Results in Engineering 24 (2024) 103042

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering

Review article

A review on sustainable machining: Technological advancements, health and safety considerations, and related environmental impacts

Ammar Elsheikh [a,b,*], Ali B.M. Ali [g], Amal Saba [c], Hosam Faqeha [d], Albraa A. Alsaati [d], Abdullah M. Maghfuri [i], Walaa Abd-Elaziem [e,f], Ahmed A. El Ashmawy [h], Ninshu Ma [j,**]

[a] Department of Production Engineering and Mechanical Design, Faculty of Engineering, Tanta University, Tanta, 31527, Egypt
[b] Faculty of Engineering, Pharos University in Alexandria, Egypt
[c] Department of Histology, Faculty of Medicine, Tanta University, Tanta, 31527, Egypt
[d] Mechanical Engineering Department, Umm Al-Qura University, Makkah, 21955, Saudi Arabia
[e] Department of Mechanical Design and Production Engineering, Faculty of Engineering, Zagazig University, P.O. Box 44519, Egypt
[f] Department of Materials Science and Engineering, Northwestern University, Evanston, IL, 60208, USA
[g] Air Conditioning Engineering Department, College of Engineering, University of Warith Al-Anbiyaa, Karbala , Iraq
[h] National Institute of Oceanography and Fisheries, Cairo, Egypt
[i] Department of Mechanical Engineering, College of Engineering and Computer Sciences, Jazan University, Jazan,45142, Saudi Arabia
[j] Joining and Welding Research Institute, Osaka University, 11-1 Mihogaoka, Ibaragi, Osaka, 567-0047, Japan

A R T I C L E I N F O

Keywords:
ustainable machining
Cutting fluids
Environmental impacts
Health issues
Sustainability assessment

A B S T R A C T

The evolution of advanced engineering materials and high-speed cutting techniques has emphasized the critical role of cutting fluids (CFs) in machining processes to meet sustainability requirements. Cutting fluids application offers several key benefits, including temperature reduction during cutting, decreased friction between the workpiece/chip and tool, extended tool lifespan, enhanced machining efficiency, and boosted surface finish. These positive outcomes are primarily attributed to the core functions of cutting fluid, namely lubrication, cooling, cleaning, and corrosion protection. However, they have serious disadvantages such as posing risks to ecosystems and human health as well as high disposal costs. Despite these disadvantages, ongoing research and development efforts are focused on improving the environmental sustainability, health and safety, and performance of metal cutting fluids through the use of green biodegradable oils, developing advanced recycling technologies, and the use of efficient application methods such as high-pressure cooling and minimum quantity lubrication (MQL). This review paper sheds light on sustainable machining technologies that are utilized to minimize the environmental impacts of conventional cutting fluids. Different types of CFs including their benefits and role in cutting operations are also introduced. Finally, sustainable assessment including economical, environmental, and social aspects of green machining technologies is discussed.

1. Introduction

Despite being a focal point for manufacturing firms over the last thirty years, the endeavor to achieve sustainability through green manufacturing continues to encounter significant challenges. Indeed, manufacturing industries play a crucial role as key stakeholders in shaping environmental sustainability. Recognizing the importance of environmental concerns, many of these firms implement diverse approaches to address such priorities. The current rate of natural resource exploitation exceeds nature's capacity for regeneration by 1.7 times [1]. Therefore, the adoption of green manufacturing practices has become essential for achieving sustainable manufacturing, requiring manufacturing sectors to prioritize environmental considerations while also balancing social and economic factors [2].

Machining operations, which involve the utilization of CFs, also referred to as metalworking fluids (MCFs), represent a critical domain where sustainability principles can be put into practice. MCFs encompass liquids like machining fluids, cutting oils, metal-washing fluids, lubricants, or coolants [3]. The usage of CFs in machining operations has been prevalent for approximately 200 years [4]. These substances are

* Corresponding author. Department of Production Engineering and Mechanical Design, Faculty of Engineering, Tanta University, Tanta, 31527, Egypt.
** Corresponding author.
E-mail addresses: ammar_elsheikh@f-eng.tanta.edu.eg (A. Elsheikh), ma.ninshu.jwri@osaka-u.ac.jp (N. Ma).

https://doi.org/10.1016/j.rineng.2024.103042
Received 19 August 2024; Received in revised form 24 September 2024; Accepted 1 October 2024
Available online 1 October 2024

commonly employed in manufacturing industries to enhance the lifespan of machines and tools, as well as to protect and treat the surface of the metal being machined [5]. CFs play a crucial role in enhancing the tribological process during machining operations. Tribology involves the study of friction in interacting surfaces, and the corresponding lubrication and wear mechanisms. In machining, it refers to the interactions between the workpiece and the cutting tool (CT). The inclusion of CFs serves several purposes: i) Debris Removal: CFs help in the removal of chips and debris generated during the machining process. This is essential for maintaining the quality of the machined surface and preventing issues such as chip entanglement. ii) Heat Reduction: CFs act as a coolant, reducing the heat generated at the cutting zone. High temperatures can lead to tool wear, reduced tool life, and potential damage to the workpiece. The cooling effect of CFs is critical for maintaining machining efficiency. iii) Lubrication: CFs provide lubrication at the tool-workpiece interface, reducing friction between these components. Lower friction levels contribute to improved surface finish, dimensional accuracy, and overall machining performance. In summary, the use of CFs is a multifaceted approach to optimize machining processes by addressing debris removal, heat reduction, and providing lubrication, ultimately enhancing the efficiency and quality of the machining operation. It is important to note that depending on the specific type of CF, exposure to these substances can have severe and long-term health implications, potentially leading to legal issues such as CF disease lawsuits [6].

In machining operations such as drilling, threading, milling, broaching, grinding, and turning, the performance of the cutting operation depends on workpiece material, workpiece geometry, tool geometry, tool coating, machine rigidity, cutting parameters, and the applied cooling technique as shown in Fig. 1 [7–9]. CFs are commonly used to provide effective lubrication over the interacting surfaces and cooling of the cutting zone [10]. The key functions of CFs include friction reduction, enhancing surface quality, facilitating chip evacuation from the cutting zone, and preventing built-up edge (BUE) formation, safeguarding the workpiece against corrosion [11]. In the manufacturing industry, there is an increasing level of interest in achieving cost-effectiveness, high-quality products, and increased profitability [12,13]. High productivity is closely linked to factors like cutting depth, cutting speed, and feed rate [14], which can lead to elevated temperatures in the cutting zone [15]. While high temperatures can impact dimensional accuracy, product quality, and tool life, dropping cutting speed and feed rate solely for surface smoothness can be inefficient [16]. Therefore, optimizing CF efficiency and parameters is crucial for producing high-quality products [17].

Exposure to CFs in the workplace, either through inhalation via the nose or the mouth, eyes, or direct skin contact, can lead to CF-related diseases as shown in Fig. 2 [18]. Respiratory diseases can arise from inhaling mist generated during the machining process, while skin-related issues can occur through direct contact with machine parts, equipment, or tools covered with metalworking fluids. Respiratory conditions resulting from improper exposure may include chronic bronchitis, lipoid pneumonia, hypersensitivity pneumonitis, occupational asthma, and others [19,20]. Direct skin contact with CFs can result in health issues such as allergic contact dermatitis and irritant contact dermatitis [21,22].

The utilization and disposal of CFs, coupled with legislation and regulations concerning health and environmental protection, have driven the development of environmentally friendly machining practices [23]. The progress of vegetable-based CFs offers a solution that is safe for proper disposal, renewable, less toxic, environmentally friendly,

Fig. 1. Factors that affect the machining performance.

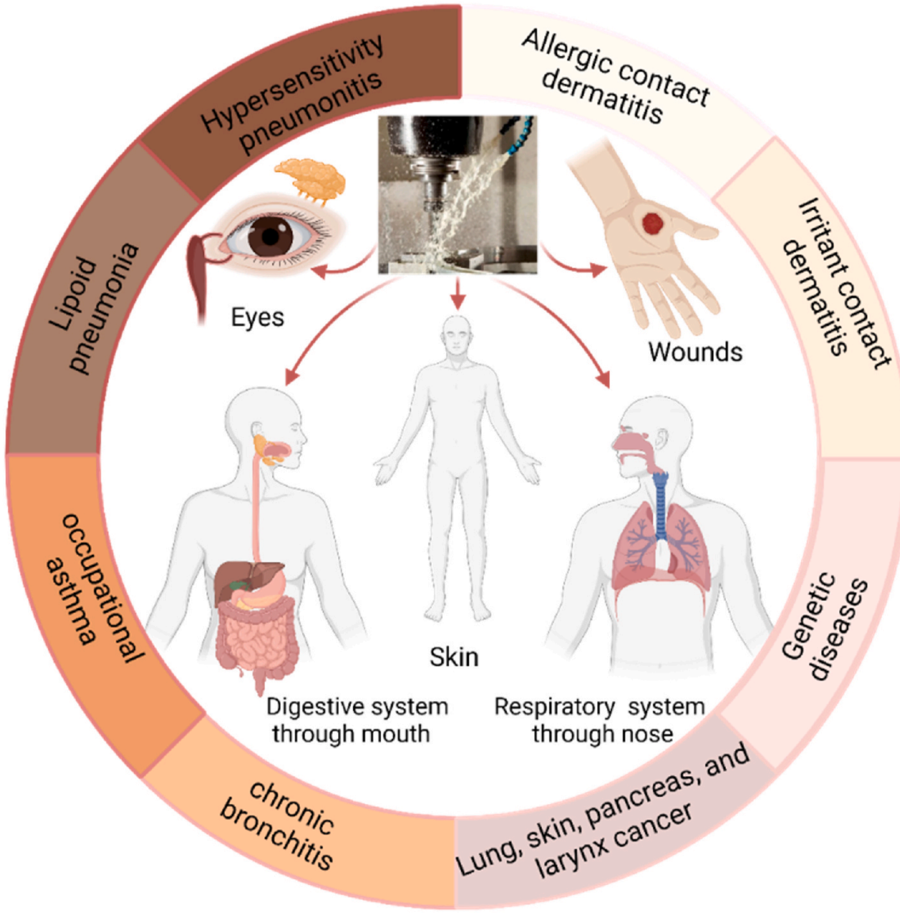

Fig. 2. Entering CFs into the human body and their related diseases.

and easily disposed of. Green technologies such as dry [24], mist cooling [25], cryogenic [26], and MQL [27] have been also proposed as eco-friendly alternatives to conventional flood cooling. These technologies have received significant attention to align with the objectives of Sustainable Development Goals (SDGs), including goals related to preserving operator health (SDG 3), ensuring sustainable industrialization (SDG-9), promoting sustainable production patterns (SDG-12), mitigating climate change (SDG-13) and land pollution (SDG- 14). Sustainable machining involves key aspects such as operational safety, decreased power consumption, environmental friendliness, waste reduction, cost reduction, and the preservation of operator health. The MQL strategy stands out as a promising cooling technique in metal-cutting operations, contributing positively to the mentioned SDGs [28].

