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REVIEW **Open Access**

Towards Sustainable Grinding of Difficult-to-Cut Alloys—A Holistic Review and Trends

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Abstract

Grinding, a critical precision machining process for difficult-to-cut alloys, has undergone continual technological advancements to improve machining efficiency. However, the sustainability of this process is gaining heightened attention due to significant challenges associated with the substantial specific grinding energy and the extensive heat generated when working with difficult-to-cut alloys, renowned for their exceptional physical and mechanical properties. In response to these challenges, the widespread application of massive coolant in manufacturing industries to dissipate grinding heat has led to complex post-cleaning and disposal processes. This, in turn, has resulted in issues such as large energy consumption, a considerable carbon footprint, and concerns related to worker health and safety, which have become the main factors that restrict the development of grinding technology. This paper provides a holistic review of sustainability in grinding difficult-to-cut alloys, encompassing current trends and future directions. The examination extends to developing grinding technologies explicitly tailored for these alloys, comprehensively evaluating their sustainability performance. Additionally, the exploration delves into innovative sustainable technologies, such as heat pipe/oscillating heat pipe grinding wheels, minimum quantity lubrication, cryogenic cooling, and others. These groundbreaking technologies aim to reduce dependence on hazardous coolants, minimizing energy and resource consumption and carbon emissions associated with coolant-related or subsequent disposal processes. The essence of these technologies lies in their potential to revolutionize traditional grinding practices, presenting environmentally friendly alternatives. Finally, future development trends and research directions are put forward to pursue the current limitation of sustainable grinding for difficult-to-cut alloys. This paper can guide future research and development efforts toward more environmentally friendly grinding operations by understanding the current state of sustainable grinding and identifying emerging trends.

Keywords Grinding, Sustainability, Cooling, Energy consumption, Carbon footprint, Difficult-to-cut alloys

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1 Introduction

Sustainable grinding refers to using environmentally and socially responsible methods in grinding materials. Grinding is a mechanical process that involves the reduction of the size of particles or materials, often to create powders or finely ground substances [1, 2]. Sustainable grinding aims to minimize energy consumption during the process. This can be achieved using advanced technologies and equipment designed to operate more efficiently, reducing the overall energy requirements [3, 4]. Efforts are made to minimize waste generation during grinding operations. This includes optimizing the process parameters, such as grinding speed and feed rates, to maximize material utilization and reduce the generation of excess waste [5–7].

Grinding processes often require using coolant (e.g., emulsion) for cooling and lubrication. Sustainable grinding practices emphasize the efficient use of coolant and the implementation of coolant recycling systems to minimize water consumption and reduce the impact on local water resources [8, 9]. Grinding processes can produce airborne dust, pollutants, and particles that could harm the environment and human health [10]. Sustainable grinding uses efficient dust collection and filtration devices to capture and manage emissions for better air quality. Sustainable grinding takes into account the effects of the procedure on society. It involves advocating for fair labor policies throughout the supply chain and considering the health and safety of employees engaged in grinding operations [11, 12].

Overall, sustainable grinding aims to minimize the environmental footprint and social impacts of grinding processes while achieving the desired outcomes. It often involves the integration of advanced technologies, process optimization, and responsible resource management to achieve these goals [13].

Grinding difficult-to-cut alloys is critical in many industrial applications, including aerospace, automotive, and medical industries. However, this process has several challenges, including high energy consumption, a significant carbon footprint, and worker health and safety concerns [14]. As the world becomes increasingly aware of the need for sustainable practices, it is essential to explore ways to increase sustainability in grinding difficult-to-cut alloys.

This paper aims to provide a holistic review of sustainability in grinding difficult-to-cut alloys, including trends and future directions. The paper will focus on four key areas: energy consumption during grinding, carbon footprint, cost performance, and worker health and safety in grinding.

The first section of the paper will examine the energy consumption during grinding, including the factors that contribute to energy consumption and the potential solutions to reduce energy consumption. The second section will focus on the carbon footprint during grinding, including the environmental impact of grinding and the strategies to reduce the carbon footprint. The third section will explore the cost performance in grinding, including the economic benefits of sustainable grinding practices. Finally, the fourth section will examine worker health and safety in grinding, including the potential health hazards and measures to ensure worker safety.

By providing a comprehensive review of the current state of sustainability in the grinding of difficult-to-cut alloys, this paper aims to contribute to the development of sustainable grinding practices that can benefit both the industry and the environment. The paper will also identify the trends and future directions in sustainable grinding practices, providing insights for researchers and practitioners in the field.

Grinding processes play a pivotal role in the manufacturing industry, enabling the production of intricate components with precise dimensions and surface finish. However, the grinding of difficult-to-cut alloys presents unique challenges due to their inherent hardness, toughness, and resistance to material removal [15, 16]. The conventional approach to grinding these alloys involves high energy consumption, significant carbon emissions, and potential risks to worker health and safety [17]. There has been a growing emphasis on increasing sustainability in grinding difficult-to-cut alloys to address these concerns and strive for a more sustainable manufacturing approach.

Sustainable grinding of difficult-to-cut alloys encompasses a multidimensional perspective that considers the environmental, economic, and social aspects of the grinding process. It involves the application of innovative technologies, practices, and strategies to reduce energy consumption, minimize carbon footprint, optimize cost performance, enhance worker health and safety, and ensure efficient use of resources. By adopting sustainable grinding practices, manufacturers can mitigate the environmental impact of their operations, improve profitability, comply with regulatory standards, and contribute to a safer and healthier working environment.

One of the critical areas in achieving sustainability in grinding difficult-to-cut alloys is applying cooling and lubrication techniques. Cooling and lubrication are crucial in reducing friction, dissipating heat, and prolonging tool life during grinding operations. Traditionally, flood cooling with large quantities of water-based coolant has been widely employed. However, this approach presents several challenges, including high water consumption, potential coolant contamination, disposal issues, and adverse environmental effects [18, 19]. Therefore, there is a need to eliminate (or avoid) the use of coolant or explore alternative cooling and lubrication methods that can offer effective heat dissipation while minimizing the environmental impact [20, 21].

One such sustainable method is to transfer out grinding heat with high efficiency by passive thermal devices, such as heat pipes [22]. The grinding heat can be dissipated in time with the help of thermal devices instead of gathering in the grinding zone. Therefore, the grinding temperature can be controlled, and the usage of hazardous coolant can be significantly reduced or even avoided. Energy and resource consumption, carbon emission, and production costs can be reduced.

Another sustainable approach is the application of minimum quantity lubrication (MQL) in grinding processes. MQL involves using a small amount of lubricant, typically oil or a water-soluble substance, to reduce friction and dissipate heat [23]. The benefits of MQL include reduced coolant consumption, lower disposal costs, improved surface quality, and enhanced tool life [24]. Additionally, MQL can contribute to a healthier working environment by reducing worker exposure to hazardous aerosols and mists associated with conventional flood cooling.

Another emerging trend in sustainable grinding is the use of cryogenic cooling. Cryogenic cooling involves the application of liquid nitrogen or carbon dioxide as a cooling medium during grinding [25]. The extremely low temperatures achieved through cryogenic cooling can effectively control heat generation, reduce grinding forces, and enhance surface integrity. This approach offers advantages such as reduced energy consumption, improved tool life, and minimized environmental impact compared to traditional cooling methods. However, cryogenic cooling also poses challenges related to equipment cost, handling of cryogenic fluids, and potential surface damage due to thermal shock [26].

Various metrics and indicators have been developed to assess the sustainability performance of grinding processes. These metrics encompass factors such as energy consumption, carbon dioxide (CO_2) emissions, and cost performance. Energy consumption in grinding is a significant concern due to its direct impact on the carbon footprint and operating costs [27, 28]. Manufacturers can reduce their environmental impact and improve their bottom line by optimizing energy usage through efficient process parameters, tool design, and equipment selection. Carbon footprint assessments evaluate the total greenhouse gas emissions associated with grinding operations, considering factors such as electricity usage, coolant consumption, and transportation [29]. By quantifying and monitoring carbon emissions, manufacturers can identify areas for improvement and implement strategies to mitigate their environmental impact.

Cost performance assessments in grinding focus on analyzing the economic efficiency of the process. Factors such as tool wear, productivity, labor costs, and maintenance expenses are considered to evaluate the overall cost-effectiveness of grinding operations [30]. Sustainable grinding practices aim to minimize costs while maintaining or improving process performance and product quality. This involves optimizing parameters such as grinding speed, feed rate, and depth of cut and exploring cost-efficient cooling and lubrication techniques.

Other factors connected to sustainability in grinding hard-to-cut alloys include waste management, resource use, and social responsibility. These factors include energy consumption, carbon footprint, and cost performance. Aiming to reduce the production of grinding waste, maximize recycling and reuse, and ensure correct disposal of hazardous materials are effective waste management techniques. The optimal use of energy, raw materials, and consumables during the grinding process is the emphasis on resource utilization. Creating a safe and healthy work environment, guaranteeing compliance with laws, and fostering moral behavior within the manufacturing sector are all examples of social responsibility.

In conclusion, achieving sustainability in grinding difficult-to-cut alloys is a multidimensional challenge that requires a holistic approach. This paper aims to comprehensively review and analyze the various aspects of sustainable grinding practices. It explores the application of cooling and lubrication techniques, examines sustainability metrics such as cost, energy consumption, and CO_2 emissions, and discusses other relevant considerations. By understanding the current state of sustainable grinding and identifying emerging trends, manufacturers and researchers can work towards enhancing the sustainability of grinding operations, reducing environmental impact, and promoting a more responsible and efficient manufacturing industry.

2 Scope and Objective of the Research

The scope of this paper is to explore the various aspects related to sustainability in the context of grinding processes for difficult-to-cut alloys. The paper aims to provide a comprehensive understanding of the challenges and opportunities associated with enhancing sustainability in grinding operations and to highlight the emerging trends in this field.

The development of grinding technologies with increasing material removal rate is first summarized, and responding changes of the specific energy are focused. The sustainability aspects of grinding processes are also concentrated on. It specifically addresses the following key areas:

- Energy consumption during grinding: The paper examines the energy consumption patterns associated with grinding operations for difficult-to-cut alloys. It explores the energy-intensive nature of grinding processes and discusses strategies for optimizing energy usage. Various energy-efficient technologies and approaches to reduce energy consumption in grinding are reviewed, considering their impact on sustainability.
- Carbon footprint during grinding: This section investigates the carbon footprint of grinding processes, considering the emissions generated during the production and operation stages. The paper explores the environmental impact of grinding operations for difficult-to-cut alloys and discusses potential mitigation measures to reduce carbon emissions. It examines sustainable practices and technologies that can minimize the carbon footprint of grinding processes.
- Cost performance in grinding: This section delves into the economic aspects of grinding difficult-to-cut alloys, focusing on the cost performance of these processes. It explores the factors contributing to the overall cost of grinding operations and analyzes the potential cost savings through sustainable practices. The paper discusses strategies for optimizing cost efficiency while maintaining sustainable grinding practices.
- Worker health and safety in grinding: The paper also considers the crucial aspect of worker health and safety in grinding operations. It examines the potential health hazards associated with grinding difficult-to-cut alloys, such as exposure to hazardous substances and ergonomic issues. The focus is on sustainable measures and technologies that can enhance worker safety and well-being, including using safer abrasive materials and efficient ventilation systems.
- Cooling lubrication application in grinding: This section provides a detailed exploration of the cooling lubrication techniques employed when grinding difficult-to-cut alloys. It discusses the importance of effective cooling and lubrication in achieving sustainable grinding practices. The paper reviews various cooling lubrication methods, such as minimum quantity lubrication (MQL) and cryogenic cooling, highlighting their benefits, challenges, and potential for improving sustainability in grinding.

The scope of this paper explicitly excludes the analysis of machinability factors like cutting forces, temperature, and surface quality, as the primary focus lies on the sustainability aspects of grinding operations. However, a brief understanding of these factors may be provided to provide context and establish the relevance of sustainability improvements.

