regulations

Environmental protection policy is one of the factors affecting the development of sustainable machining. Research on the rise in the electric bicycle industry in China found that the government has shaped the development track of disruptive innovation by either promoting or restricting relevant policies [188]. The implementation of much stricter environmental regulations has improved eco-efficiency and sustainability [189,190]. According to Porter’s hypothesis, appropriate environmental regulations promote company innovation, offset corporate losses, and enhance corporate competitiveness [191,192]. The role of the government in stimulating technological development entails both positive and negative effects. In formulating and implementing policies, the government should consider adopting existing technologies and new policies corresponding to the types of target technological innovations [193,194]. The panel data of 28 subsectors of the CMI from 2003 to 2013 showed that the current level of environmental supervision is insufficient to improve ecological efficiency [195]. On the basis of the execution of environmental laws to improve the dissemination of sustainable technological innovations in Chinese manufacturing companies, a tripartite evolutionary model can be constructed. Furthermore, the analysis and simulation of local stability found that environmental supervision implemented by the government is beneficial to the sustainable technological innovation of manufacturing enterprises. When government supervision reaches a certain level, the systems of manufacturing companies, innovation providers, and potential demand-oriented companies will likely gravitate toward the long evolutionary process and actively promote the diffusion of sustainable technological innovation [196,197]. The more perfect the environmental supervision is, the better the development of sustainable technological innovation. The data on China from 2010 to 2017 established that environmental policy tools at the national level generally could not provide sufficient impetus for sustainable technological innovation. The development of sustainable technological innovation is influenced not only by different environmental policy tools but also by regional factors. Sustainable technological innovation can be guided by formulating a comprehensive and differentiated environmental policy system while rationally adjusting the intensity of various types of environmental policy measures [198].

• Sustainable technological innovation

Innovation in advanced manufacturing is required because sustainable technologies can ensure the sustainability of future manufacturing systems [199–201]. The impact of advanced manufacturing technology (AMT) on sustainable innovation was explored, and the results showed that AMT contributes to the performance and sustainable innovation of companies [202,203]. For enterprises, the success factors for sustainable innovation include technical preparation, organizational preparation, and environmental preparation [204]. Research on a sample of A-share listed manufacturing companies in China from 2011 to 2017 showed a significant spatial correlation between regional innovation capability and sustainable technology manufacturing efficiency in addition to their spatially heterogeneous boundaries [205]. Take Jiangsu province as an example. The government should emphasize the macrocontrol and supervision of manufacturing sustainable technologies, optimization of environmental management, improved incentives for innovative green talent, and strengthened research on sustainable technology [206]. The essence of the sustainable transformation of the manufacturing industry is to establish a sustainable manufacturing system, and sustainable technological innovation is the foundation of the development of the whole sustainable manufacturing system [207,208]. Furthermore, incentives and strength selection both positively influence sustainable technological innovation [209]. In sustainable manufacturing, associated R&D has higher efficiency than independent R&D [210]. In the innovation-driven context, sustainable manufacturing technological innovation is an important support mechanism for upgrading the CMI. The "Made in China 2025" strategy has been proposed as a long-term plan to encourage technological innovation in sustainable manufacturing [211]. The industry classification standard of the value-added trade database was used to integrate the CMI from 2006 to 2015. The empirical results further showed that the rise in the global value chain position can significantly promote sustainable technology innovation efficiency. The aforementioned research results have provided some management inspiration for the manufacturing industry in developing countries and have even fostered a new impetus for sustainable economic growth [212].

7 Conclusions

This study expounds on the necessity of sustainably upgrading the manufacturing industry, establishes the concept of sustainable processing, comprehensively reviews sustainable processing, identifies the current processing technologies with sustainable development potential, and offers relevant development suggestions. The following concluding remarks can be inferred from the extensive review:

(1) New technologies and equipment can promote the development of sustainable machining. Research on the sustainable development of machine tools mainly focuses on three aspects: lightweight components, motor energy-saving optimization, and hydraulic component energy-saving optimization. For some difficult-to-machine materials, alloy and cermet cutting tools offer good cutting and environmental performance. Nanofluid cutting fluids, water-based cutting fluids, and vegetable oil-based cutting fluids are the development directions of green cutting fluids.

(2) The current study on promising sustainable machining processes includes dry cutting, minimal quantity lubrication, microcutting, cryogenic cutting, and multidirectional cutting. Without the use of cutting fluids, self-lubricating FGCC cutting tools can be used for product processing to realize dry machining. When cutting fluid is regarded as a necessity, minimal quantity lubrication can reduce environmental pollution and manufacturing costs. Microcutting mainly includes micromilling, microlinear cutting, and laser microcutting. Nonetheless, the control of laser sawing power and heat-affected zones remains challenging. In contrast to traditional dry and wet machining, cryogenic cutting has the advantages of a small cutting force, low cutting temperature, and long tool life. Multidirectional cutting has no zero return, and it can save turning time, improve production efficiency, and contribute to a flexible and diverse turning path.

(3) Strategies for sustainable machining include the energy-saving control of machine tools, processing simulation, and process optimization. The energy-saving control of machine tools can improve energy efficiency and machining efficiency, including the start–stop and acceleration control of spindles, which requires the monitoring system of machine tools to consume energy. Process simulation technology is a virtualization technology supported by computer-aided technology, improving the processing efficiency and optimizing the mechanical production structure. Process optimization focuses on the relationship between machining parameters, energy efficiency, and machining quality, with the aim of achieving the optimal solution. Two of the most important steps are modeling and solving.

(4) Policy and sustainable technological innovation

affect the development of sustainable machining. The government should establish and improve sustainable machining supervision, support policies and regulations, and support the development and application of sustainable machining. Meanwhile, manufacturing enterprises should vigorously identify and develop sustainable processes and equipment for the machining process and strengthen international cooperation.

With regard to suggestions for the future, more research on advanced sustainable manufacturing technologies is needed to attract the global manufacturing industry to adopt clean manufacturing. As the goal of future research, not only should energy consumption be considered, but the sustainability of society, the environment, and the economy should also be evaluated. More research on the sustainability of the manufacturing industry that considers quantitative measures should be initiated.

Nomenclature

AMT	Advanced manufacturing technology
CMI	China's manufacturing industry
CNC	Computer numerical control
CRM	Critical raw materials
FGCC	Functionally graded cemented carbide
MOPSO	Multi-objective particle swarm optimization
MQL	Minimal quantity of lubricant
Mtce	Million tons of coal equivalent
PCBN	Polycrystalline cubic boron nitride
PVD	Physical vapor deposition
R&D	Research and development
RBR	Rule-based reasoning
RSM	Response surface method
TRC	Tool radius compensation
VMT	Virtual machine tool

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Conflict of Interest The authors declare that they have no conflict of interest.

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