In recent years, dry machining has attracted considerable attention due to its ability to eliminate water and air pollution, reduce swarf waste, and support sustainable manufacturing by enhancing recyclability [29]. Its environmental and economic advantages position dry machining as a viable alternative to traditional methods [30]. However, increased friction and heat generation, particularly in high-speed machining, often lead to accelerated tool wear and reduced tool life [31]. The absence of lubricants and coolants typically results in poor surface quality and dimensional inaccuracies, especially with challenging materials like superalloys and hardened steels. Additionally, the lack of cooling can cause thermal deformation in both the tool and workpiece, compromising process stability and precision. Dry machining is also limited in handling high cutting forces, restricting its use to certain materials. In contrast, MQL offers an optimal balance between lubrication and cooling while minimizing fluid consumption [32]. MQL systems, particularly those using hybrid nanofluids, have shown superior performance in heat dissipation, tool longevity, and surface finish compared to both dry and wet machining. These developments align with the growing focus on using statistical modeling to optimize machining parameters, as seen in various studies [33], highlighting the critical role of modeling in advancing sustainable machining techniques.

This review article sheds light on sustainable machining technologies aimed at lessening the environmental footprint of conventional CFs. It introduces various types of CFs, delineating their benefits and roles in cutting operations. Furthermore, it investigates sustainable assessments, encompassing economic, environmental, and social aspects of green machining technologies.

2. Sustainable machining technologies

Flood cooling, commonly found in CNC machines, involves a continuous flow of fluid through a nozzle directed at the tool's tip for cooling [34]. However, its use has diminished in machining operations as a result of environmental concerns, excessive coolant/lubricant usage, challenges in waste disposal, and potential harmful impacts on labors' health. The volumetric flow rate of CF is notably high, ranging from approximately 600 L/h for single-point CT operations to 13000 L/min per tooth for multiple-point CT operations. The overuse of CF in flood-cutting processes can lead to several issues that impact tool performance. Thermal shock, tool damage, and tip breakage are common problems attributed to the large volume of CF used [35]. Additionally, residual CF left on the workpiece surface can have adverse effects. Under specific environmental conditions, these residues may contribute to the growth of micro cracks on the cut surface. This not only diminishes the performance of the parts but can also lead to component failure in severe cases. Therefore, careful management of CF application is essential to mitigate these issues and ensure optimal machining outcomes. Indeed, the cost associated with CF is notable, encompassing various aspects such as procurement, treatment, and disposal [36]. Studies suggest that these expenses can amount to a substantial portion of the total manufacturing cost, ranging from 6 % to 18 % [37]. Consequently, optimizing the usage of CFs, exploring alternative methods like dry machining where feasible, and implementing efficient recycling and disposal strategies can contribute to overall cost reduction in manufacturing operations [38]. The use of flood cooling fluids in metal cutting presents various drawbacks, such as an increase in the overall cost of cutting and challenges associated with fluid disposal. Therefore, sustainable environmentally friendly technologies such as dry, high-pressure cooling, mist cooling, MQL, and dry machining appear to be viable alternatives for achieving effective cooling during machining [39–41]. Recent technological advancements have introduced various cooling techniques, including solid lubricants, ionic fluids, and nano-lubricants, aiming to enhance productivity and product properties. Various cooling technologies, such as MQL [42], dry cutting [31], and cryogenic cooling [43], exhibit distinctive characteristics in terms of efficiency, disposal, energy consumption, cost, and environmental impact. The choice of a specific cooling technique depends on the explicit requirements of the machining process and the desired balance between efficiency and ecological considerations to achieve different SDG goals related to sustainable manufacturing [44]. Sustainable machining encompasses several key aspects, each aligned with specific SDGs as shown in Fig. 3 such as:

Environmental Friendliness: Sustainable machining aims to reduce environmental impact, lower emissions, and minimize resource consumption, contributing to SDG-13, SDG-14, and SDG-15 for mitigating climate change, and preservation of marine ecosystems and terrestrial ecosystems.

Cost Reduction: Sustainable machining seeks to optimize processes, minimize waste, and reduce overall costs, aligning with economic sustainability and indirectly contributing to various SDGs, including SDG-8 for fostering opportunities for sustainable economic growth.

Operational Safety: Ensuring safe working conditions and minimizing health risks for operators corresponds to SDG-3 for promoting good health and well-being for individuals.

Waste Reduction: Sustainable machining aims to lessen waste generation, promote recycling, and adhere to circular economy principles, supporting SDG-12 for encouraging responsible production and consumption practices.

Reduction of Power Consumption: Sustainable machining focuses on energy-efficient practices, aligning with SDG-7 for promoting the accessibility and use of affordable and clean energy sources.

Preserving Operator Health: Prioritizing the health and well-being of machine operators is directly linked to SDG-3 for ensuring good health and well-being for all individuals.

By addressing these aspects, sustainable machining contributes to achieving multiple SDGs, fostering a holistic and responsible approach to manufacturing processes. The choice of machining method depends on the explicit requirements of the application and the trade-offs between different factors.

In this section basic concepts of different sustainable machining technologies are introduced.

2.1. Dry machining

Dry machining refers to the absence of CFs in machining processes, and it has gained traction in the manufacturing industry due to several advantages [45]. The benefits of dry machining include ecological friendliness, improved operator satisfaction, compliance with governmental regulations and laws, reduced coolant costs, and prevention of leakage flow. Despite its advantages, dry machining may lead to imprecise workpiece dimensions and a decrease in tool lifespan [8], and it can result in elevated temperatures in the machining area [46]. Dry machining employs high-performance CTs to maintain efficiency [47].

Fang et al. [48] developed AlTiN/AlTiBN coatings with multiple bilayers to assess their resistance to high-frequency repeated impacts and their performance in high-speed dry-cutting operations. The AlTiN/AlTiBN coatings demonstrated enhanced performance in dry-cutting operations on Ti-6Al-4 V alloy at high speeds. Specifically, the five-layer coated tool outperformed the bare tool by 55 % at a cutting speed of 80 m/min and this enhancement reached a higher value of 180 % at a cutting speed of 100 m/min. The enhanced performance can be credited to the optimized multilayer architecture, which provided enhanced adhesion, thermal stability, and impact fatigue resistance. Bakar et al. [49] studied tool wear scheme in dry machining during the milling of AISI H13 steel using uncoated carbide CTs with different cutting-edge

Fig. 3. Sustainable machining encompasses several key aspects, each aligned with specific SDGs.

radii. It was observed that the size of the cutting-tip radius significantly impacts the CT life. A sharper tool with a smaller cutting-tip radius tends to result in higher flank wear compared to a larger cutting-edge radius. Regarding the induced wear, adhesive, and abrasive wear were recognized as the primary types of wear generated under dry machining conditions. Ronadson et al. [50] applied various surface modification methods to cutting insert, including textured tools, TiN-WS2 coated tools, and hybrid textured and coated tools, for cutting of Ti-6Al-4V. These modified tools were then compared with a commercially available tool. The coated textured tool exhibited a 47 % decrease in the friction coefficient and a 7.5 % increase in the shear angle. The improved performance of the CT was primarily attributed to the reduction in the length of tool-chip contact. Specifically, the coated textured tools demonstrated a 13 % reduction in the contact length of chip and tool compared to commercial CTs. It was also reported that in textured inserts, the textures serve as channels for trapped air molecules, facilitating the heat transfer via the convection mechanism and consequently reducing friction between chip and CT. However, the affinity of the workpiece for commercial coatings in textured tools led to the formation of BUE, resulting in a reduced CT life in comparison to CTs coated by TiN-WS2. The tool life of the coated textured tools was upgraded by about 43 % compared to commercial CTs.

Patel and Patil [51] developed an extremely chemically stable ceramic insert made of Al_2O_3-ZrO_2 to investigate the impact of feed rate, depth of cut, and cutting speed on CT wear mechanism and surface roughness during the cutting of titanium alloy. The findings indicate that at low depth of cut and cutting speed, the primary tool wear mechanisms are chipping and abrasion. However, at high levels of depth of cut and cutting speed, diffusion is observed at the crater, which cause the formation of a BUE that results in catastrophic fracture of CT. At elevated temperatures, the diffusion of elements such as titanium, oxygen, carbon, and others from the workpiece to the CT acts as the seed of the built-up-layers (BUL) formation. When cutting at high cutting speeds and depths of cut, the high chip flow rate disbands these layers, leading to degradation in the hardness of the tool. This degradation progresses to catastrophic fracture of the CT. Moreover, when the cutting speed is a high and the depth of the cut is low, the roughness of the cut surface is increased by about 69.6 %.

As the use of advanced CTs with special geometry or advanced material properties is the only pathway to augment the performance of the dry cutting process, it is recommended to apply advanced coating materials and special texture geometry on the CT to outstanding the elevated temperatures of the dry cutting process. Dry machining stands out as an environmentally friendly practice that avoids environmental pollution and eliminates the need for hazardous CFs, contributing to sustainable machining [52]. Additionally, the performance of dry machining can be enhanced by incorporating self-lubricating tools and employing conservative machining strategies. Dry machining offers several advantages [53–55].

i. Environmental benefits: Dry machining eliminates environmental pollution such as water and air pollution that may occur with wet machining processes.
ii. Recycling of swarf: Swarf generated during dry machining, including chips and metal dust, has the potential for recycling, contributing to sustainable manufacturing practices. In flood machining, the swarf is cleaned using costly chemical treatments, but this is unnecessary in dry machining, making dry machining swarf more valuable.
iii. Operator safety: Dry machining is skin-friendly, allergy-free, and non-hazardous for operators, providing a safer working environment.
iv. Cost savings: In wet machining, the expense associated with coolant is usually three to four times higher than the cost of the tool itself, and additional costs include storage, disposal, maintenance, and labor operating costs. Dry machining eliminates these expenses.
v. Reduction in cutting force: During high-speed machining, the high temperature at the cutting zone in dry machining can lower the flow stress of the material, ultimately reducing cutting forces.
vi. Improved tool life: In intermittent or non-continuous machining operations, dry machining can improve CT life compared to wet machining, as wet machining may cause thermal shock due to temperature differences.

Health concerns, particularly skin disorders like irritant and allergic contact dermatitis, remain a significant issue for workers exposed to CFs during machining. To reduce these risks, it is essential to implement strict control measures, such as modifying machining processes, enclosing equipment to limit aerosol exposure, transitioning to alternative CFs, and employing local exhaust systems to capture and eliminate harmful substances. Additionally, residual CFs on workpiece surfaces can lead to further exposure and environmental contamination. Research, including [56–58], indicates that CFs can represent a considerable portion of manufacturing costs, making the optimization of CF usage a critical approach for reducing expenses and improving safety. By adopting these strategies, manufacturers can enhance both worker health and sustainability while achieving more cost-efficient production.

This machining technology not only improves efficiency but also aligns with sustainability goals in the machining industry. Dry machining offers an effective solution to mitigate health risks associated with prolonged exposure to CFs, including respiratory diseases, skin infections, dermatitis, and cancer. Furthermore, it has the potential to boost the overall performance of cutting operations.