By comprehensively addressing the above-mentioned aspects, this paper offers a holistic review of sustainability in grinding processes for difficult-to-cut alloys. It strives to contribute to the knowledge and understanding of sustainable practices in the field and also identifies the emerging trends that can guide future research and development efforts towards more sustainable and environmentally friendly grinding operations. Driven by the gradual evolution of grinding technology towards enhancing efficiency and quality and paralleled by a gradual rise in awareness regarding grinding sustainability, new theories, technologies, and equipment have gradually emerged. This paper first reviews the development of grinding technologies for difficult-to-cut alloys in Section 3. The sustainability performance of grinding is summarized in Section 4. The new technologies, such as heat pipe (or oscillating heat pipe) grinding wheels, minimum quantity lubrication, cryogenic cooling, process optimization, focus on decreasing hazardous coolant, coolant-related energy, and resource consumption and are reviewed in Section 5. The logic of this paper is shown in Figure 1.

3 Grinding of Difficult-to-Cut Alloys

3.1 Development of Grinding Techniques

Grinding is the most commonly used technology in abrasive machining and one of the most critical technologies for precision manufacturing difficult-to-cut alloys such as superalloys [2, 15, 31] and titanium alloys [32, 33] with high strength. It is meaningful to study and improve the sustainability of grinding technology.

Grinding depends on the randomly distributed grains on the grinding wheel to remove materials [34–36]. The grains have undefined cutting edges with negative rake angles. The chip formation is generated by the non-continuous contact between the workpiece and grains with relatively high velocity [37]. In this case, the material removal progress includes robbing (elastic deformation), ploughing, and cutting (chip formation), which results in relatively high specific energy. For example, the specific energy of hard turning of 4319 steel with 60 HRC is under 10 J/mm^3, while the specific energy of grinding the same material ranges from 40 to 90 J/mm^3 [38]. In addition, the useful energy is only consumed in the cutting period, and the robbing and ploughing periods "waste" a large proportion of energy [39, 40]. The specific grinding energy is defined as Eq. (1) [15]:

$$e_{\mathrm{s}} = \frac{F_{\mathrm{t}} \cdot v_{\mathrm{s}}}{v_{\mathrm{w}} \cdot a_{\mathrm{p}} \cdot b}, \tag{1}$$

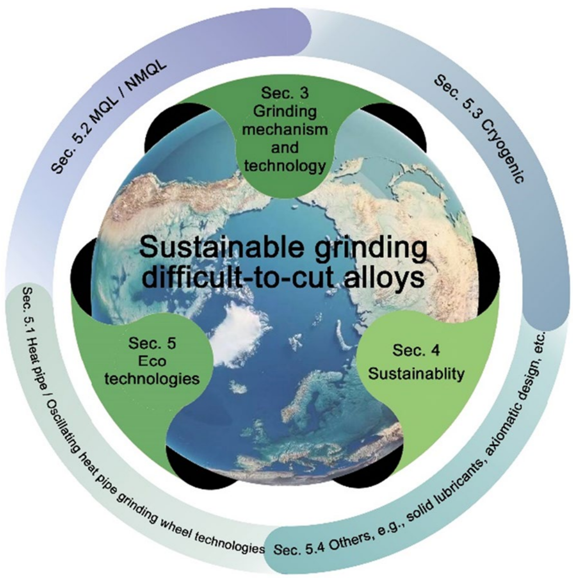

Figure 1 The logic of this review

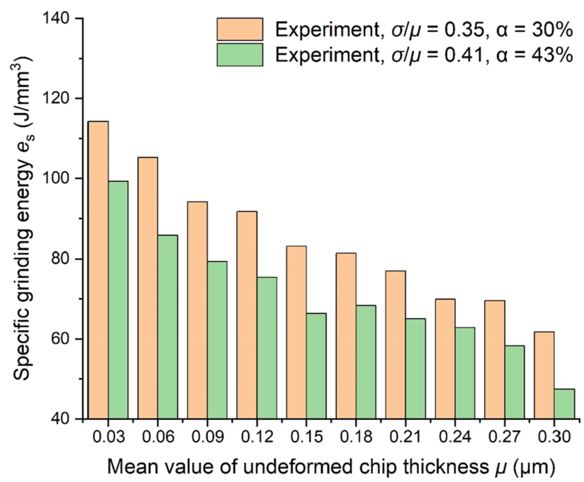

Figure 2 Effect of the undeformed chip thickness on specific grinding energy

where e_s is the specific energy, F_t is the tangential grinding force, v_w is the feed rate, a_p is the depth of cut, and b is the width of the grinding wheel. It is clear that the grinding parameters significantly impact the specific energy, and in turn, the grinding parameters affect the sustainability of grinding.

As mentioned above, the grinding parameters include grinding speed (v_s), feed rate (v_w), depth of cut (a_p), and width of grinding (b). The combination of grinding parameters distinguishes grinding into four types, i.e., conventional grinding, high-speed grinding, creep feed grinding, and high-performance grinding. The productivity (or material removal rate, MRR, Q'_w) of grinding has something to do with the feed rate and depth of cut instead of grinding speed, $Q'_w = v_w \cdot a_p$. While the grinding speed affects the chip thickness, a large grinding speed results in a thin chip thickness, leading to higher specific energy, as shown in Figure 2 [34].

Conventional grinding has a low material removal rate and grinding speed. When increasing the grinding speed, the high-speed grinding also has a relatively low material removal rate. Based on the maximum undeformed chip thickness relationship (Eq. (2)) [15, 41], since the grinding speed is increased, the grinding force and chip thickness reduce, and the accuracy and surface roughness also improve.

$$a_{g\,\max} = \sqrt{\frac{4v_w}{v_s N_d C}\sqrt{\frac{a_p}{d_s}}}, \tag{2}$$

where $a_{g\max}$ is the maximum undeformed chip thickness, N_d is the active cutting point, and C is a constant related to the shape of grains. In addition, the high grinding speed leads to a higher rotating wheel speed and a thicker air barrier layer [42]; the coolant is more difficult to fully enter the contact zone between the workpiece and wheel to lubricate and cool effectively. As a result, thermal damage can occur [43, 44]. The cooling pressure and flow rate are usually increased, with more energy and resource consumption [45].

Based on Eq. (2), creep feed grinding (CFG) is introduced, which can have a high material removal rate with a low grinding speed [46, 47]. For example, the maximum undeformed chip thickness can be unchanged when doubling the depth of cut and decreasing the feed rate by around 30% (by $(1-\sqrt{2}/2)$ times). The material removal rate can increase by approximately 41% (by $(\sqrt{2}-1)$ times). Besides, the proportion of energy transferring to the workpiece as heat for CFG accounts for under 10%, and 70%–80% of energy dissipates into the coolant. On the contrary, for conventional grinding, around 90% of energy enters the workpiece [48, 49]. In this case, the grinding temperature for CFG is usually under 150 °C, and a better surface quality is achieved [50]. The large depth of cut increases the closure degree of the CFG, coolant is challenging to enter the contact zone, and it is easy to have a film-boiling that fails to control the temperature [51, 52]. As a result, a high-pressure jet cooling technique is commonly used to replace flood cooling. The pressure of the coolant jet can reach 2 MPa with a flow rate of 200 L/min, which consumes more energy and resources.

When further increasing the grinding speed, there is high-performance grinding (also called high-efficiency deep grinding, HEDG) with high material removal rate and grinding speed [53]. High-performance grinding combines the advantages of high-speed grinding and creep feed grinding. The proportion of energy taken by robbing and ploughing is much lower than that of cutting. Consequently, the specific energy is relatively low [54]. For example, the specific energy of CFG varies from 10 to 100 J/mm^3, and the specific energy of high-performance grinding ranges from 7 to 20 J/mm^3 [55]. The four types of grinding can be seen in Figure 3.

Increasing the material removal rate by changing the grinding strategies and parameters can decrease the specific energy, as shown in Figure 4 [56]. When the material removal rate increases from 0.1 to 5 mm^3/mm·s, the specific energy can drop dramatically from around 1700 to nearly 300 J/mm^3. And continuing to enhance the MRR even up to 70, the specific energy remains stable between 100 and 200 J/mm^3 (see Figure 4).

3.2 Material Removal Mechanism

The abrasive grains on the grinding wheel removing difficult-to-cut materials experience three stages, i.e., material rubbing, ploughing, and cutting [57]. In the rubbing stage, the abrasive grain starts to contact the workpiece, the depth of cut is nearly zero, and only elastic deformation occurs. There is currently no material removal in this instance. When ploughing, the applied tension exceeds the material's yield limit as the depth of cut increases, causing plastic deformation of the material. Along the grinding groove, the material begins to flow to the two sides perpendicular to the infeed direction.

Additionally, there is no material removal at this step. Chips form and slide along the rake face of the abrasive grains as they cut deeper because the force exceeds the material's ultimate strength. Now the grinding process

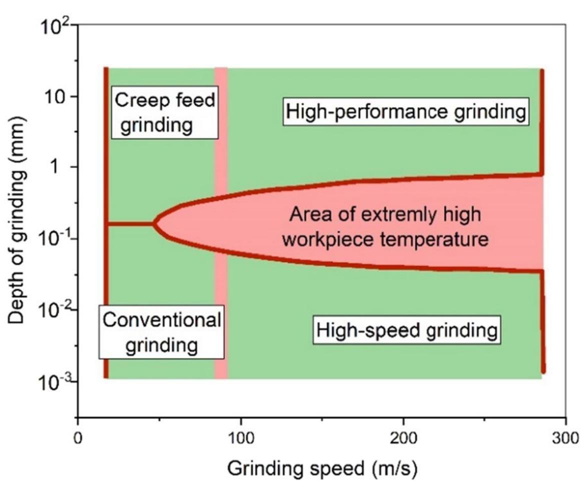

Figure 3 Four types of grinding

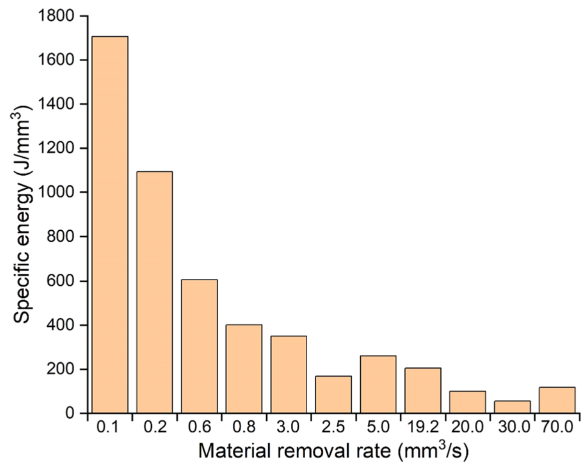

Figure 4 Specific energy under different MRR

of single grain enters the cutting stage, and material is removed [58], as shown in Figure 5. Therefore, at the stages of rubbing and ploughing, the consumed energy is not used to remove material, in other words, it is non-effective energy in the grinding and should be decreased. In comparison, the energy consumed at the stage cutting removes the material. The greater the proportion of cutting in the three stages, the lower the energy consumption of grinding processes.

It is essential to decrease the proportion of rubbing and ploughing stages and their energy consumption. In this case, the critical thickness of chip formation (i.e., the minimum depth of cut of abrasive grains to form chips) is significant, particularly the influence of grinding speed on the critical thickness of chip formation. A novel material removal experiment method by single grain grinding of difficult-to-cut materials is proposed by Tian et al. to investigate the effect of grinding speed on the critical thickness of chip formation deeply [40]. The workpiece is ground by single grain twice to generate the material removal process maintaining the rubbing, ploughing, and cutting stages, as shown in Figure 6.

As for Inconel 718 superalloy, with the increase of grinding speed from 20 m/s to 100 m/s, the critical thickness of chip formation decreases from 1.4 μm to the smallest 0.6 μm. And when the grinding speed rises to 165 m/s, the critical thickness of chip formation increases to 1.5 μm [40]. This results from competition between the strength effect of strain rate and the thermal softening effect [59]. When the critical thickness of chip formation is lower, it is easier to form the chip and remove materials; as a result, more consumed energy is used to remove material, and less energy is wasted in the rubbing and ploughing stages.

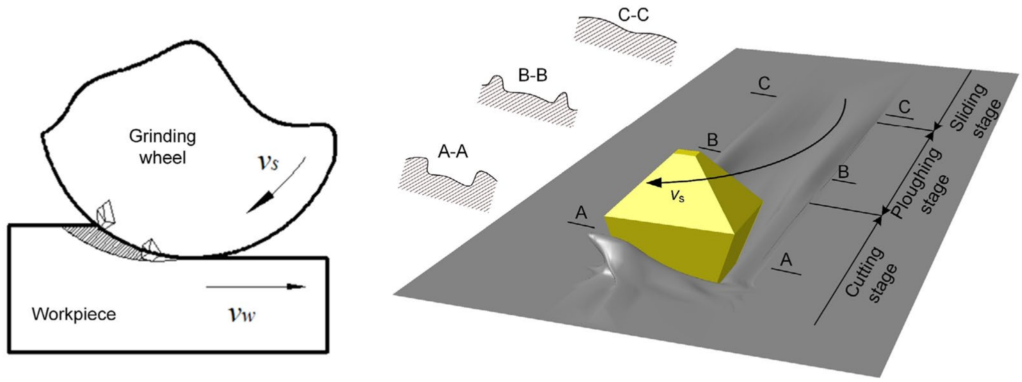

Figure 5 The three stages of single grain grinding process

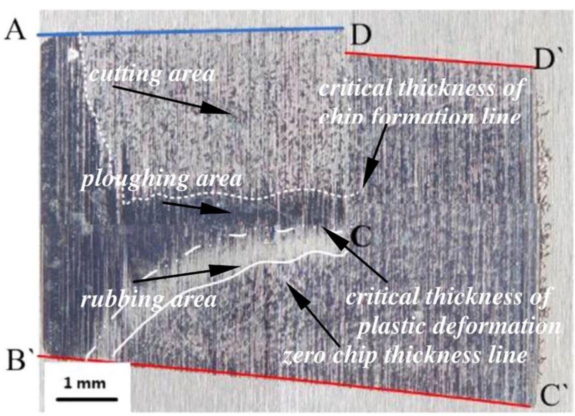

Figure 6 The novel material removal experiment method by twice single grain grinding [40]

In addition, the specific grinding energy decreases when the undeformed chip thickness of grinding increases [15, 37]. In other words, with an optimal combination of grinding parameters (i.e., grinding speed, feed rate, and depth of cut), the consumed energy by removing unit material can be reduced.

3.3 Grinding Wheel and Its Dressing

The grinding wheels are generally divided into two parts, conventional and superabrasive. The conventional grinding wheels are entirely made of abrasive materials, including silicon carbide, alumina, or sol-gel corundum. The superabrasive grinding wheel consists of a wheel body, bond, and superabrasives, e.g., diamond or cubic boron nitride (CBN) [60].

The energy involved in the fabrication of conventional grinding wheels is about 450 MJ, of which 49% is used to fabricate the grain materials, and 42% is used to sinter the grain and bond materials [13]. When the conventional grinding wheel is worn out, it is difficult to recycle and should be disposed of, which may take more energy [54]. However, the manufacturing of a superabrasive wheel takes over 1200 MJ energy, while the embodied energy in the body material and machining energy for body material account for 16% of total energy, respectively, and the energy for bond and grains takes only 12% of total energy [13], as shown in Figure 7. In addition, the superabrasive wheel can be reused when the working layer wears out [54]. Its lifetime can increase over 1000 times that of the conventional wheel [61]. Therefore, the superabrasive wheel generally consumes less energy than the conventional wheel, but the cost is higher now, restricting its application in industries.

As the grinding wheel removes materials, it gradually wears, in particular for difficult-to-cut materials such as superalloys or titanium alloys. The machining cost index mainly caused by tool wear of superalloys and titanium alloys are 3.4 and 5.1. In comparison, aluminum alloy has a machining cost index as low as 0.4 [62]. As the grinding wheel wears out, the grinding forces and temperature gradually increase, and more importantly, the consumed grinding power rises, which means the grinding takes more and more energy due to the lower grindability of a blunt wheel. Therefore, it is necessary to dress the grinding wheel to maintain its sharpness, keep the grinding power as low as possible, and have a good surface quality [63].

The dressing of grinding wheels includes dressing depth, feed rate, stroke numbers, etc. The dressing circumstances determine the wheel quality (sharpness, roundness, run-out, surface patterns, etc.) and dressing time. Despite increasing production time and decreasing product efficiency, the dressing process is crucial for reducing grinding energy consumption and maintaining acceptable grinding quality [13]. Therefore, it is important to optimize the dressing parameters to improve the effectiveness and quality of the dressing.

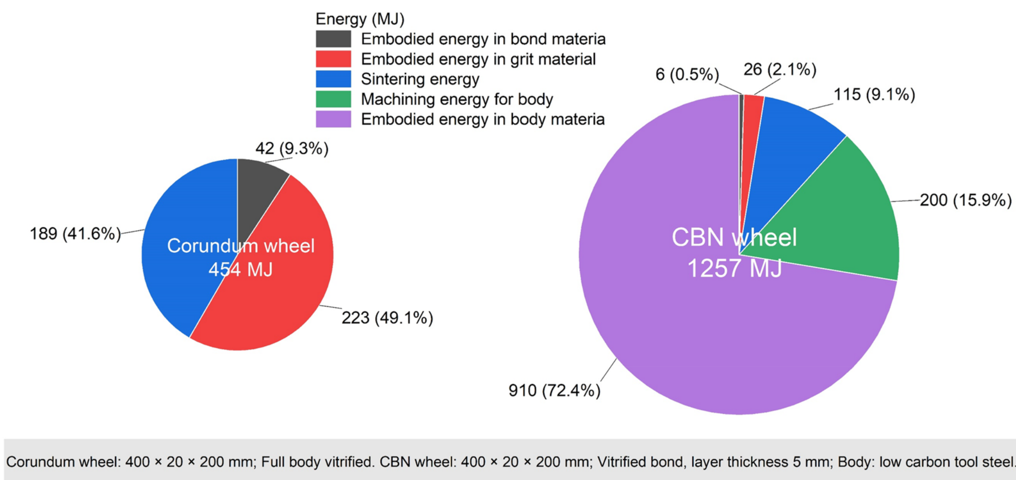

Figure 7 Energy consumption in wheel fabrication

3.4 Cooling Conditions for Grinding

The cooling and lubrication brought about by applying coolant are important in grinding difficult-to-cut alloys. The main functions of the coolant include reducing heat generation, dissipating massive heat, cooling the workpiece and wheel, removing chips and cleaning wheels, and corrosion protection of machine tools, etc., [18].

The coolant can generally be divided into oil-based and water-based cooling fluids. Water-based cooling fluids have a good heat capacity and cooling effect, while oil-based cooling fluids have a good lubrication ability [45]. Because of the superimposition of the cooling and lubrication of cooling fluids, it is difficult to clearly classify the advantages of cooling fluids, and the application of cooling fluids depends on the grinding requirement [13, 45].

In addition, when grinding difficult-to-cut alloys, mass heat will be generated. The instinct study is to deliver the cooling fluid into the contact zone directly and efficiently. The geometry of the nozzle for supplying cooling fluid is optimized. Novel round or shoe-shaped nozzles and multi-nozzle systems are proposed to gather the cooling jet and efficiently deliver the cooling fluid to the grinding zone [64–67]. Besides, the closer the nozzle is to the grinding wheel, the better the cooling effect on the grinding zone. In this way, even with a low-pressure cooling fluid supply and low coolant outlet speed, the cooling effect on the grinding zone can be guaranteed due to the large contact area between the coolant and the grinding wheel surface and the good wetting effect of the coolant on the grinding wheel surface [45].

The high-speed rotation of the grinding wheel can bring about an air barrier around the wheel which prevents the cooling fluid from entering the grinding zone. The speed of the coolant jet is brought up to 300 m/s. In this case, the coolant has sufficient pressure to break through the air barrier and enter the grinding zone for good lubrication and cooling effects [68]. In addition, an air scrapper is developed to break down the air barrier. Thus, the cooling fluid can enter the grinding zone more efficiently, even at low jet speed [64, 69].

The efficiency of using external jets to deliver coolant into the grinding zone is relatively low, and to make more coolant enter the grinding zone, internal cooling by the grinding wheel is proposed. The grinding wheel is specially designed with cooling channels, and the cooling fluid can be supplied through the channels directly from the wheel to the grinding zone [70–72] (Figure 8). The grinding wheel with internal cooling channels can improve the efficiency of coolant entering the grinding zone to some extent. However, high pressure, jet speed, and coolant consumption are still required for the coolant to break through the air barrier, particularly with higher grinding speed.

The essence of the above methods, whether external jet or internal cooling by the grinding wheel, is to send as much coolant as possible into the grinding zone. The supplied coolant in the grinding zone transfers grinding heat to prevent the coolant from film-boiling. These methods fail to consider the actual efficiency of coolant utilization but simply increase the amount of coolant and jet flow rate. Some studies have shown that only 5%–17% of the coolant can enter the grinding zone [74]. These techniques employ the coolant to transport heat away from the grinding zone and raise the fraction of heat allotted to it from a heat transfer perspective. The improved heat transfer process of coolant is unstable and challenging to successfully control, and the cooling effect of coolant depends on the kind of grinding, the condition of the

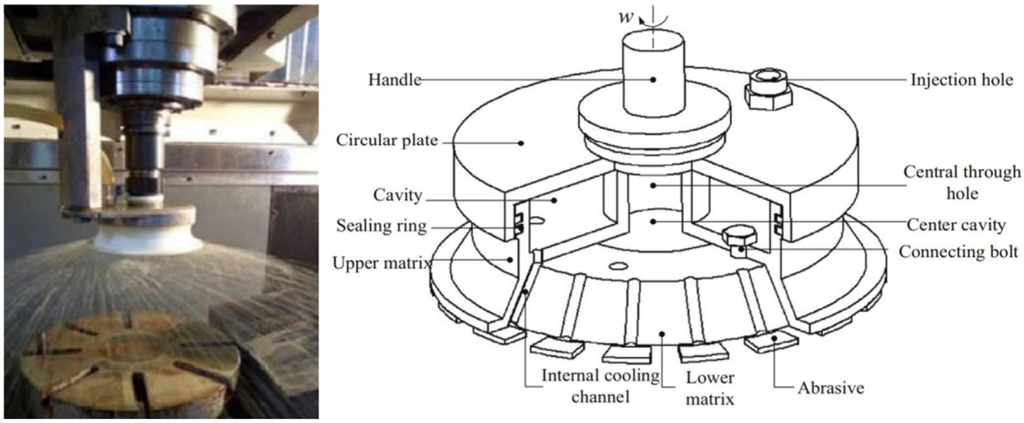

Figure 8 Illustration of internal cooling grinding wheel [73]

grinding wheel, the material of the workpiece, and the coolant supply. Additionally, the rapid and intense application of coolant results in a rise in resource and energy consumption as well as carbon emissions. For instance, in accordance with Zhao et al. [31], when HEDG of DZ125 superalloy with electroplated CBN wheel, with the increase of coolant jet speed from 20 to 45 m/s and increment of grinding speed from 30 to 150 m/s, the power consumed by grinding ranges from 1.1 to 1.2 kW; while the power consumed by coolant delivery rises from 0.2 up to 7.8 kW, 5.5 times higher than the grinding power; and the power lost caused by the coolant increases from 0.2 up to 3.2 kW, 1.7 times higher than the grinding power, as illustrated in Figure 9.

4 Sustainability Performance of Grinding

Nowadays, environmental concerns and the search for environmentally friendly techniques have contributed to industrial development toward sustainability. Production without social and environmental impact is one of the main goals of engineering research. Grinding is an essential technology used for difficult-to-machine alloys. Still, the process consumes more energy and generates more waste than other processes, such as turning and milling, as it typically requires powerful grinding spindle drive and cooling technologies as well as elaborate auxiliary processes such as grinding fluid processing and mist collection, as shown in Figure 10. Besides, the reuse and disposal of the lubricant impose severe environmental impact and can cause an inevitable consumption process of energy and resources. Therefore, issues such as energy consumption, carbon footprint, cost performance, and worker health and safety should be considered during processing.