2.2. Mist cooling technique

Mist cooling involves the ejection of liquid coolant from a pressurized nozzle, forming droplets that disperse and condense as liquid in the form of a thin film on the cooled surface [59]. This technique is used in machining processes where flood cooling is impractical. This technique is typically accomplished with water-based CFs and is considered more effective than conventional flood cooling with lower ecological impact. The mist is dispersed at a flow rate of 0.05–0.5 L/h, significantly lower than flood cooling situations [60].

The mist cooling system includes a compressor, a nozzle, and a mist generator, providing high-speed/pressure impingement on the cutting zone. Compared to flood and dry environments, mist cooling shows less CT wear. In flood conditions, tool wear tends to be lower compared to dry conditions, likely attributed to lubrication action and the resulting lower temperatures in the cutting zone. Mist application proves to be more effective than flood and dry environments, depending on cutting parameters. For instance, in drilling titanium alloy, mist cooling with water-oil (ester oil) mist spray increased tool life by 66 % compared to dry environment [61]. Gautam et al. [62] investigated the machinability of Ti6Al4V using SiAlON ceramic and AlTiN-coated carbide tools under dry conditions and mist conditions by applying biodegradable oil in water. The anti-adhesion characteristics of coated CTs minimizes chip-tool contact during alloy machining, leading to reduced cutting forces. Additionally, mist conditions help decrease the fragment of the cutting edge for these tools. However, SiAlON ceramic tools show inferior performance in dropping cutting forces and wear attributable to their lower thermal conductivity. Moreover, mist conditions did not enhance the performance of ceramic CT during Ti6Al4V alloy cutting. While mist conditions reduce chip-tool contact length by about 13 % for coated carbide tools, ceramic tools without an anti-adhesion coating exhibit significantly higher contact length. Turning Ti6Al4V under mist conditions has been theoretically and experimentally investigated by Ref. [63]. The cooling effect of mist prevails over its lubricating action at higher temperatures resulting from frictional wear, especially at higher cutting speeds. Thick mist, characterized by low droplet diameter, facilitates effective heat subtraction from pores, thereby enhancing its performance. Mist cooling exhibits a more pronounced effect on reducing temperatures at the tool-chip interface during lower cutting speeds compared to higher speeds. It represents a greener alternative to flood cooling in manufacturing operations and offers improved performance in terms of workpiece quality and tool longevity compared to dry machining conditions.

2.3. Minimum quantity lubrication (MQL)

MQL is a micro-lubrication technique designed to enable near-dry machining [64]. This approach replaces large quantities of traditional CFs, often water and mineral oil-based, with a minimal amount of environmentally friendly lubricant, commonly derived from vegetable oils, mixed with air [65]. It is characterized by the combination of compressed air with a small quantity of oil applied to the cutting zone at rates ranging from 0.01 to 0.15 L/h [66]. MQL facilitates the efficient penetration of lubricant, thereby decreasing friction at the machining interfaces and preventing heat generation caused by friction. Hence, besides cooling, the implementation of MQL improves lubrication conditions [67]. Utilizing compressed air for MQL application also aids in the effective dissipation of heat via forced convection [68]. Machining under MQL conditions has demonstrated improved machinability of different materials, boosting tool lifetime, as well as improved workpiece quality when compared to both flood and dry machining alternatives [69]. Indeed, MQL occupies a middle ground between flood cutting and dry cutting [70]. In contrast to flood cutting, MQL offers the advantage of reducing the consumption of CF, thereby cutting costs associated with fluid procurement and eliminating the need for treating waste liquid generated during the machining process. Additionally, when compared to dry cutting, MQL can offer some degree of cooling and lubrication to the cutting zone, enhancing tool life and improving machining efficiency.

MQL is widely applied across grinding, milling, turning, and drilling to deliver lubrication, cooling, and chip evacuation. Conventional MQL utilizes compressed air (0.4–0.6 MPa), which atomizes the CF into fine droplets and delivers it to the cutting zone via a nozzle [71]. Throughout the machining process, the CF serves three primary functions: cooling the cut materials and CT, evacuating chips var away from the cutting region, and lubricating the chip-tool interface. Extensive experimental studies have demonstrated MQL's efficacy in providing efficient lubrication and cooling across several machining operations. In comparison to dry environment, MQL exhibits advantages in reducing cutting force, cutting zone temperature, and tool wear [72]. Furthermore, MQL offers significant reductions in CF consumption compared to flood cutting methods, thereby leading to cost savings in production.

Advancements in research have led to numerous innovations and developments within the realm of MQL machining [73]. Through further exploration of this domain, researchers have pioneered novel and environmentally sustainable approaches to machining [74]. Closed-loop Minimum Quantity Lubrication (MQL) systems have been engineered to recycle cutting fluid after machining, effectively filtering out chips and contaminants before reintroducing the purified fluid back into the nozzle for reuse. This method drastically reduces fluid consumption. Moreover, employing compressed air as the carrier for lubricant in place of oil offers benefits in reducing ecological impact. Employing high-frequency waves induces the formation of microcavities within the CF, resulting in diminished friction, tool wear, and heat generation [75]. Using laser technology to heat the CF locally at the tool-workpiece interface creates a vapor film, leading to excellent cooling and lubrication properties [76]. The applications of advanced sensing technology in MQL systems to monitor real-time vibration and temperature, have significantly aided in adjusting air pressure, flow rate, and nozzle position, thus augmenting machining performance [77]. Incorporating magnetic nanoparticles to enhance the capacity of infiltration in grinding has resulted in enhanced surface integrity and tribological characteristics, especially in large contact-length grinding [78].

Nevertheless, there are limitations to MQL application in controlling heat generation and friction, particularly when cutting materials with bad thermal properties. The addition of nanoparticles into CFs used in MQL has been proposed to boost the thermophysical and tribological properties of the CFs to obtain nanofluids with improved thermophysical properties [79]. The cutting nanofluid, consisting of a base fluid containing nanoparticles, is mixed with compressed air for application. This combination enhances cooling significantly, while the nanofluid augments lubrication conditions at machining interfaces by stimulating a rolling action and creating a shielding lubricating layer between them [80]. The sliding action of various nanoparticle layers contributes significantly to improving tribological properties. When exposed to high loads and temperatures, the nanoparticles positioned between two adjacent surfaces flatten out, creating a "sliding arrangement" that minimizes friction and wear. This arrangement also forms a sliding system during machining, further reducing friction and wear. Moreover, it leads to the formation of a liquid film with non-heterogeneous nanoparticle dispersions on the surface, a common phenomenon that results in decreased friction and wear. In other words, the infusion of nanoparticles into micro-pits alongside cutting oil lessens the contact area between tool and chip pairs, leading to a notable decrease in heat generated via friction action at the interface, thereby enhancing cooling performance during machining, termed the surface repairing effect. The utilization of nanoparticles with superior strength and hardness effectively dislodges surface chips between friction pairs, a phenomenon known as the polishing effect. Additionally, nanoparticles roll within the friction pairs along with cutting oil, a mechanism referred to as the rolling mechanism. Lastly, nanoparticles have the capability to form a shielding film on the contact surface, greatly enhancing lubrication performance during machining.

The selection of the appropriate base oil, nanoparticle type, nanoparticle concentration, and flow rate are identified as crucial aspects that influence the effectiveness of cooling performance of the nano-MQL (NMQL) [81]. Senol Sirin et al. [82] examined the impact of dry, flood, and NMQL on various machinability measures including cutting force, cutting temperature, surface roughness, micro-hardness, and flank wear during the turning process of X-750 Nickel alloy by employing a vegetable oil enriched by boron nitride nanoparticles. They found that surface roughness improved by approximately 39 % and 42 % with MQL and NMQL, respectively. Additionally, the use of NMQL leading to the lowest temperature generation, cutting force, and minimal flank wear.

Makhesana et al. [83] examined the effectiveness of various lubricating conditions, including dry, MQL, and NMQL with sunflower oil enriched with molybdenum disulfide or Graphite, aiming to enhance the machinability of Inconel 625. The lowermost friction coefficient, with an average reduction of 35 % and 41 %, is attained with 1.5 % graphite and molybdenum disulfide, respectively. This reduction is credited to the layered structure of the nanoparticles used, which facilitates the formation of a lubricant layer between the friction counterparts, thereby decreasing friction. Moreover, the inclusion of molybdenum disulfide and graphite nanoparticles in the base fluid raised both thermal diffusivity and viscosity. The enhanced performance of NMQL is credited to the efficient penetration of the lubricant into the machining interfaces and the lubricant mixture's ability to form a film. Additionally, the utilization of MQL with pressurized air enabled smooth removal of chips and efficient heat transfer in the cutting environment. The combination of sunflower oil droplets and compressed air enables smooth sliding of chips over the rake surface of the CT, effectively reducing friction and tool wear. Compared to dry and MQL machining, where significant abrasion wear and chip flow damage are observed on the CT, NMQL led to less abrasion wear. The implementation of NMQL with molybdenum disulfide led to the lowest temperature among the tested conditions, surpassing dry machining, MQL, and NMQL with graphite. Specifically, relative to dry machining, MQL, graphite NMQL, and molybdenum disulfide NMQL exhibited reductions in the temperatures of cutting region by 18 %, 25 %, and 35 %, respectively.

Lv et al. [84] utilized Fe_3O_4 nanofluid in NMQL machining of 430 stainless steel. In contrast to MQL, the utilization of NMQL led to reductions of approximately 35.5 % in temperature, 52.4 % in flank wear, and 43.2 % in cutting force. The chips generated by NMQL exhibited a higher degree of serration compared to those produced by MQL. These chips were simpler to fracture and expel, thus averting adherence to the CTs. The Fe_3O_4 nanofluid droplets demonstrated enhanced penetration and heat flow capabilities, leading to improved friction conditions at the tool-chip contact area and a reduction in frictional heat generation. Consequently, the workpiece failure strain diminished even more, resulting in a higher degree of chip serration.

Wang et al. [85] suggested utilizing water-based graphene nanofluid for the micro-milling process of a titanium alloy (TC4) using diamond inserts under NMQL conditions. Tool wear was detected due to the existence of different wear mechanisms such as adhesive and abrasive wear, fragmentation, edge chipping, and graphitization. Tool wear intensified with increased machining distance. However, compared to dry conditions, there was a decrease in the extent of tool wear in the NMQL environment. This reduction can be attributed to the transition from direct contact (workpiece-tool) to indirect contact (workpiece-graphene-tool) facilitated by the utilized nanofluids. Consequently, the friction and impact between the chipping and workpiece on the CT were impeded by the presence of graphene.

Sarikaya et al. [86] performed turning operations on Haynes 25 superalloy under diverse cutting conditions, namely dry, MQL, and NMQL by employing a vegetable oil enriched by boron nitride, molybdenum disulfide, or graphite nanoparticles, by varying feed rate and cutting speed. The thermal conductivity was increased by 16.29 % and the cutting temperature was lessened by 34.95 % when molybdenum disulfide nanofluid was employed in comparison to the pure CF followed by graphite nanofluid (14.12 % and 29.32 %) and boron nitride nanofluid (11.90 % and 27.18 %). The best surface quality was obtained after turning ung graphite NMQL, while boron nitride NMQL had minimal tool wear compared with other cutting conditions. They also reported that agglomeration is a critical issue that hinders the good application of nanofluids in metal cutting. Ultrasonic vibrations offer an effective solution for addressing agglomeration issues in nanofluid MQL and consequently, machining efficiency is improved [87–89].