4.1 Energy Consumption during Grinding

Based on the machining processing sequence, the energy consumption of machine tools is usually categorized into three different modes: idle mode, run-time mode, and production mode. Abundant research has been performed to analyze the energy consumption in the three modes. Drake et al. verified that both the start-up process

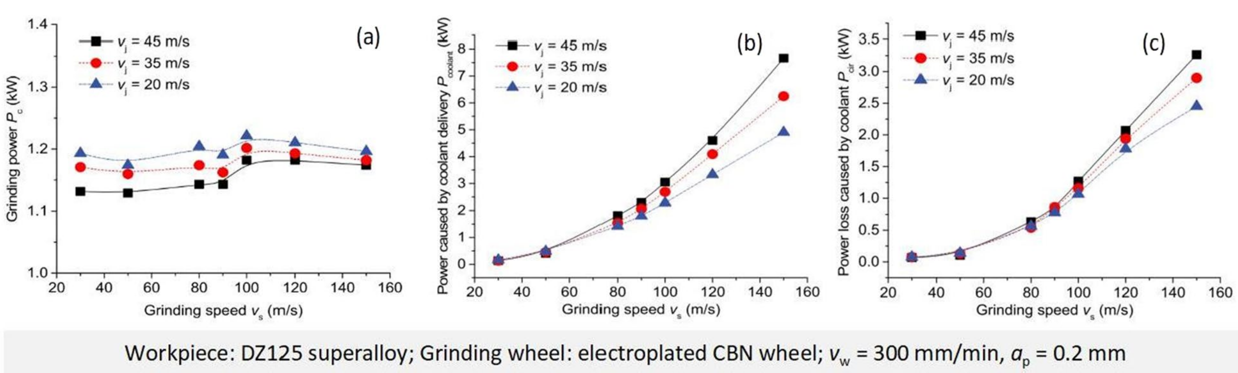

Figure 9 The electrical power consumed during grinding: (**a**) Grinding power, (**b**) Power caused by coolant delivery, and (**c**) Power loss caused by coolant

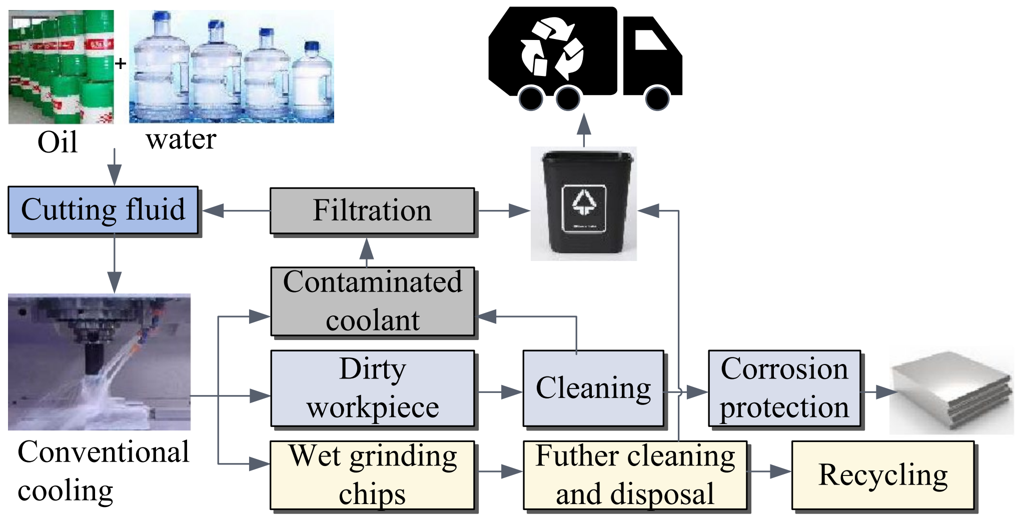

Figure 10 Process of coolant lubrication disposal

and the idle mode of the machine consume a significant amount of energy [75]. Mouzon et al. proposed a methodology to minimize energy consumption and the total completion time of manufacturing by optimizing the production scheduling objectives [76]. Since processing time is a critical factor influencing the energy demand of machine tools, Diaz et al. proved that increasing the material removal rates by a higher cutting speed would decrease processing time, thus reducing the overall energy consumption [77].

Ding et al. categorized energy consumption into four parts. Firstly, a significant amount of energy consumption is caused by material removal related to the grinding force and the grinding parameters such as wheel speed, workpiece speed, and depth of cut. The second part of energy consumption is the essential energy consumed due to the coolant pump, lubricant pump, and electric cabinet. The third part is frequency-converted energy consumption, which refers to the energy consumption of the grinding wheel motor and guide wheel motor in no-load. The fourth part is the response energy consumption, which includes additional guide wheel drive motor power load caused by the tangential friction force between the workpiece and the guide wheel. According to research by Ding et al. [78], the proportion of the mentioned energy consumption was analyzed by the related CO_2 emissions, as shown in Figure 11, in which cylindrical workpieces with a diameter of 20 mm are ground in MK 1080 centerless grinding machine. The workpieces were made of 45-gauge steel, and the depth of cut is 0.2 mm. Material removal accounts for the most significant energy consumption, about 56%. The frequency-converted energy consumption, the primary energy consumption, and the response energy consumption are about 35%, 8%, and 1%, respectively. Although the concrete value should be related to the machine loads, it can still indicate that the grinding process consumes more specific energy, which is also confirmed by Feng et al. [79]. The results from their research show that the minimum specific energies are much larger than the corresponding melting energy because of sliding, ploughing, and the influence of the high strain rate effect. The specific energy increases with the rise of the wheel velocity for creep-feed grinding. With the increased depth of cut between abrasive grits and workpieces, the energy consumption is increased due to more chip formation.

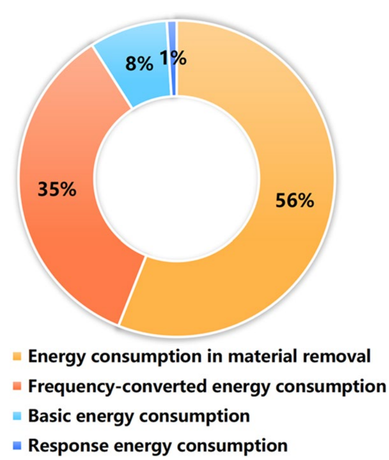

Figure 11 Quantitative analysis results of proportion for energy consumption

4.2 Carbon Footprint during Grinding

Nowadays, global warming is extensively discussed as one of the most critical global issues. Low carbon manufacturing that produces low carbon emissions intensity and uses energy and resources efficiently and effectively during the process has been extensively concerned.

Carbon footprint (C) is closely related to each process of energy consumption (E), and it also exists during the processes of resource utilization (R) and waste disposal (W). Hence, a generic ERWC approach was applied by Ding et al. [78] to quantitatively analyze the equivalent carbon dioxide emission in the grinding process. The proportion of each part can be further summarized as shown in Figure 12. We can see that about 50% of the carbon footprint is generated by energy, in which 56% is generated during material removal. Besides, 48% of the carbon emission is induced by resource utilization, in which the usage of grinding wheel, grinding fluid, and lubricant oil are considered. Waste disposal produces a carbon emission of about 2% concerning workpiece disposal.

4.3 Cost Performance in Grinding

Cost performance is another essential factor that should be considered in grinding. Optimization of the grinding process is usually carried out based on minimizing the grinding time and maximizing the volume of material removal rate. Previous studies have established and solved optimal problems with different objective functions and sets of variables in specific applications. The primary variables that have been considered are wheel parameters, machine parameters, grinding parameters, and dressing parameters. The grinding process takes into account its time and cost goals. According to Pi et al.'s regression formula, which can reduce both the cost and the time of grinding, the ideal grinding diameter can be determined [80]. In their investigation of the ideal replacement wheel diameter for internal grinding stainless steel, Tran et al. concluded that the ideal value would result in the lowest possible grinding expense [81]. To identify the ideal exchanged grinding wheel diameter based on the grinding process parameters, optimization of the grinding cost in external cylindrical grinding was also researched [82]. Recently, a study has been carried out on optimizing grinding parameters for minimum grinding time when grinding tablet punches by a CBN wheel on a CNC machine. The influences of the grinding parameters, such as the depth of cut, the feed rate, and the grinding speed, are discussed, and optimal conditions are found to ensure the least grinding time [83].

The economic cost performance is usually caused by the machine purchase, space costs, energy costs, repairs and maintenance costs, compressed air costs, and capital commitment costs. The proportion of these parts considered in machining is reported in Yoon's research, as shown in Figure 13, in which the energy costs account for about 17% [84]. Besides, the grinding process involves a lot of heat generation. Cooling fluids are usually employed in grinding to provide lubrication and cooling action. Therefore, the cost caused by the acquisition, storage, and maintenance of fluids cannot be ignored. According to Ramesh, the portion might be 7%–17% of the total machining cost [85]. Moreover, since most cutting fluids are not biodegradable, strict processes such as filtration, cleaning, and separation of chemical residues should be executed before discard. In this way, as reported by Shokrani et al., the costs of the subsequent process might be up to four times the cost of the cooling fluid itself [86].

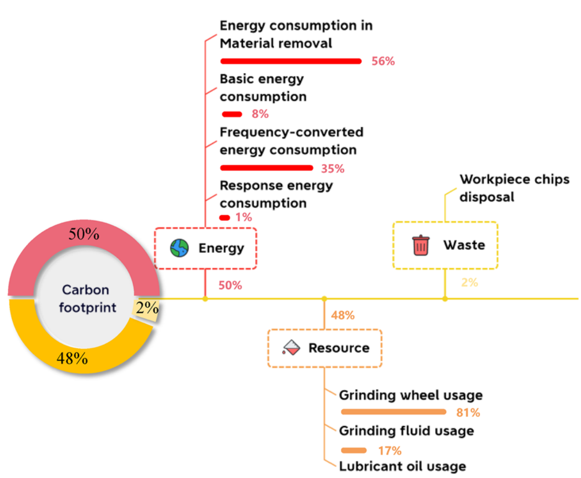

Figure 12 Quantitative analysis results for the proportion of factors influencing equivalent CO_2 emissions

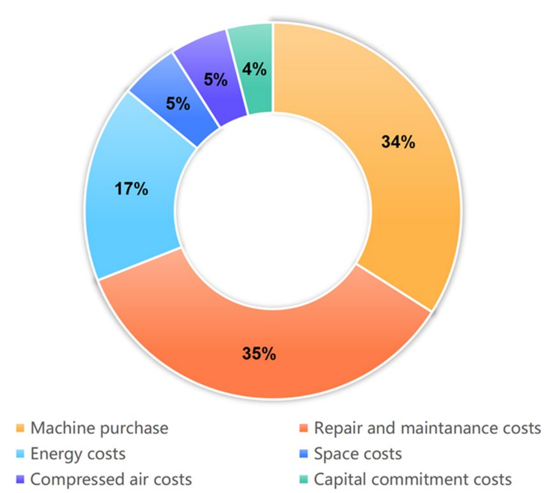

Figure 13 Total cost of ownership for a production machine

4.4 Worker Health and Safety in Grinding

Besides the high costs that the cooling fluid might cause, another disadvantage is the hazard to workers' health and the environment. During machining, machine operators and persons close to the process come in contact with cutting fluids through liquid form or mist, which can be touched and inhaled. So, additives, biocides, allergenic metals, and other toxic substances in contact with the skin may cause damage related to respiratory problems, dermatitis, and cancer [87]. Currently, 85% of the cutting fluids used in the industry have petroleum-derived oil in their composition, which may cause skin cancer, according to the International Agency for Research on Cancer (IARC) [88]. The sum of the above factors listed corroborates that 80% of the cases of occupational skin diseases worldwide are caused by contact with cooling fluid [89]. Therefore, the damage to health resulting from the application of these fluids is contrary to the worldwide guideline for the preservation of workers and also causes an increase in the cost to the industry due to indemnities, health care, and replacement of human resources [86].

In recent years, environmental challenges have drawn attention. Inappropriate disposal of cooling fluids causes unsustainable socio-environmental impacts on the eco-friendly industry of the future, which cannot be solved by technological or societal science. Therefore, governments nowadays establish rigorous laws to protect the environment [90].

Hence, the increasing consciousness for green manufacturing globally and consumer focus on environmentally friendly products have put increased pressure on industries to minimize the use of cutting fluids.

5 Application of New Technology in Grinding to Achieve Sustainability

Due to the high requirement of the machined surface quality and the final service performance of the machined part, the heat and temperature generated in the abrasive-machining process must be controlled and dissipated in time. Cooling fluids are commonly used, while the production and disposal of the cooling fluid need a lot of resources, e.g., fresh water, and may cause health issues for the operators, such as irritation to the eyes and respiratory tract or skin allergies. The residual chips stained with the coolant are usually treated as hazardous waste, which is costly to dispose of or recycle. In addition, the energy consumption related to the cooling and auxiliaries accounts for 32% of the total energy usage of the plant [13]. In this case, reducing and even eliminating the coolant usage can significantly increase the sustainability of the abrasive-machining processes. Lots of research has been focused on this topic.

5.1 Heat Pipe and Oscillating Heat Pipe Grinding Wheels

When using abrasive machining, materials that are difficult to cut, including titanium alloys and superalloys, can produce a lot of heat and fast burnout. Heat pipe grinding wheels are suggested to remove heat quickly using less coolant. Designing and making the heat pipe for the grinding wheel matrix is the main concept. The grinding wheel's capacity for heat transport can be increased by the heat pipe, a passive heat transfer device with outstanding thermal performance. In this case, the grinding heat can be transferred out in time directly through the grinding wheel, as shown in Figure 14. An axial-rotating heat pipe grinding wheel was first introduced in 2009, the brazed diamond heat pipe grinding wheel was designed, and successfully dry-grinds the Ti-6Al-4V alloy [91, 92]. The heat transfer mechanism inside the AR-HPGW is studied, and the guide for the design of the AR-OHP is introduced in detail [93, 94].

The heat transport capacity of the AR-HPGW is tested in the dry-grinding of Ti-6Al-4V alloy, and the results show that the AR-HPGW can reduce the grinding temperature by 45%, control the workpiece temperature under 100 °C and effectively avoid the grinding burnt-out under the dry-grinding conditions [95, 96]. The research on the sustainability of the AR-HPGW shows that the AR-HPGW can prevent the usage of the hazard coolant, eliminate coolant-related energy and resource consumption (see Table 1), simplify the costly disposal-and-recycle process, the green grinding of titanium can be achieved [10, 96].

Another heat pipe grinding wheel is the radial-rotating heat pipe grinding wheel (RR-HPGW). A circulat-shaped heat pipe is embedded in the grinding wheel matrix to increase the heat transfer performance of the grinding wheel [97]. The grinding heat can be dissipated in time to

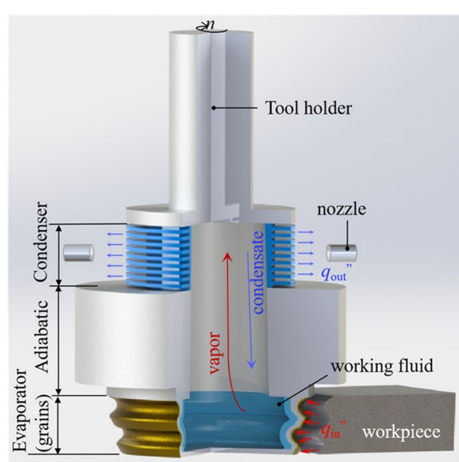

Figure 14 Illustration of AR-HPGW

avoid accumulation and high temperature, as illustrated in Figure 15.

The design and fabrication method of the RR-HPGW is introduced [98]. The heat transfer mechanism of RR-HPGW is deeply investigated. The circular phase change of the inside working fluid contributes to excellent thermal performance [99]. The heat transfer performance is then tested and studied through simulations and experiments. The results show that under the heat load of 60 W/mm^2, the RR-HPGW can effectively control the temperature under 400 °C [22, 100, 101] and shows great potential in applying in the dry grinding of hard-to-cut materials to eliminate the harmful coolant. The RR-HPGW has successfully ground the carbon steels [22], titanium alloys [102, 103], and superalloys [104] with an absence of cooling fluid, the grinding temperature is effectively controlled, and the grinding burnt-out is avoided. In this case, the eco-benign grinding is achieved [101], as illustrated in Figure 16.

Although the heat pipe grinding wheel has excellent potential to achieve dry/near-dry grinding and sustainability, its thermal performance deteriorates with the increase in grinding speed. In particular, the thermal performance fails to meet the requirement of heat dissipation when the grinding speed exceeds 45 m/s. The reason is that the high centrifugal acceleration caused by the high rotational speed suppresses the circular phase change of the working fluid in the HPGW, which leads to the decease of the thermal performance [99].

An oscillating heat pipe grinding wheel (OHPGW) is suggested in Figure 17 as a solution to the aforementioned issue. The oscillating heat pipe, a brand-new kind of heat pipe, is built inside the grinding wheel and uses the motion of the working fluid's liquid plugs and vapor slugs to transfer heat [105, 106]. The oscillating heat pipe can also start up in time due to the internal flow of the charged working fluid to achieve a good heat transport capacity for enhanced heat transfer [107, 108]. During the grinding processes, the OHPGW can withstand the impacts of centrifugal acceleration and maintain a high heat transmission capacity [109, 110]. The design, fabrication, and thermal performance test of the prototype OHPGW are conducted [111–113]. The OHPGW conducts the dry-grinding of titanium alloys and superalloys, and the life-cycle analysis is carried out. The results show that during the grinding of superalloy, the OHPGW

Table 1 Coolant-related resources consumption of AR-HPGW v.s. flood cooling [10]

Test No.	Coolant power		Conventional method		AR-HPGW	
	Coolant speed (m/min)	Coolant power (W)	Coolant pump energy (kJ)	Carbon emission (g)	Coolant pump energy (J)	Carbon emission (kg)
1	45	500	93.75	24	0	0
2	35	300	45	11	0	0
3	20	100	12.5	0.32	0	0

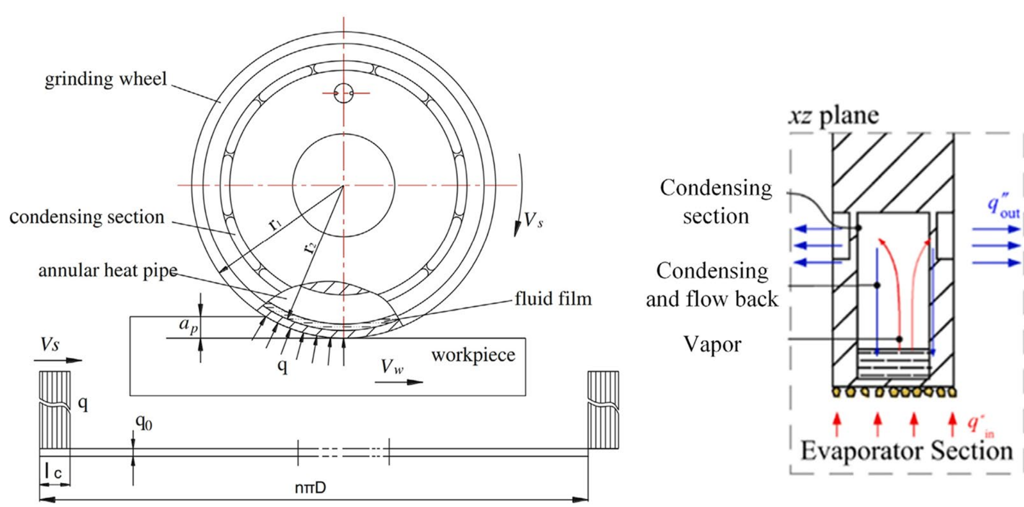

Figure 15 Illustration of enhanced heat transfer of RR-HPGW [102]

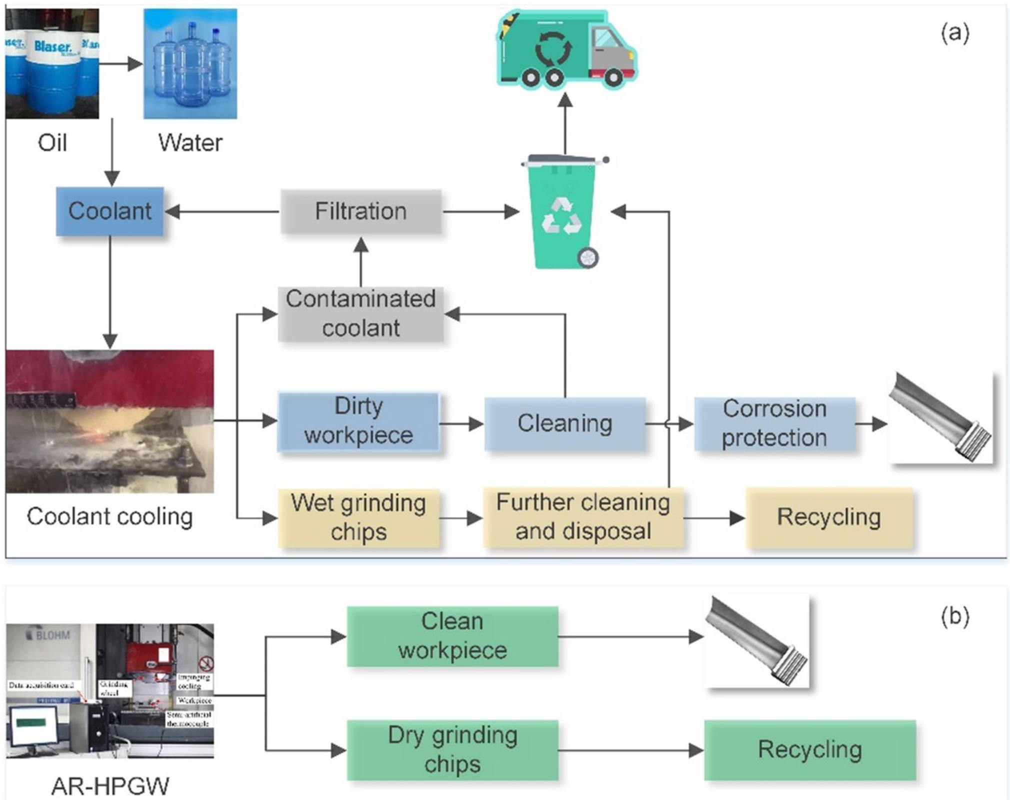

Figure 16 Comparison between conventional coolant cooling and RR-HPGW

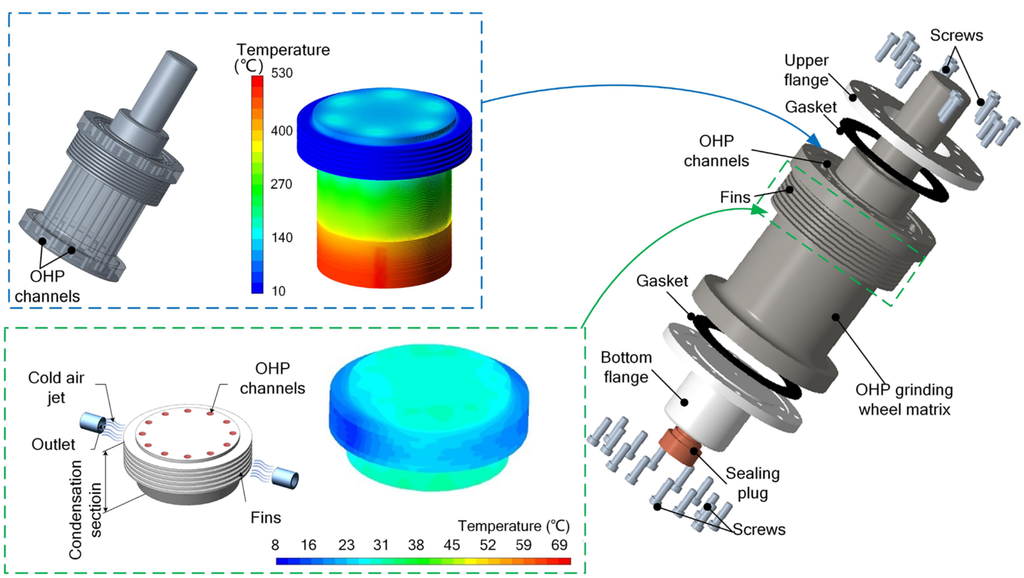

Figure 17 Concept, design, and assembly of the OHPGW

can transfer more than 67% of the grinding heat, and less than 33% of the total grinding heat can enter the workpiece to cause a temperature rise. On the contrary, for the grinding by the wheel without OHP, more than 80% of grinding heat transfers to the workpiece, generating a high temperature (> 600 °C). In this case, the OHPGW can effectively control the grinding temperature without cooling fluid. Moreover, the OHPGW can consume 26%–42% less energy, emit 45%–56% less CO_2, and reduce costs by up to 41% [114, 115]. The OHPGW can achieve high-quality, earth-friendly grinding and sustainability from the economic, social, and environmental aspects, as shown in Figure 18.