The adoption of MQL has notably enhanced heat dissipation, tool life, tool wear, cutting force, and surface integrity. However, optimizing process control parameters and MQL settings, including flow rate of CF, nozzle angle, nozzle location, and compressor pressure, is essential. Furthermore, when aiming for sustainable manufacturing, careful consideration of the material and CT is crucial in determining the MQL fluid type and operational parameters. Many inestigations have consistently shown that MQL-improved hybrid nanofluids outperform dry-cutting conditions as well as mono-nanofluids [90–93]. However, due to the various combination of variables that can influence performance, more comprehensive investigations are necessary. Increasing the nano-additives concentration in NMQL can slow down the wear process. In some other investigations, it was declared that mono-nanofluids could outperform hybrid-nanofluids in NMQL cutting processes.

Usluer et al. [94] used a hybrid nanofluid enriched by multi-walled carbon nanotubes and molybdenum disulfide nanoparticles in NMQL cutting of S235JR steel. Cutting with NMQL using a mono-nanofluid showed better machining performance than NMQL cutting with a hybrid-nanofluid. The total machining costs were significantly reduced under the NMQL cutting using mono-nanofluid, with reductions of up to 76 % in comparison to dry machining, up to 73 % in comparison to MQL cutting, and up to 61 % in comparison to NMQL cutting using hybrid-nanofluid. These reductions were attributed to improved tool life and decreased energy consumption compared to other parameters. The same conclusion was reported in Ref. [95] for the milling of compacted graphite iron under NMQL cutting conditions using a hybrid nanofluid enriched by multi-walled carbon nanotubes and molybdenum disulfide nanoparticles. The most effective cutting conditions for all sustainability indicators and machining responses are as follows: NMQL with mono-multi-walled carbon nanotubes, NMQL with hybrid nanofluid, NMQL with mono-molybdenum disulfide, MQL, and dry, in that order. Employing the NMQL using multi-walled carbon nanotubes-based nanofluid led to reductions in carbon emissions amount, resultant force, cutting temperature, surface roughness, and overall machining cost by 7.6 %, 54.4 %, 38.2 %, 57.5 %, and 24.5 %, respectively. Compared to the dry-cutting condition. Adjusting the nanofluid mixture ratio appropriately has been reported to significantly impact the performance of the machining process. Thus, further experimental investigations should be carried out to optimize the nanoparticle's concentrations and ratios to maximize the machining performance. MQL in machining and metal cutting offers several benefits:

Reduced Environmental Impact: MQL systems use significantly less lubricant compared to traditional flood coolant systems, resulting in reduced coolant consumption, waste generation, and environmental pollution.

Cost Savings: By using minimal amounts of lubricant, MQL systems can lead to significant cost savings associated with purchasing, disposing of, and managing coolant fluids.

Improved Health and Safety: MQL systems reduce operator exposure to potentially hazardous coolant mists and chemicals, creating a safer working environment. Additionally, the reduction in coolant usage minimizes the risk of skin irritation and respiratory issues among machine operators.

Enhanced Tool Life: While providing sufficient lubrication to the CT and workpiece, MQL systems help reduce friction and heat generation in the cutting region, thereby extending tool life and lessening tool wear.

Better Surface Finish: MQL can contribute to improved surface finish on machined parts by reducing the risk of surface defects such as built-up edge formation, smearing, and surface discoloration often associated with excessive heat and poor lubrication.

Increased Productivity: By minimizing the need for tool changes and interruptions due to coolant replenishment, MQL systems can help improve overall machining productivity and reduce downtime.

Machining of Heat-Sensitive Materials: MQL is particularly beneficial for machining materials sensitive to heat such as aerospace alloys and stainless steels, where excessive heat generation can cause thermal damage and dimensional inaccuracies. The reduced heat generation and effective lubrication provided by MQL help mitigate these issues.

Chip Evacuation: MQL systems can aid in chip evacuation by reducing chip adhesion to the CT and workpiece surface, promoting better chip flow and preventing chip re-cutting, which can cause tool wear and poor surface finish.

Concisely, MQL offers a balance between effective lubrication and minimal environmental impact, making it an attractive option for various machining applications, especially those requiring high precision, improved tool life, and enhanced surface finish.

2.4. Cryogenic machining

Cryogenic cooling involves reducing the cutting temperature in metal cutting processes by utilizing cryogenic fluids as coolants. The usage of liquid nitrogen as a lubricant in cryogenic machining is considered environmentally safe and eliminates the need for disposal facilities [96]. In this process, liquid nitrogen is employed in the cutting area to minimize consumption. Cryogenic cooling has been associated with benefits such as enhanced surface finish, reduced cutting force, improved tool life, improved chip handling and breaking, better dimensional accuracy, increased productivity, and decreased production costs.

Khanna et al. [97] carried out a comprehensive analysis of the sustainability aspects involved in machining titanium tubes, considering environmental and economic factors under various conditions, namely flood and cryogenic cutting. Additionally, they investigated machinability characteristics, including power consumption and tool wear, which are integral to the sustainability assessment. Cryogenic turning was found to be more sustainable and cost-effective compared to flood machining. Total machining costs decreased by approximately 27 % when machining under a cryogenic condition in comparison to flood conditions. When machining titanium tubes, the cryogenic environment emits less carbon compared to dry and flood-cutting conditions. Carbon emissions were observed to be 9 % lower in cryogenic machining than in wet machining. In terms of tool wear, flank wear is a vital factor for tool failure when turning titanium alloys. Cryogenic machining has demonstrated greater sustainability and efficiency in turning titanium tubes at high speeds compared to dry and flood machining methods. The introduction of liquid CO_2 in cryogenic environments reduces temperatures adjacent the cutting area, resulting in reduced tool wear. For instance, at a cutting speed of 150 m/min, tool life significantly augmented by 38.68 % in cryogenic machining compared to flood machining, and by 72.24 % compared to dry machining. Additionally, there is a reduction in power consumption by 19 % and 14 % at cutting speeds of 150 m/min and 200 m/min, respectively, in cryogenic machining compared to flood machining. This reduction in power consumption is credited to the absence of the need for motor power to deliver lubricant to the cutting area in cryogenic turning. It is also worth noting that there is a significant power consumption of 3 kW during idle conditions in wet turning. It was evident that the overall cost would be lower under a cryogenic condition. This suggests that choosing this cutting environment would result in lower expenses for the same cutting length. The cost lessening can be credited to several factors, including reduced tool wear, reduced energy consumption, and improved efficiency.

The augmented tool life, reduced power consumption, lower costs, and decreased carbon emissions demonstrate the superior sustainability and machinability of the cryogenic machining process in comparison to traditional machining processes. Cryogenic cooling offers several benefits in machining and metal cutting:

Increased Tool Life: Cryogenic cooling can significantly lessen the temperature of the CT and workpiece, effectively minimizing tool wear and extending tool life. This is especially beneficial for CTs made of carbide or high-speed steel.

Enhanced Machining Speeds: Lower temperatures at the cutting area reduce the risk of thermal deformation and tool failure, allowing for higher cutting speeds and feeds without compromising lifespan of CT or part quality.

Improved Surface Finish: Cryogenic cooling helps control heat generation and chip formation, resulting in smoother surface finishes on machined parts. This can reduce the need for secondary finishing operations and improve overall part quality.

Reduced Cutting Forces: The application of cryogenic coolant can reduce cutting forces, leading to less stress on the CT, machine, and workpiece. This can result in improved machining accuracy, especially for complex geometries or thin-walled parts.

Minimized Built-up Edge: Cryogenic cooling helps avert the creation of BUE on the CT, which can negatively impact surface finish, tool life, and dimensional/geometrical accuracy. This is particularly important when machining sticky or gummy materials.

Effective Chip Evacuation: Cryogenic cooling can aid in chip evacuation by reducing chip adhesion to the CT and workpiece. This helps maintain consistent chip flow and prevents chip re-cutting, which can cause tool wear and impair surface finish.

Machining of Heat-Sensitive Materials: Cryogenic cooling is especially beneficial for machining materials sensitive to heat including titanium alloys, nickel-based superalloys, and composites, where traditional cooling methods may cause thermal damage or material degradation.

Environmental Benefits: Unlike traditional coolant fluids, cryogenic coolants including liquid nitrogen or carbon dioxide evaporate without leaving residue, minimizing environmental impact. Additionally, cryogenic cooling systems typically consume less coolant, reducing waste generation.

Concisely, cryogenic cooling offers significant advantages in terms of tool lifespan, machining speed, surface finish, and environmental sustainability, making it a valuable option for several machining applications, particularly those involving challenging materials or high-precision requirements.

2.5. *High-pressure cooling (HPC)*

HPC systems are employed in cutting hard materials to reduce tool wear and production costs. In this method, high-pressure coolant, typically ranging from 5 to 35 MPa, is directed into the machining area through a nozzle [98]. The elevated pressure facilitates efficient penetration of the fluid into the interfaces between the workpiece and CT, as well as between the chip and CT [99]. As a result, optimal lubrication and cooling occur precisely at the anticipated location. This reduces the temperature at the cutting area and enhances the lubricating characteristics over the cut material.

Adjusting the flow rate and pressure of the fluid in turning operations is an efficient technique to lessen the temperature in the cutting area, enhance efficiency, and control chip formation [100]. Compared to traditional cooling methods, HPC effectively penetrates into the cut material to a deep depth, providing a more substantial cooling effect [101]. The use of HPC has been reported to reduce friction during machining operations, making it a valuable technique for improving cutting efficiency [102]. Additionally, CFs, including HPC, have a direct influence on the environment [103]. In comparison to dry conditions, the use of duplex HPC has shown improvements in tool life [104]. The HPC jets contribute to reduced force, tool wear, reduced heating, and chip reduction coefficient (CRC) by guaranteeing adequate lubrication. An increase in feed and cutting speed resulted in a lower CRC value, likely due to temperature rise, and chip stretching and thinning [105]. The combination of textured CTs with HPC has demonstrated a substantial impact on material cutting, leading to extended CT life and improved productivity due to surface texturing [106].

Sultana and Dhar [107] developed a novel rotary HPC to deliver high-pressure coolant jets without requiring significant modifications to the solid end mill cutter during the milling of Ti-6Al-4V titanium alloy. Biodegradable VG-68 cutting oil was selected as the CF attributable to its excellent thermo-physical characteristics, including higher flash points. Machinability was evaluated across different cutting speeds and feed rates. The assessment considered cutting force, cutting temperature, surface roughness, and flank wear as key parameters. Dry milling exhibited the least favorable results for evaluated measures, primarily due to extreme flank wear resulting from the absence of lubrication and cooling. In comparison, HPC demonstrated improvements, reducing cutting force, cutting temperature, and surface roughness by 8.63–13.12 %, 11.21–21.57 %, and 6.29–28.4 %, respectively. Rotary RHPC further enhanced these outcomes, achieving reductions of 14.05–21.18 %, 15.39–27.27 %, and 16.48–41.04 % for the same parameters.