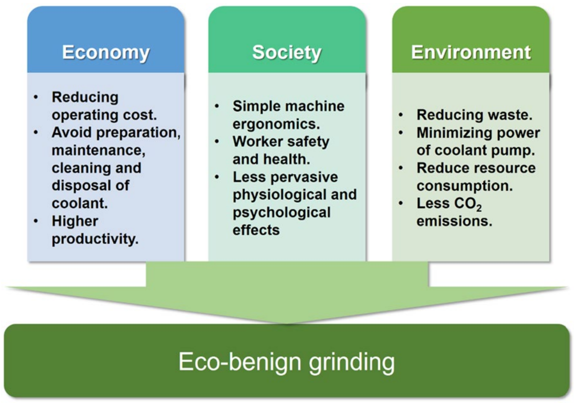

Figure 18 Sustainability of the RR-HPGW

5.2 MQL and Nanofluid MQL Applications

Minimum quantity lubrication (MQL) is a fast-developing technique in the abrasive-machining. MQL mixes high-velocity air with several to a dozen milliliters of coolant per hour for lubrication and cooling [116, 117]. MQL technique uses nozzles or ultrasonics to disperse the coolant into micro-droplets (Figure 19). The coolant micro-droplets combined with compressed air are delivered to the contact zone to create a film between the workpiece and abrasives [118, 119]. The MQL employs a minimal amount of coolant (10–100 mL/h) and can be treated as a near-dry condition [120]. The micro-film formed by MQL between the workpiece and abrasives improves the lubrication conditions of the abrasive machining. The coolant mist acts as the lubricant, and the compressed air serves as

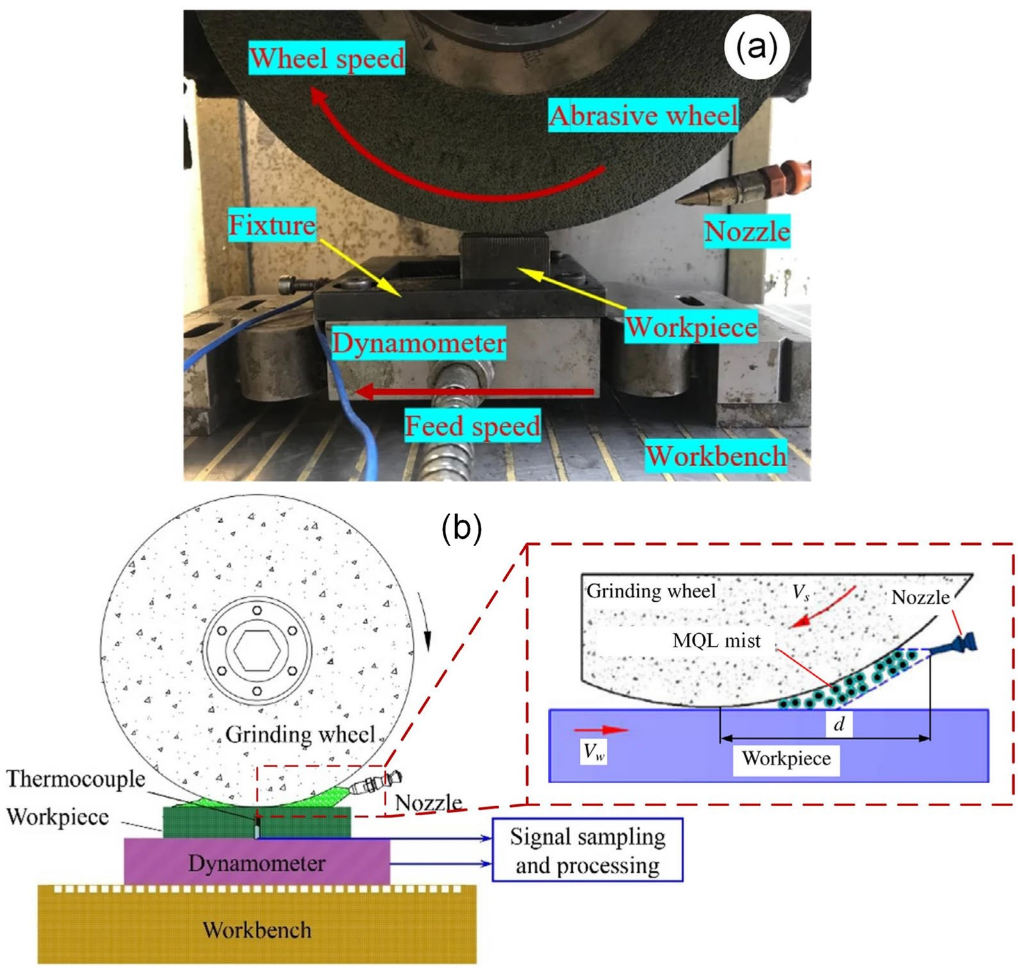

Figure 19 Illustration of grinding with MQL: (**a**) Photo of the grinding process and (**b**) Illustration of MQL process [122, 127]

the cooling medium. As a result, the tangential force can be reduced significantly, and the consumed power, in turn, is reduced [121]. Owing to the improved lubrication and cooling by MQL, a good grinding surface quality can also be guaranteed, as shown in Figure 20 [122]. In addition, compared with conventional grinding, the Product Sustainability Index (PSI) of grinding with MQL is 46.06% more sustainable [119].

The coolant used in the MQL is mainly synthetic oil or mineral oil [123, 124]. Even though a small amount of coolant is used in MQL, the MQL with synthetic or mineral oil still has negative impacts on the environment and the health issues of operators [125]. Biolubricants, which mainly include natural plant oils, are now used to increase the sustainability of the MQL [126]. Natural plant oil has significant advantages of good biodegradability and low toxicity and is also renewable. In this case, it can somewhat avoid overexploitation of the resource [118]. Plant oil with high-content unsaturated fatty-acid, such as coconut or palm oil, is used due to its proper viscosity and surface tension. Such oil can have a good balance between cooling and lubrication, while the oil has weak stability because of the easy-oxidability of its C=C bond. Plant oils with high-content saturated fatty acids, e.g., peanut oil, soybean oil, are used for the excellent lubrication effect caused by the high viscosity [125].

The MQL technique has the outstanding advantage of sustainability and cost-reducing in abrasive machining. The cost of the machining with conventional flood cooling, MQL, and dry conditions is compared in Table 2. Compared with conventional flood cooling, the cost associated with coolant materials, pumps, piping, filtration, chiller, and waste disposal can be reduced. In this case, machining with MQL has the potential to save up to 15% of the cost.

The MQL can also reduce energy consumption. In abrasive machining with conventional flood cooling, the machining, flood cooling, and compressed air account for 25%, 30%–40%, and 15%–20% of energy consumption, respectively. For the MQL, the energy associated with flood cooling no longer exists, and the MQL can help increase the machining efficiency and reduce the cycle time. As a result, energy can be significantly saved, as shown in Figure 21 [129]. However, compared with flood cooling, MQL will increase the use of compressed air, which may reduce the energy benefit achieved through cycle time and coolant pumping improvements.

In addition, the MQL technique can provide a good lubrication and cooling effect in the grinding process. The grinding tangential force, grinding temperature, and surface roughness can significantly reduce [120]. In particular, the lubrication effect is outstanding for oil with high viscosity. Therefore, the grinding force has a dramatic decrease, while the cooling effect may be limited, and in turn, the grinding temperature has a little reduction [126, 130].

In light of this, the nanofluids with high thermal performance are combined with MQL (NMQL) to enhance the cooling effect [131]. Nanoparticles such as MoS_2 [132, 133], SiO_2 [134–136], Al_2O_3 [127, 137, 138], carbon nanotube [139, 140], graphene nanoplatelets [141], with a size of 5–200 nm is mixed with the base oil. The nanofluids show good thermophysical and tribology properties

Figure 20 Grinding surface quality: (**a**) Dry grinding, (**b**) Flood cooling, and (**c**) MQL [122]

Table 2 Cost comparison for various lubrication/cooling techniques [128]

	Raw material cost	Fluid consumption	Equipment cost	Tool cost	Cleaning cost	Disposal cost
Flood cooling	High	High	High	Low	High	High
MQL	Low	Low	Low	Low	Low	Low
Dry	Very low	Very low	Very low	High	Very low	Very low

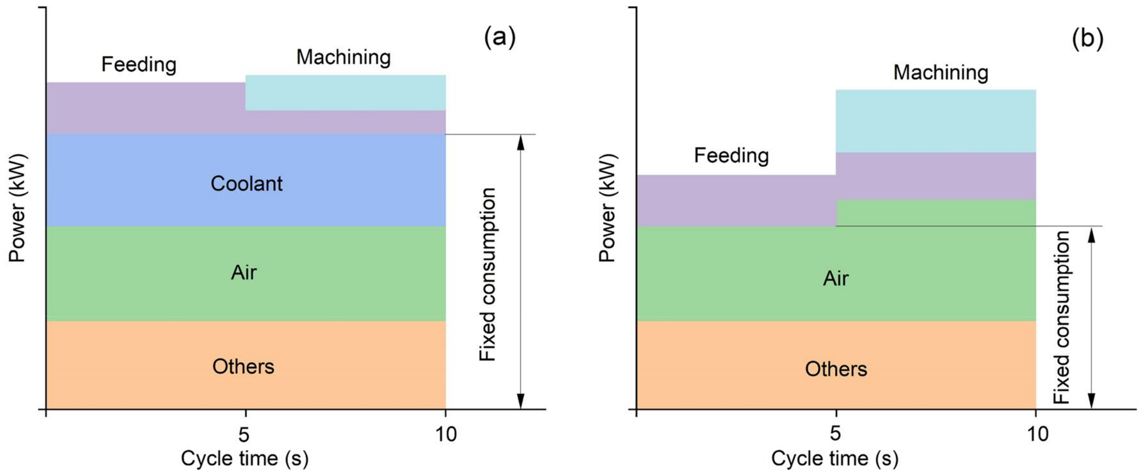

Figure 21 Energy consumption of machining with (**a**) flood cooling and (**b**) MQL

in the MQL. As a result, the machining force, temperature, and tool wear can be reduced [142].

The NMQL can greatly enhance the cooling and lubrication conditions during abrasive machining. As a result, it is claimed that the specific energy consumption is lower when compared to flood cooling and MQL by 29% to 33% and 35% to 60%, respectively [133]. In addition, NMQL grinding reduces abrasive wheel wear by 48% to 55% compared to MQL with traditional flood cooling [132]. Along with enhancing the quality of abrasive machining, the NMQL considerably lowers energy consumption and wheel wear [122, 143].

However, the application of nanofluids in the MQL still has some constraints, e.g., the instability of the nanofluids and the economic and health issues [144]. The stable and homogeneous dispersion of nanoparticles in the base fluid in the long term is the key to achieving the good thermal performance of the NMQL. While nanoparticles are very easy to agglomerate and precipitate, resulting in weakened dispersion. However, increasing the surfactant will weaken the cooling performance of the nanofluids [144]. Besides, the addition of nanofluid in the MQL will increase the usage cost, eliminating the advantage of the cost-saving of MQL.

On the other hand, the MQL or NMQL will form a coolant mist with a small size, usually under 10 μm; the mist of the coolant will enter the human body through inhalation, dermal contact, or oral intake even without notice [10, 145]. The nanoparticles will be toxic to human eyes, lungs, or stomach; some nanoparticles may not be biocompatible with human peripheral blood lymphocytes or decrease human cell viability [146]. In this case, the toxicity of the MQL or NMQL should be considered when applying this technique, and the necessary protection is needed. In addition, when grinding with a large depth of cut, e.g., in deep cut creep grinding or high-performance grinding, the MQL or NMQL makes it difficult to fully enter the contact zone between the grinding wheel and the workpiece. Therefore, the cooling and lubrication effect is eliminated. MQL or NMQL in the grinding with large depth of cut to improve sustainability is now one of the research hotspots and frontiers.

5.3 Cryogenic Cooling

One of the most important pursue in abrasive machining is to achieve high-quality parts with lower environment impact and machining cost [147, 148]. Due to the high energy consumption and heat generated in the grinding process, cooling is essential in this case [149, 150]. The cooling fluid accounts for almost one-quarter of the total machining cost [151]. Due to technological and environmental issues, academics and industries are forced to adopt less harmful coolants and use smaller amounts [152, 153]. In Section 5.2, grinding with MQL is introduced as a near-dry machining technique, showing a significant sustainability advantage. At the same time, the MQL has an inevitable shortcoming, i.e., insufficient cooling [154]. Therefore, cryogenic cooling receives more attention. In cryogenic cooling, the liquid gases, e.g., liquid carbon dioxide (LCO_2) [155, 156], supercritical carbon dioxide (SCO_2) [157], liquid nitrogen (LN_2) [158], liquid helium (LHe) [151, 159], are used as an alternative coolant rather than the conventional water or oil-based fluid [158, 160]. Carbon dioxide is now generally considered a greenhouse gas (an air pollutant), and CO_2 is heavier than air; in this case, it can cause a problem of lack of oxygen in the factory, which can be dangerous for the operators. In addition, helium is very expensive, and it is economically unaffordable to use as a cryogenic cooling fluid in grinding [86]. Nitrogen is the major constitute of the air (78%), and is a non-toxic, colorless, odorless gas. The fabrication of liquid nitrogen is now mature, the cost and price drop down to an acceptable level. Therefore, the liquid nitrogen is widely used in the cryogenic machining [161, 162].

Cryogenic grinding is similar to grinding with a conventional cooling system; the cryogenic gas tank containing LN_2 and specially designed tubes (e.g., rubber tubes), nozzles, flow meters, and valves (pressure regulators) are involved, as illustrated in Figure 22. The nitrogen gas is directly delivered to the contact zone between the grinding wheel and workpiece. Because the nitrogen has a high liquid-gas expansion rate and a low boiling temperature (− 196 °C), when the LN_2 is delivered to the contact zone, the liquid nitrogen turns into vapor quickly, and the surrounding temperature decreases dramatically to have an excellent cooling effect [163]. Besides, cryogenic cooling can also change the properties of the workpiece materials; the ductility of the material reduces while the grains on the grinding wheel retain high sharpness [164]. The grinding performance can be improved, and the heat generated in the grinding process can be decreased [164–168]. The grinding force, temperature, and tool wear can be reduced, and the grinding quality can be improved [169–172]. It is reported that the metal material removal occurs mainly by shearing and fracture as the chip formation mechanism. In this case, in the material removal process, the plastic deformation reduces, the fractures such as shearing, high ridges, or grooves decrease, and the surface quality improves [172, 173].

When cryogenic grinding the difficult-to-cut alloys such as superalloy, titanium alloy, or hardened steel, the specific grinding energy (the energy consumed by removing unit material) decreases by 33% than the grinding with conventional cooling, the temperature, and grinding force reduces significantly. The surface tensile residual stress can also decrease [165, 169, 171]. The G-ratio of cryogenic grinding is 2–2.6 times higher than dry grinding and conventional grinding. At the same time, in the same research, it is reported that cryogenic grinding can increase grinding power consumption to some extent [168]. The cryogenic grinding can greatly extend the life of the wheel and reduce the cost due to the greater G-ratio [174].

Additionally, as nitrogen is lighter than air, it can scatter in the air after cooling during cryogenic grinding, leaving a residue on chips, workpieces, and equipment. As a result, after the grinding process, there is no need for cleaning, and minimal work is required to maintain and remove requirements [175, 176]. As shown in Table 3, the benefits of cryogenic grinding are underlined compared to dry grinding, flood grinding, and grinding with MQL. For cooling the abrasive machining process to regulate grinding heat, prevent thermal damage, and increase productivity, product quality, and profitability, cryogenic grinding can be an effective, efficient, economical, and environmentally conscious technology. While the initial setups of the cryogenic cooling equipment and maintenance are expensive, the liquid nitrogen cost is also relatively high right now. Therefore, in the future, when the running and nitrogen costs decrease, cryogenic

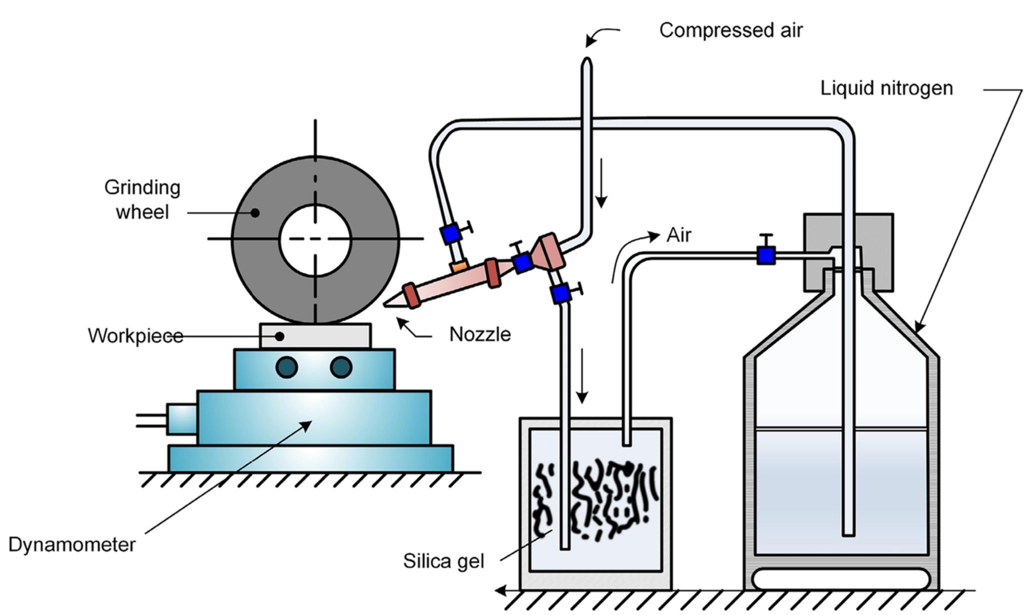

Figure 22 The schematic of cryogenic grinding setups

Table 3 The comparison of different cooling strategies [177, 178]

Strategies	Dry	Flood	Cryogenic	MQL
Cooling	Poor	Good	Excellent	Moderate
Lubrication	Poor	Excellent	Moderate	Excellent
Metal removing efficient	Poor	Good	Good	Moderate
Product quality	Poor	Good	Excellent	Good
Material cost	Low	High	High	Low
Tool cost	High	Low	Low	Low
Cleaning cost	Low	High	Low	Moderate
Disposal cost	Low	High	Low	Moderate
Sustainability concerns	Poor quality, efficiency, and high tool cost due to thermal damage	Water pollution, high material, and energy consumption	High initial cost and LN_2 cost	Harmful oil mist

grinding will have a higher sustainability and get wide-application in industries.

5.4 Other Sustainable Designs or Methods

- *Solid lubricants*

  Avoiding cooling fluid is the primary goal of achieving sustainable grinding. At the same time, massive heat may be generated in the dry abrasive-machining processes due to severe friction, and consequently, the machining quality can deteriorate, and tool life can be sharply shortened. Solid lubrication has been investigated for use in the abrasive-machining processes, particularly in grinding [179, 180]. Four kinds of solid lubricants are studied, i.e., laminar solids (e.g., graphite) [181], metal oxides (e.g., PbO, MoO_3) [182], metal fluorides (e.g., CaF_2) [183], and polymers (e.g., B-cyclodextrin) [184]. As a laminar solid, graphite can have a good lubricity beyond 450 °C, since most laminar solids are efficient lubricants up to 450 °C. The metal oxides and metal fluorides are effective between 500 °C and 1000 °C [185]. Graphite, CaF_2, B-cyclodextrin, and MoS_2 are used to fabricate the grinding wheel to improve the lubricity in the grinding process. As a result, the friction is significantly reduced, the grinding forces, specific grinding energy, and tool wear decrease, the lifetime of the wheel increases, and the cost of the tool declines. The solid lubricant can improve the sustainability of the grinding process to some extent [179, 181, 183, 186]. At the same time, the kind of solid lubricant and its dosage should match the grinding wheel and process. Otherwise, the strength of the grinding wheel may deteriorate, which causes fast wheel wear, high cost, and poor grinding quality [183]. In addition, the grinding of difficult-to-cut alloys with solid lubricants still needs subsequent cleaning and disposal, and the resource and energy consumption in this procedure cannot be saved.
- *Biodegradable lubricant*
  A biodegradable lubricant, vegetable oil, with small quantity lubrication (SQL, 200 mL/h), is introduced to reduce the environment impact of the grinding process. The grinding of difficult-to-cut materials can be accomplished without soil and water pollution by using a negligible amount of biodegradable coolant, e.g., castor oil (the most efficient), groundnut, sunflower, or soybean oil, with effective cooling and lubrication [187, 188].
- *Structured grinding wheel*
  The structured or patterned grinding wheels are introduced. One kind of patterned grinding wheel is to fabricate multiple micro-grooves on the working layer, as shown in Figure 23. The patterned grinding wheel can reduce the grinding force and heat during the process, which has the potential to reduce the usage of harmful coolant, in this case, the coolant-related energy and resource consumption, as well as carbon emission, can be reduced [189, 190].

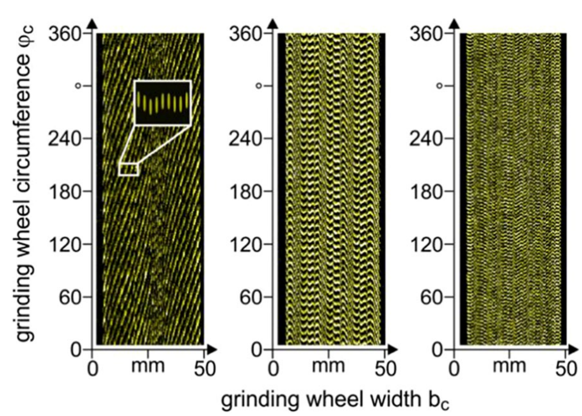

Figure 23 Illustration of the patterned grinding wheel [189]

The other type is the segmented grinding wheel, which has internal cooling channels between segments. In this case, it can significantly increase the coolant delivery efficiency and achieve the same cooling effect with reduced coolant usage, as shown in Figure 24. Therefore, the proposed segmented grinding wheel also has the potential to reduce the coolant-related carbon emission and energy and resource consumption [191, 192].