High-pressure cooling in machining and metal cutting offers several benefits, including:

Improved Tool Life: High-pressure cooling aids in dispersing heat generated during machining more effectively, plummeting tool wear and augmenting tool life. This is particularly useful when machining tough and hard materials or using high levels of speeds.

Enhanced Surface Finish: By efficiently removing chips and cooling the cutting area, high-pressure cooling may result in smoother surface finishes on machined parts, reducing the need for additional finishing operations.

Increased Productivity: With better heat dissipation and chip evacuation, machining processes can run at higher feeds and speeds without compromising CT lifespan or part quality, leading to increased productivity and shorter cycle times.

Better Chip Control**:** High-pressure coolant aids in breaking and flushing away chips from the cutting area, averting chip re-cutting and minimizing the risk of built-up edge formation, which can degrade surface finish and tool life.

Reduced Risk of Workpiece Deformation: Cooling the workpiece effectively during machining helps minimize thermal distortion, which is especially critical for precision machining operations where tight tolerances are required.

Improved Lubrication: High-pressure coolant can act as a lubricant between the CT and the workpiece, plummeting friction and resulting in smoother cutting action, which further contributes to improved tool lifespan and surface finish.

Machining of Difficult-to-Machine Materials: High-pressure cooling enables the efficient machining of difficult-to-cut materials such as heat-resistant alloys, hardened alloys, and exotic metals by effectively managing heat and reducing the likelihood of thermal damage to the workpiece and CT.

Environmental Benefits: High-pressure cooling systems typically use less coolant compared to traditional flood coolant systems, resulting in reduced coolant consumption and waste generation. This can lead to cost savings and a smaller environmental footprint.

Concisely, high-pressure cooling in machining and metal cutting offers a comprehensive set of advantages that contribute to improved machining performance, tool life, part quality, and environmental sustainability.

3. Cutting fluids' role in machining

The central roles of a CF involve lubricating and cooling the workpiece during cutting operations. The lubricating feature of cutting coolant diminishes adhesion and abrasion at small cutting speeds values, while also lubricating the contact zones between moving chips and the CT rake face. Currently, there is a wide range of CFs available, and their effectiveness depends on factors such as cooling strategies, cutting parameters, and the type of machining being performed.

The characteristics of CFs should remain consistent within specified ranges of temperature, pressure, and time, maintaining a good chemical stability. For example, CFs must avert corrosion of the cut materials, as well as lubricate the slides and machine bearings.

Metal cutting is the procedure of take away a thin layer of material from a workpiece. In this process, a sharp-edged tool is positioned to a specific cutting depth and transfers in the cutting direction over to the workpiece. The chips formation is a common outcome in all machining processes, resulting from the deformation of the cut material on the machined surface with the assistance of a CT. The size and shape of the chips vary based on the cutting control factors, work material, cutting strategies, and tool geometry. The primary goal of machining operations is to enhance productivity and quality while minimizing machining costs. During machining, the cutting process involves overcoming the shear strength of the workpiece, leading to the generation of a significant amount of heat through severe plastic deformation mechanisms. This occurs as the cutting forces strive to overcome the shear strength of the workpiece material at high strain rates. Additionally, friction between the tool and the chip/workpiece contributes to heat generation. Following the metal cutting principles, heat generation takes place in three main deformation zones (DZ) during the metal cut process: the primary, secondary, and tertiary DZs as shown in Fig. 4. Each zone contributes to heat generation as follows.

1. Primary DZ: Heat is developed due to plastic work done at the shear plane.

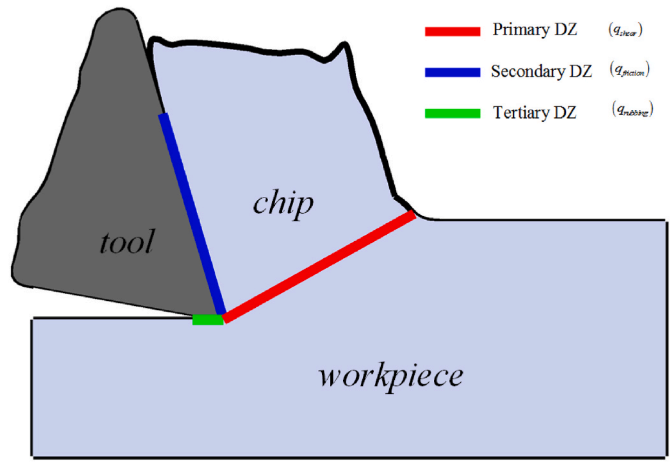

Fig. 4. Main heat sources during cutting operations.

2. Secondary DZ: Heat is developed as a result of work done in chip deformation and overcoming friction occurred during sliding of chip over CT.
3. Tertiary DZ: Heat is developed as a result of work done in overcoming friction occurred during the sliding of the tool flank face on the fresh machined surface.

Utilizing CFs in machining operations can diminish cutting power. These fluids play a role in facilitating chip evacuation and preventing tool and BUE clogging. The efficiency of chip evacuation is contingent on the flow rate and viscosity of the CFs. CFs with enhanced viscous characteristics exhibit lower efficacy in evacuating chips from the machining area in comparison to fluids with poor viscous characteristics.

CFs, also known as metalworking fluids, serve several important roles in machining processes. As coolants, CFs serve to lower cutting temperatures by dissipating heat. When water-based fluids are employed, cooling becomes more crucial than lubrication. Experimental evidence indicates that the effectiveness of CFs in reducing temperature diminishes with higher cutting speeds and cutting depths. As a lubricant, the CF functions to minimize the contact area between the tool and the chip. Its efficacy depends on its capacity to infiltrate the chip-tool interface swiftly and form a thin layer within a short timeframe. This layer is established chemically via reaction or physically via adsorption and must exhibit shearing resistance lower than the material's resistance in the interface. Consequently, it indirectly acts as a coolant by reducing heat generation and, consequently, cutting temperature. The CF's capability to clear chips from the cutting zone is influenced by its viscosity, volume flow, the type of machining operation, and the formed chip type. This function holds particular significance in certain cutting operations, such as drilling and sawing, where it plays a crucial role in preventing chip obstruction and, consequently, tool breakage. Some of the key roles of CFs include.

i. Cooling: CFs help dissipate heat generated during machining processes, preventing overheating of the tool and workpiece. This is crucial for maintaining the dimensional accuracy of the workpiece and extending CT life.
ii. Lubrication: CFs act as lubricants, reducing friction between the CT and the workpiece. This lubrication minimizes wear on the tool and workpiece surfaces, enhancing the overall machining process.
iii. Chip Evacuation: The presence of CFs aids in the efficient removal of chips or swarf from the cutting zone. This prevents chips from accumulating and interfering with the cutting action, leading to improved surface finish.

iv. Tool Cooling: CFs cool the CT directly, preventing it from reaching high temperatures that could initiate tool wear or even failure. Cool tools are more effective and durable.
v. Corrosion Protection: CFs create a protective film on the machined surfaces, preventing corrosion and rusting. This is especially important for materials prone to corrosion.
vi. Improving Surface Finish: The use of CFs can contribute to achieving a smoother and more precise surface finish on the machined workpiece.
vii. Reducing Friction and Wear: CFs help reduce friction between the CT and workpiece, minimizing wear on both surfaces. This is critical for maintaining the accuracy of the machined parts.
viii. Improving Machining Accuracy: By facilitating effective chip lubrication, removal, and cooling, CFs contribute to maintaining tight tolerances and achieving accurate machining.
ix. Extending Tool Life: Proper lubrication and cooling provided by CFs contribute to the longevity of CTs, dropping the frequency of tool changes and associated costs.
x. Environmental Considerations: In recent times, there is a growing emphasis on environmentally friendly CFs that are biodegradable and have minimal environmental impact.

It is imperative to note that the choice of CF and its application depends on factors such as the material being machined, the cutting process, and environmental considerations. The choice of CF in machining is influenced by several factors, including:

Material Being Machined: Different materials have varying machining characteristics and requirements. For example, ferrous metals like steel may benefit from a different type of CF compared to non-ferrous metals like aluminum or titanium alloys.

Machining Operation: The specific machining operation being performed, such as turning, milling, drilling, or grinding, can dictate the type of CF required. Some operations may generate more heat or friction than others, necessitating different lubrication and cooling properties in the CF.

Tool Material and Coating: The type of CT material (e.g., carbide, high-speed steel) and any coatings (e.g., TiN, TiAlN) can influence the choice of CF. Certain fluids may be more compatible with particular tool materials or coatings, leading to better tool performance and longevity.

Machining Conditions: Factors such as cutting speed, feed rate, cutting depth, and machining environment (e.g., dry, semi-dry, or wet) play a central role in selecting the appropriate CF. For example, high-speed machining may require a CF with better cooling properties to dissipate heat effectively.

Surface Finish Requirements: The desired surface finish of the machined part can impact the choice of CF. Some fluids may help achieve smoother surface finishes by reducing friction and minimizing built-up edge formation.

Environmental and Health Considerations: Increasingly, there is a focus on selecting CFs that are environmentally friendly and pose minimal health risks to machine operators. Water-based CFs are often preferred over oil-based ones due to their lower environmental impact and reduced health hazards.

Cost Considerations: The cost of the CF, including purchasing, disposal, and maintenance costs, is an important factor in the selection process. While some high-performance CFs may come at a higher initial cost, they may offer long-term benefits such as improved tool life and productivity.

Regulatory Compliance: Compliance with local regulations and industry standards regarding CF usage, disposal, and workplace safety is essential. Choosing CFs that meet relevant regulatory requirements helps ensure legal compliance and safe working conditions.

By considering these aspects, manufacturers can make informed decisions when selecting the most suitable CF for their machining processes, balancing performance, cost, environmental impact, and safety considerations.

4. CFs types

CFs can be categorized into two main types, namely oil-based, water-based, and gas-based [108,109] as shown in Fig. 5. The CF should have many important features such as.

i. Effective lubricating properties.
ii. Efficient thermal conductivity to facilitate effective cooling.
iii. High heat-absorbing capacity.
iv. A high flash point to avoid fire incidents.
v. A suitable viscosity that allows efficient flow on the workpiece and dripping from the workpiece and the formed chips.
vi. Must exhibit stability against oxidation.
vii. Must not promote discoloration or corrosion of the cut material.
viii. Should provide some corrosion protection to freshly machined surfaces.
ix. There should be no unpleasant odor emitted during the cutting process.
x. Should not generate gummy or solid precipitates at typical working temperatures.
xi. It must not result in skin contamination or irritation.
xii. Types of CFs

4.1. Oil-based CFs

CFs based on oil are formulated with oil as the primary fluid. These fluids exhibit excellent biological stability but may have inadequate cooling performance [110]. They are commonly employed in slow or heavy-duty processing applications. Traditional CFs typically comprise mineral-based petroleum oils, which offer effective performance but pose challenges due to their toxicity and disposal difficulties. Consequently, these fluids present hazards to both human health and the environment.