- *Grinding process optimization*

  A new grinding strategy, skiving for rough machining and dry-grinding for finish machining, is proposed to avoid using cooling fluid while grinding gears. The new method, which eliminates the oil in the gear grinding, can decrease 75% the electrical energy consumption, 1.38 GW·h/year, and 12000 kg/year carbon emission, and it can save 0.045 €/gear cost for the manufacturing plant [193]. In addition, the proposed strategy of eliminating oil brings ecological benefits and provides a healthier environment for workers.

- *Axiomatic design for sustainable grinding*

  A novel grinding process design methodology is created on the foundation of the axiomatic design principle. The description of the axiomatic grinding process, which considers process, tool, and coolant characteristics, is coupled to metrics for sustainability. An axiomatic process model can be used to examine the life cycle impact of grinding and process improvement can then be performed to make it more sustainable [194].

  An eco-efficiency model is also built to assess the energy and resource efficiency of the grinding process. The interrelationship among process parameters, energy, resource consumption, and quality performance is revealed in the model. The optimized grinding process with a trade-off between energy consumption and quality performance can be achieved, and sustainability can be increased without sacrificing the grinding quality [195].

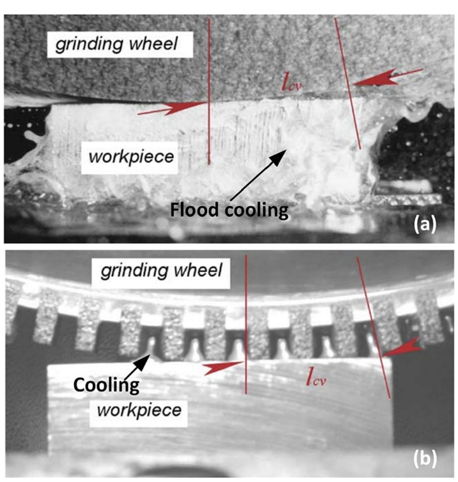

Figure 24 Entrainment of the coolant: (**a**) Conventional cooling and (**b**) structured grinding wheel [192]

6 Future Directions and Research Challenges

The development trends and future research directions of sustainable grinding for difficult-to-cut materials mainly include the following aspects:

- High-Efficiency Processing Technologies: To improve production efficiency and reduce production costs, researchers will continue to explore new processing technologies, such as high-speed grinding and efficient grinding, to improve processing efficiency [196, 197].
- Intelligent Manufacturing and Digital Processing: With the continuous development of technologies such as artificial intelligence, the Internet of Things, and cloud computing, future green grinding for difficult-to-cut alloys will become more intelligent [198–200] and digital [201, 202], including aspects such as automated, information-based, and intelligent processing.
- Green Manufacturing and Environmentally Friendly Grinding: With the continuous increase in environmental awareness, future green grinding for difficult-to-cut alloys will prioritize ecological protection and sustainable development, reducing pollution to the environment and waste of resources through the use of environmentally friendly materials and green manufacturing technologies [203].
- High-Precision and High Surface Quality Processing: Difficult-to-cut alloys require high precision and high surface quality, so future research will continuously focus on improving processing precision and surface quality, such as through the use of ultra-precision grinding and nanometric grinding technologies [204, 205].
- Application of New Difficult-to-cut Alloy: With the continuous emergence of new materials, future green grinding for difficult-to-cut alloys will continuously explore the processing methods and application fields of new materials, such as new high-strength lightweight materials and high-performance composite materials [206, 207].
- Comprehensive Optimization and System Integration: Future green grinding for difficult-to-cut materials will prioritize comprehensive optimization and system

integration by integrating different processing technologies, manufacturing processes, equipment, materials, and other elements to achieve comprehensive optimization and system integration [208, 209], thereby improving production efficiency and product quality.

In addition, the thermal management in grinding processes will be studied in detail. The thermal management can form an energy loop, as shown in Figure 25. The grinding parameters and cooling methods will be optimized to control (or reduce) the consumed electrical power and generated grinding heat. Passive thermal devices will transfer The grinding heat out of the grinding zone for further recovery. Then the grinding energy, including the heat in the grinding zone and the kinematic energy of the cooling jet, will be recovered or harvested by thermoelectric generators [210–212], triboelectric generators [213], etc. The electrical energy will be either stored or transferred back to the grid. In this way, energy consumed can be reduced, but the waste heat can be harvested, and sustainability can significantly increase. The research challenges in this aspect include grinding heat transfer from the grinding zone to the heat recovery. The heat in the grinding is supposed to be transferred out by passive thermal devices. The suitable design and fabrication of the devices need deep investigation. Furthermore, another challenge is harvesting energy with high efficiency. The waste heat in grinding is usually low-grade heat, and it is difficult to recover with a high thermoelectric conversion rate.

7 Conclusions

This paper comprehensively reviews the advances in increasing sustainability in grinding difficult-to-cut alloys. Driven by the gradual evolution of grinding technology towards enhancing efficiency and quality and paralleled by a gradual rise in awareness regarding grinding sustainability, new theories, technologies, and equipment have gradually emerged. The core ideas focus on decreasing hazardous coolant, coolant-related energy, and resource consumption. At the same time, new methods are proposed to reduce energy consumption in grinding processes. The main conclusion is drawn as follows.

Developing grinding techniques for difficult-to-cut alloys, progressing from conventional to high-speed, creep feed, and high-performance grinding aims to increase the material removal rate (MRR). This increment in MRR, achieved by enhancing the cutting period for a single grain, leads to more energy utilization for material removal. The specific energy decreases as MRR increases, potentially reducing overall energy consumption in grinding processes. Conventional and superabrasive grinding wheels are employed, with conventional wheels having lower fabrication energy but posing recycling challenges. Superabrasive wheels demand three times more energy for manufacturing, yet over 88% is effectively utilized in machining and recycling. Efficient coolant delivery becomes problematic at higher grinding speeds and depths for a greater MRR. Solutions involve adjusting nozzle shape and position, and increasing coolant flow. However, the cooling effectiveness depends on

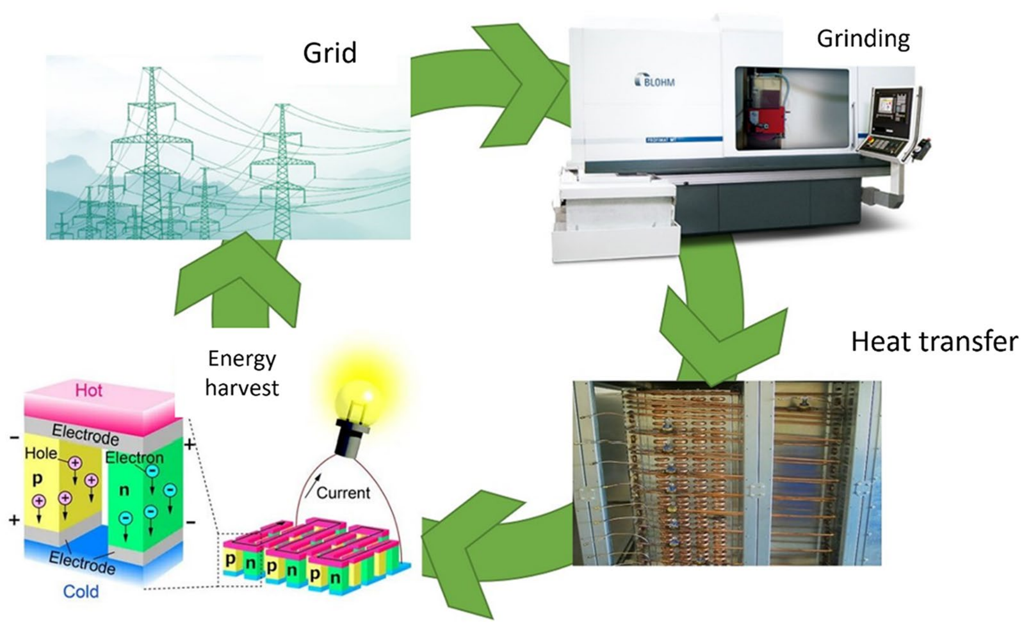

Figure 25 Concept of thermal management in grinding processes

various factors, and the unstable heat transfer process complicates effective control. Massive coolant application with higher pressure and speed increases resources, energy consumption, and carbon emissions.

The sustainability performance of grinding is assessed in terms of energy consumption, carbon footprint, cost, and worker health and safety. Energy consumption is categorized into four parts, including material removal, frequency-converted energy for the grinding wheel and guide wheel motor, basic energy for coolant/lubricant pumps and electric cabinet, and response energy due to tangential friction force. Material removal contributes the most to energy consumption. Carbon footprint, linked to energy processes, constitutes about 50%, with additional percentages during resource utilization (48%) and waste disposal (2%). Cost performance considers economic and time costs, with machine purchase, space, energy, repairs, maintenance, compressed air, and capital commitment contributing 34%, 5%, 17%, 35%, 5%, and 4%, respectively. Time costs are optimized by adjusting cutting parameters. The substantial use of cooling fluid raises concerns about worker and environmental safety. Global attention to green manufacturing and consumer demand for eco-friendly products heightens the industry's responsibility to reduce cutting fluid usage.

New technologies, such as heat pipes, oscillating heat pipes (HPGW and OHPGW), minimum quantity lubrication (MQL), MQL with nanofluid (NMQL), and cryogenic cooling, aim to eliminate hazardous coolant used in grinding, reducing energy consumption, resource use, and carbon emissions. HPGW and OHPGW enhance heat transport in grinding wheels, enabling efficient heat transmission and achieving dry/near-dry grinding by controlling temperatures. OHPGW, for example, can reduce energy by over 26% and CO_2 by 45%. MQL and NMQL disperse minimal coolant as micro-droplets, reducing energy and resource consumption while decreasing grinding forces. Biolubricants, like natural plant oils, enhance sustainability in MQL. Cryogenic cooling, utilizing liquid gas, improves grinding quality, and wheel lifespan, and reduces specific energy. While cryogenic cooling is efficient and environmentally friendly, initial setups are expensive, limiting widespread application. Research focuses on economical devices and techniques with high cooling effects to address these limitations.

Other methods, such as solid lubricants, biodegradable lubricants, structured grinding wheels, grinding parameters optimization, axiomatic design, are used to increase the sustainability in grinding difficult-to-cut alloys. Solid lubricants improve lubricity, reducing energy consumption and wheel wear. Biodegradable lubricants with minimal quantities are eco-friendly, decreasing environmental impact and simplifying disposal. Structured grinding wheels and segmented designs reduce forces, heat, and improve coolant delivery efficiency, lowering coolant-related energy, resource use, and carbon emissions. Process optimization and axiomatic design contribute to sustainability without compromising quality.

The developing trend of sustainable grinding focuses on high-efficiency technologies, intelligent and digital grinding, green techniques, high precision, new materials, optimization, system integration, and thermal management. Researchers must innovate, strengthen interdisciplinary collaboration, and develop advanced technologies for improved efficiency and quality. Environmental protection, safety, and sustainable development are vital, fostering green grinding's sustainable and innovative growth in manufacturing.

Abbreviations

AR-HPGW	Axial-rotating heat pipe grinding wheel
MQL	Minimum quantity lubrication
NMQL	Nanofluid minimum quantity lubrication
OHPGW	Oscillating heat pipe grinding wheel
PSI	Product Sustainability Index
RR-HPGW	Radial-rotating heat pipe grinding wheel

List of Symbols

a_{gmax}	Maximum undeformed chip thickness
a_p	Depth of cut
C	Constant related to the shape of grains
b	Grinding width
d_s	Diameter of the grinding wheel
e_s	Specific grinding energy
F_t	Tangential force
N_d	Active cutting point
Q'_w	Material removal rate
v_s	Grinding speed
v_w	Infeed speed

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Authors' Contributions
NQ wrote the original draft, curated data, analyzed data, and acquired funding. JC curated and analyzed data and wrote the original draft. AMK reviewed and edited the draft and supervised the research. BZ curated and analyzed data and wrote the original draft. YC wrote the original draft. WD reviewed and edited the draft, supervised the research and acquired funding. YF reviewed and edited the draft and supervised the research. JX supervised the research and acquired funding. All authors read and approved the final manuscript.

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Declarations

Competing Interests
The authors declare no competing financial interests.

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