Neat-cutting oils are not mixed with water. Originally, oil-based CFs were derived from vegetable and animal oils. However, due to the susceptibility of vegetable and animal oils to degradation during usage, they are substituted with mineral oils. They typically consist of mineral oil blended with vegetable, marine, or animal oils to enhance lubricating and wetting properties. Compounds like chlorine, sulfur, and phosphorus may be used as additives to boost the lubrication properties of the CF for high-pressure applications. Two key categories of neat cutting oils are active and inactive.

Active oils have sulfur that is loosely bound to the oil. Therefore, the sulfur is easily released by reacting with the workpiece during the cutting operations. These oils exhibit effective lubrication and cooling properties. Specifically, formulated blends with increased sulfur content are designed for demanding heavy-duty machining operations. They are well-suited for challenging materials such as low carbon and chrome-alloy steels, commonly used in thread-cutting applications. Moreover, they prove beneficial in grinding processes by preventing the grinding wheel from accumulating debris, thereby extending the life of the grinding wheel.

Inactive oils such as mineral oils contain sulfur that is firmly attached to the oil. While mineral oils offer outstanding lubrication characteristics, they are less effective at dissipating heat from the workpiece and CT. Mineral oils are well-suited for non-ferrous materials like brass, magnesium, and aluminum. Mixtures of mineral oils are also utilized in grinding processes to achieve high surface finishes on both non-ferrous and ferrous metals.

With advancing technology and growing environmental awareness, sustainable manufacturing practices emphasizing environmental friendliness, energy efficiency, and resource conservation have become increasingly significant. To mitigate the environmental impact and treatment costs associated with CFs, scholars have explored the use of various vegetable oils in different cutting processes. Vegetable oil-based

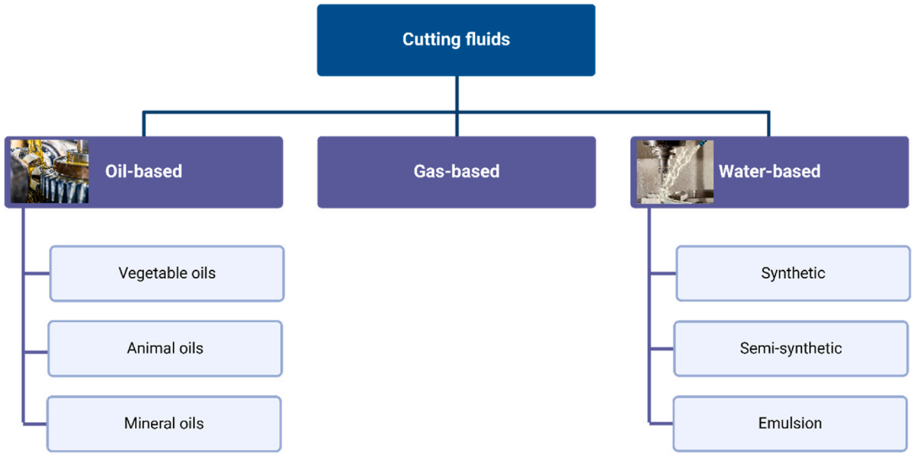

Fig. 5. Categories of CFs.

CFs, derived from natural sources, are readily accessible, environmentally friendly, and pose no harm to human health. Additionally, they are renewable resources, further enhancing their sustainability [111]. However, different types of vegetable oils possess distinct physical and chemical properties, leading to variations in their lubricating performance [112]. Hence, it is crucial to carry out investigations regarding the lubrication performance of several common vegetable oils and declare the one exhibiting superior lubricating properties as the preferred oil for metal-cutting applications. Recently, great attention has been paid to vegetable oils, such as rapeseed oil, soybean oil, corn oil, peanut oil, castor oil, palm oil, and sunflower oil, as an ecofriendly alternative to mineral oils [113].

4.2. Water-based fluids

Water-based CF is frequently utilized in high-speed machining to guarantee machining precision. Water-based CFs can also be categorized into synthetic and semi-synthetic fluids as well as emulsions. Emulsions are created by blending base oil and water in specific proportions, with an oil content ranging from 60 % to 90 % [114]. The particle size is typically between 1 and 10 μm, and it has a milky nature and white color. Emulsions serve both lubrication and cooling functions. However, they exhibit poor stability and are susceptible to bacterial growth during use.

Semi-synthetic fluids combine the benefits of synthetic fluids and emulsion. In comparison to emulsion, they incorporate more surfactants, resulting in smaller oil droplet sizes ranging from 50 nm to 100 nm. This makes them less susceptible to deterioration and more stable. Semi-synthetic fluids have a transparent or translucent appearance, making it easy to observe the cutting area during machining. Synthetic solution, devoid of oil, uses additives like water-soluble synthetic grease for lubrication. It has a transparent appearance and exhibits excellent cooling performance, but it may lead to machine tool rust.

The rapid development of water-based CFs is attributed to advancements in processing conditions, the demand for emission reduction and energy efficiency, and investigation on advanced additives such as corrosion inhibitors, lubricants, and bactericides. Water-based CFs are gaining popularity due to their cost-effectiveness and outstanding cooling performance.

4.3. Gas -based fluids

Gas-based fluids typically consist of substances in gaseous form at room temperature. In machining applications, these fluids can be pressure-cooled or gas-cooled. Examples include air, helium, nitrogen, and carbon dioxide. Air was among the first machining coolants, with compressed air released through a focused nozzle on the tool, proving effective in certain cases. Compressed gas-based coolants are used in heavy cutting conditions where traditional cooling methods may struggle to penetrate the tool-chip interface. Liquid nitrogen, for instance, has been widely used in machining hard materials such as titanium and hard steels. The use of liquid nitrogen has been associated with a decrease in the cutting zone temperature and an improvement in tool life during the cutting of titanium alloy. The utilization of cryogenic coolant, specifically liquid nitrogen, resulted in an enhancement of surface integrity during the cutting of titanium alloy. Cryogenic machining is considered environmentally friendly and has demonstrated a significant improvement in product quality.

Choosing the appropriate CF is crucial and depends on several factors.

i. Material and Tool:

Consideration: The kind of material being cut and the specific tool used.

Importance: Ensures compatibility and optimal performance with the chosen material and tool.

ii. Operation Type:

Consideration: Whether it's a drilling, cutting, or another machining operation.

Importance: Different operations may have varying requirements, and the fluid must be suitable for the specific task.

iii. Cooling Requirements:

Consideration: The degree of cooling effect needed during the machining process.

Importance: Ensures that the CF provides the necessary cooling for efficient and effective machining.

The right selection considers these factors to tailor the CF to the specific conditions and requirements of the metal-cutting operation. At small values of cutting speeds, the emphasis is less on cooling, and lubrication plays a crucial role in minimizing friction and preventing the formation of built-up edges. In such scenarios, it is generally recommended to use an oil-based fluid. On the other hand, at high cutting speeds, the circumstances are less conducive to fluid penetration, making it challenging to reach the interface and act as a lubricant. In these situations, cooling becomes more critical, and a water-based fluid is preferred. In its role as a lubricant, the CF functions to minimize the contact area between the chip and the CT. Its efficacy hinges on its capacity to permeate the chip-tool interface and form a thin layer within the limited available time. This layer can be established chemically via a reaction or physically via adsorption and must possess shearing resistance lower than the material resistance in the interface. Consequently, it also serves indirectly as a coolant by mitigating the heating of the cutting area and reducing the cutting temperature.

5. Factors influencing the CFs performance

Water-based coolants, including synthetic and semi-synthetic fluids as well as emulsions, offer significant potential for reducing the environmental footprint of machining processes. Emulsions, which are created by blending base oil and water, and semi-synthetic fluids, which combine the benefits of both synthetic fluids and emulsions, provide efficient cooling while minimizing environmental hazards. Gas-based fluids, such as air, helium, nitrogen, and carbon dioxide, offer another sustainable alternative due to their ability to reduce fluid consumption and waste generation. These fluids, particularly when used with pressure or gas cooling systems, present substantial benefits from both environmental and energy management perspectives. Recent studies [115–117], demonstrate the effectiveness of these coolants in reducing energy consumption and emissions, aligning with global sustainability and energy efficiency goals. The broader geographic and industrial scope of these solutions further emphasizes their potential for large-scale adoption, fostering more sustainable manufacturing practices across diverse regions.

The main factors governing both chemical characteristics of fluids and metals behavior and corrosion are temperature and pH [118]. Therefore, heat generation from cutting machines could exhibit chemical changes in cutting fluids, affecting their stability and composition. In addition, the elevated temperatures may cause chemical reactions within the fluid, leading to degradation, the formation of byproducts, and a reduction in effectiveness over time. Furthermore, the pH of fluids is highly influenced by the temperature, where under high temperature the pH tends to decrease which intern arise the chance for metals corrosion as well [119]. Hence, still a challenging aspect for better developing CFs able to resist heat and holds buffering behavior that could resist the pH change over temperature. Additionally, high temperatures may accelerate hydrolysis and oxidation reactions in cutting fluids [120]. Hydrolysis breaks down fluid components especially water-based fluids, while oxidation involves the reaction of fluid molecules with oxygen from the air. These reactions can alter the chemical composition of the fluid, leading to decreased lubricity, increased viscosity, and the formation of acids or other harmful byproducts. Additionally, so far most of CFs are synthetic and contain artificial chemical additives such as corrosion inhibitors, biocides, and extreme pressure agents [121]. Heat can impact the effectiveness of these additives by accelerating their decomposition or altering their chemical properties. This can diminish the overall performance of the cutting fluid and compromise machining outcomes. Concisely, the utilization of natural sources for producing cutting fluids and additives remains limited, posing a challenge in providing sustainable and environmentally friendly cutting fluids. Research in this area is still ongoing.

6. Environmental aspects

The environmental impact of CFs has become a significant concern due to their toxic effects, emerging as a problematic aspect in recent years. Reports indicate that approximately 80 % of all infections among operators are linked to skin contact with CFs [122]. The complexity of CF composition poses a potential risk, as it may act as an allergen or irritant, even when the raw materials are considered safe. Petroleum-based CFs containing polyaromatic and heterocyclic rings are carcinogenic. Exposure to such fluids could lead to skin cancer. The presence of hazardous substances and the low biodegradability of CFs contribute to significant techno-environmental issues and pose serious health risks, including respiratory diseases, genetic diseases, lung cancer, and dermatological issues. Moreover, the evolution of bacteria in CF leads to the existence of microbial masses and endotoxins in the workshop environment. To control bacterial growth, biocides are added to CFs. Nevertheless, discharging cutting fluids containing biocides can interfere with the natural decomposition process, and certain municipalities prohibit the disposal of biocides into sewage systems. Furthermore, many biocides have been found to release formaldehyde, a potential carcinogen. Machining fluids are notably complex, given the diverse range of chemicals added to enhance their physical properties and extend their operational lifespan. Typical additives encompass corrosion inhibitors, biocides, and surfactants. The additives selection and their used quantities are typically decided at the plant level. Consequently, the fluids composition varies from one plant to another. In addition to the intentional additives, various contaminants are generated during the use of fluids.

Occasionally, chlorinated paraffin is incorporated into CFs as an additive due to its favorable properties, including low acute toxicity, viscosity, chemical stability, and flame resistance [123]. However, the use of CFs encompassing chlorinated paraffins as high-pressure additives is no longer permitted due to legal restrictions. This is for the reason that, under heat and pressure, chlorinated paraffin in extreme-pressure CFs can transform into dioxin, causing chlorine acne. Additionally, the disposal of CFs containing chlorinate is permitted through burning in specialized incineration sites, as the toxic dioxins produced can pose risks to human health and the environment. Consequently, these fluids are classified as hazardous waste. Furthermore, the use of CFs encompassing chlorine additives is not recommended for cutting titanium alloys due to the potential risk of causing corrosion on the machined surface [124]. Furthermore, the vaporization and atomization of CFs under high temperature or pressure during cutting operations can lead to the formation of CF mist. Mist, odors, smoke, and fumes, produced by CFs, especially those with chemical additives like chlorine, sulfur, phosphorus, biocides, and hydrocarbons, may result in skin reactions and respiratory problems [125].

The contamination of CFs with metallic particles and tramp oil during their circulation in the cutting machine is a factor that diminishes their quality and effectiveness after being used for some time. Consequently, the disposal of these CFs becomes necessary. However, the waste disposal of mineral oil is expensive and has harmful environmental effects. However, it's important to note that even MQL can lead to pollution. The atomization of oil in the air flow results in the suspension of numerous oil particles in the air. To address this issue, specific system requirements are necessary, including a fully enclosed machine with protective guards and an effective exhaust system with particle control.

The usage of mist often involves the complete loss of the CF applied. Even with a low oil flow (lower than 0.05 L/h), it is essential to calculate and take into account fluid consumption. For instance, if there is a neat oil flow of approximately 10 ml/h, used continuously for 8 h a day (assuming one work shift per day), the daily consumption would be 80 ml. Over a month (22 working days), this would amount to 1760 ml of fluid. In three months, over 5 L of fluid would be atomized. Some synthetic fluids, even at a concentration of 5 %, might have lower consumption. For instance, considering a machine tank of 60 L, it would require 3.15 L of fluid to achieve this concentration. These products can be used continuously with a lifespan exceeding six months. Even accounting for potential losses, the consumption of this product over this period could be lower than when misting is employed.

The use of MQL involves the intermittent use of compressed air throughout the machining process. These air lines produce considerable noise, often exceeding the tolerable range for the human ear (above 80 dB). This not only poses a risk to human health but also hinders effective communication, negatively impacting the environment. The attempt to implement MQL for machining can be viewed as an intermediate approach between conventional fluid use and dry cutting. However, current research results do not conclusively support the widespread adoption of this procedure in the industry. To circumvent these issues, the preferred scenario is dry cutting, sometimes referred to as ecological machining. Significant progress has been made in this area recently. Moreover, in some cases, dry cutting proves to be economically advantageous.

Public awareness of environmental issues has been steadily increasing, leading to the adoption of a philosophy that emphasizes environmental consciousness—"go green, think green, and act green". Consistent with this notion, bio-based cutting fluids, which are eco-friendly, renewable, less toxic, and highly biodegradable, are increasingly recognized as alternatives to petroleum-based counterparts. Consequently, top-notch cutting fluids should not only demonstrate outstanding lubricant and coolant properties but also be safe for disposal after appropriate treatment.

Studies on biodegradable CFs has surfaced as a top priority in lubrication, leading to the development of ecofriendly CFs in the market. Nevertheless, biodegradable lubricants are gradually taking the place of synthetic lubricants. Biodegradable CFs, which minimize environmental contamination, offer satisfactory economic conditions and excellent reliability. Additionally, the usage of bio-based CFs results in cleaner output with less mist in the air, thereby decreasing occupational health risks. Biodegradability is a crucial aspect of ecofriendly products.

Biodegradable substances can undergo biochemical breakdown facilitated by microorganisms. During the primary degradation process, the original molecule of a biodegradable substance disappears. Eventually, biomass, hydrogen, and carbon dioxide form during the ultimate degradation. Ultimate biodegradability is crucial as it ensures the safe reintegration of organic material into the natural carbon cycle. Additionally, the sustainability of CF use can be assessed from two perspectives. Firstly, the source of the CFs distinguishes between fossil and renewable raw materials. Secondly, the environmental impact related to the use and disposal of CFs is considered. Renewable products adhere to a closed carbon cycle, where the carbon dioxide released during the breakdown of organic chemicals is balanced by the amount absorbed by plants. On the contrary, mineral oil-based products have an open carbon cycle, contributing to increased carbon dioxide emissions and, subsequently, global warming.

When evaluating biodegradability, esters, and vegetable oils emerge as preferable choices for formulating CFs as base fluids. This preference is due to their higher biodegradability compared to mineral oil. In a study assessing the biodegradability of a new CF formulated from mineral oil and castor oil, the results indicated high degradation rates for the new CF [126]. In contrast, mineral oil exhibited lower biodegradability, with degradation rates ranging from 20 % to 60 %. Another experiment compared vegetable-based synthetic ester and rapeseed oil, showing that they were 100 % biodegradable, while neat oil attained a biodegradability rate of only 20–30 %. As a result, mineral oil is not classified as readily biodegradable.

The increasing demand for biodegradable CFs has created an opportunity for the exploration of ecofriendly vegetable oils as a substitute for mineral-based CFs. In contrast to the 2 % growth rate for the overall lubricant market, ecofriendly lubricants are anticipated to experience an annual rate of growth more 8 % in the United States [23].

Vegetable oils offer not only a robust lubricant film with strong interactions with metallic surfaces but also contribute to reducing wear and friction. This is attributed to the polarities of fatty acids, which allow for the formation of thin films, imparting anti-wear and lubrication characteristics. The substantial intermolecular interactions result in a good viscous characteristic, making the lubrication robust to temperature variation. In essence, the fatty acids present in vegetable oils play a pivotal role in lubrication. Moreover, vegetable oils have high values of flash point in comparison to mineral-based CFs, which mitigates the risk of fire hazards and smoke formation [127]. The flash point refers to the lowest temperature at which a CF can generate an ignitable mixture in the air close to its surface. A lower flash point indicates that the material is more prone to catching fire [128]. As a result, CFs are required to have high values of flash point to endure the high temperatures encountered in machining. Nevertheless, vegetable oils come with certain drawbacks, including low oxidative stability, poor thermal stability, and bad anti-corrosion characteristics [122]. Many studies in the literature indicate that CFs based on vegetable oils exhibit superior performance and are more readily biodegradable [129,130].

The main factors influencing worker exposure to CFs are machine type, worker's proximity to the machine, extent of machine enclosure, indoor humidity, availability of local exhaust, age of the machine, and outdoor temperature [20].

Park et al. [131] reported a notable increase in mortality rates for laborers subjected to CFs from stomach cancer, lung cancer, rectal cancer, and stroke with proportional mortality ratios (PMR) ranging between 1.35 and 3.04. The findings suggest potential health risks associated with grinding exposure, including a statistically significant correlation between grinding exposure and stomach cancer. These observations highlight the importance of workplace safety measures and health monitoring for individuals engaged in grinding occupations.

Eisen et al. [132] investigated mortality rates for laborers subjected to neat, soluble, and synthetic oils. They reported high standardized mortality ratios (SMR) from stomach cancer, pancreatic cancer, lung cancer, brain cancer, leukemia, esophageal cancer, liver cancer, and laryngeal cancer ranging between 1.60 and 1.70. The primary cause of mortality in the mentioned context was liver cancer. This indicates that liver cancer had the highest mortality rate among the observed health conditions, highlighting the significance of addressing risks and implementing preventive measures related to this specific form of cancer in the relevant population. In another study, SRM ranging between 0.55 and 1.98 for esophagus cancer, brain cancer, stomach cancer, lung cancer, colon cancer, laryngeal cancer, rectum cancer, pancreas cancer, prostate cancer, and leukemia for all tested labors subjected to different CFs types [133].

Toxicity tests demonstrate that specific additives present in CFs have the potential to cause cancer in laboratory animals. In particular, the combination of corrosion inhibitors such as nitrates with amines can lead to the creation of nitrosamines, identified as liver carcinogens [134]. This emphasizes the significance of evaluating the potential health risks linked to fluid additives and implementing measures to minimize their adverse effects.

Certain studies have documented cases where occupational asthma was suspected to be triggered by exposure to CFs due to the existence of ethanolamines, which are commonly present in synthetic CFs, which could be a potential cause of occupational asthma [135]. Symptoms such as phlegm and cough have been observed to be associated with exposure to oil aerosol. Skin disorders, including both irritant and allergic contact dermatitis, are common severe health effects resulting from exposure to CFs. Some components of CFs possess irritant characteristics, such as amines, antifoams, biocides, organic acids, mineral oils, preservatives, and emulsifiers.

Restricted measures should be applied to lessen worker exposure to CFs. The primary pathways of exposure are through inhalation of mist or vapors and skin interaction, although ingestion is also a possible route. The inhalation risk depends on the operation, type of fluid, and particle size of the mist. Synthetic and semisynthetic fluids typically produce smaller particles compared to neat and soluble oils, increasing the likelihood of inhalation into the deep respiratory tract. Such mists can lead to upper respiratory tract irritation, nasal discomfort, or bronchitis.

Significant control over exposure to CFs can be attained by modifying the machining process, enclosing the machine, switching to a different type of CFs, and incorporating local exhaust systems. Furthermore, exposure levels can be lowered by enhancing the influx of fresh air.

Government regulations are in place to govern CFs and safeguard the environment. Manufacturing engineers need to not only be cognizant of possible health risks but also comprehend how environmental apects impact manufacturing operations. Non-compliance could lead to significant civil or criminal penalties or both.

7. Sustainability assessment

The perception of sustainability has become increasingly important with technological progress, focusing on evaluating the effectiveness of cutting processes in terms of environmental, economic, and social aspects as shown in Fig. 6 [136]. Measuring sustainability metrics like total carbon emissions and machining costs can offer valuable insights for improving chip removal processes while assessing machinability. A sustainable machining approach is defined by its capacity to minimize resource consumption, be economically viable, ensure societal well-being, and mitigate adverse environmental effects.

The evaluation of sustainability performance in machine tools is crucial for the advancement of greener machinery and the selection of appropriate tools for procurement. Sustainability assessment indices such as carbon emission, total cost, production rate, energy utilization ratio, and specific energy consumption should be computed for machine tools empirically or determined through experimentation. Weights are assigned to each indicator to be analyzed using suitable multi-objective decision algorithms such as the Analytical Hierarchy Process (AHP).

7.1. Economical aspects

An essential aspect of sustainability is the economic factor. To determine the sustainability of a machining method, a cost analysis should be conducted. The primary components influencing the overall machining cost are shown in Fig. 7. These components are machinery and maintenance cost, labor cost, fluid cost, CT cost, energy and resources cost, and waste management cost. The total cost could be computed according to the following formula:

$$\begin{aligned} \textit{Total machining cost} &= \textit{Labor cost} + \textit{Machinery cost} + \textit{Cutting fluid cost} \\ &+ \textit{Cutting tools cost} + \textit{Waste management cost} + \textit{Enegy and resurces cost} \end{aligned} \tag{1}$$

Production rate is another critical economic factor that affects the sustainability assessment of any machining process. The material removal rate is a crucial factor affecting production rate and is therefore essential for any industry. It is computed as follows:

$$\textit{Material removal rate} = \frac{\textit{Volume of removed material}}{\textit{Production time}} \tag{2}$$

7.2. Environmental aspects

In the environmental aspects, indicators encompass environmental emissions, energy consumption, and energy efficiency.

Assessing carbon emissions is a critical aspect of determining the sustainability of a machining process. This assessment relies primarily on three factors: energy usage, material consumption, and waste generation as shown in Fig. 8.

Carbon emissions resulting from energy usage are a significant consideration in assessing the sustainability of a machining process. Besides cutting conditions, optimizing processing time and enhancing process factors can lead to machining components with lower energy consumption compared to traditional parameters. High-speed cutting operations typically consume less energy than slower ones, as they produce parts in shorter timeframes [137]. Therefore, fast-speed cutting is more energy-efficient, resulting in lower specific energy consumption [138]. The emitted carbon due to the energy consumption during the machining process is computed as:

$$E_{Eng} = CEF_{Eng} \times EC_{Mach} \tag{3}$$

where E_{Eng}, EC_{Mach}, and CEF_{Eng} denote carbon emitted due to energy consumption, total consumed energy, and carbon emission factor related to energy consumption (0.54–0.74 kgCO_2/kWh) [137,139]. The CEF for electricity can vary based on factors like type and the location of energy sources, such as hydro, coal, solar, wind, or nuclear power.

$$EC_{Mach} = CEF_{Eng} \times EC_{Mach} \tag{4}$$

Carbon emissions from materials depend on factors such as the extraction, production, and transportation of raw materials, as well as the disposal of waste materials generated during machining processes. Choosing sustainable materials and optimizing material usage can help reduce carbon emissions associated with machining operations. Additionally, recycling and reusing materials whenever possible can further minimize the environmental impact. The carbon emissions stemming from the utilization of CTs and coolant in machining processes contribute significantly to the overall carbon footprint of the operation. To assess comparable carbon footprints from materials, emissions from both cooling/lubricating fluids and tools are combined.

$$E_{Tool} = \frac{r_{Mach}}{t_{tool}} \times CEF_{Tool} \times M_{Tool} \tag{5}$$

$$E_{Fluid} = CEF_{Fluid} \times V_{Fluid} \tag{6}$$

where E_{Tool}, E_{Cool}, CEF_{Tool}, CEF_{Fluid}, M_{Tool}, V_{Fluid}, r_{Mach}, and t_{tool} denote carbon emitted due to tool use, the carbon emitted due to CF use, carbon emission factor related to the tool, carbon emission factor related to CF, the weight of the cutting weight, amount of the CF, chip removal rate, and tool life.

Carbon emissions resulting from waste in machining processes are another important aspect to consider in evaluating sustainability [140]. This includes emissions generated during the disposal or treatment of waste materials produced from the machining operation. After a certain period, the CFs and tools employed in machining degrade, necessitating the recycling of chips, lubricants, and tools. The emission from chip, tool, and CF is computed as follows:

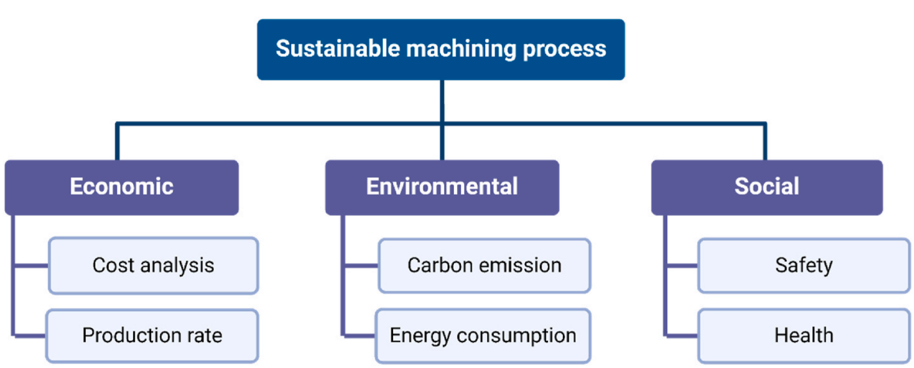

Fig. 6. Aspects of sustainable machining process.

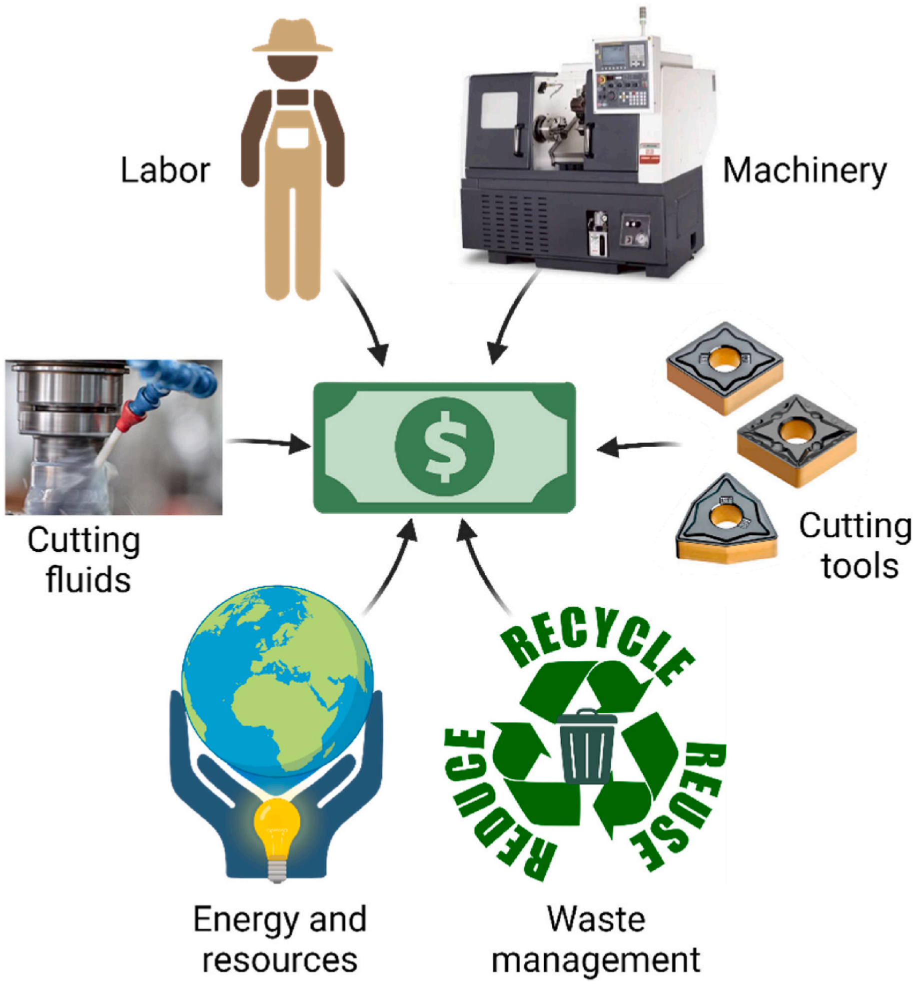

Fig. 7. The primary components influencing the overall machining cost.

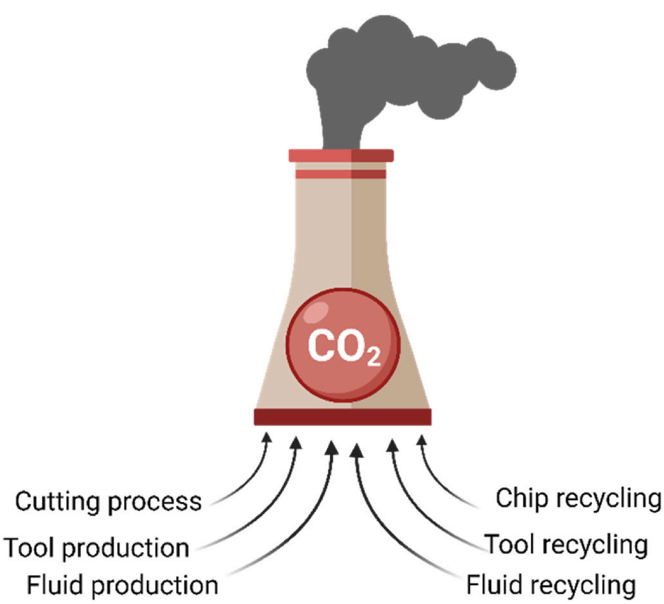

Fig. 8. Carbon emission related to the machining process.

$$E_{R\ Chip} = EC_{R\ Chip} \times CEF_{Eng} \times V_{Chip} \times \rho_{Chip} \tag{7}$$

$$E_{R\ Tool} = CEF_{R\ Tool} \times M_{Tool} \tag{8}$$

$$E_{R\ Fluid} = CEF_{R\ Fluid} \times V_{Fluid} \tag{9}$$

where $E_{R\ Chip}$, $E_{R\ Tool}$, $E_{R\ Fluid}$, $EC_{R\ Chip}$, $CEF_{R\ Tool}$, $CEF_{R\ Fluid}$, V_{Chip}, and ρ_{Chip} denote carbon emitted due to chip recycling, the carbon emitted due to tool recycling, the carbon emitted due to fluid recycling, the carbon emission factor related to tool recycling, the carbon emission factor related to CF recycling, the volume of the chip, and chip density.

Other important environmental indicators that should be computed to assess the sustainability of the machining process are specific energy consumption (SEC) and energy utilization ratio (EUR) which characterize the consumed energy by a machine to remove the unit volume of the metal and the ratio between cutting energy consumed during chip removing process and the total consumed energy consumed by the machine.

$$SEC = \frac{Total\ machining\ energy}{Volume\ of\ cut\ material} \tag{10}$$

$$EUR = \frac{Cutting\ energy}{Total\ machining\ energy} \tag{11}$$

7.3. Social aspects

Social aspects of sustainability encompass social and human performance related to cutting processes and machine tools. The key social performance indicators used in the sustainability assessment of machining processes include dust and mist level, physical load index, job satisfaction level, exposure to chemicals, and noise level. Social indicators have greater uncertainties compared to economic and environmental indicators.

8. Government regulations on cutting fluids

In the context of machining processes, government regulations play a crucial role in managing the use and disposal of CFs to ensure environmental protection and worker safety. This section outlines the key regulations and strategies under Environmental, Social, and Governance (ESG) frameworks and other governmental control systems that oversee industry practices related to cutting fluids.

8.1. Environmental regulations

Environmental regulations are designed to minimize the ecological impact of cutting fluids. In the United States, the Resource Conservation and Recovery Act (RCRA) governs the management and disposal of hazardous waste, including used cutting fluids, requiring their proper treatment to prevent environmental contamination. Similarly, the European Union's REACH Regulation, which stands for Registration, Evaluation, Authorization, and Restriction of Chemicals, mandates that manufacturers provide safety data and risk assessments for chemicals used in cutting fluids to ensure they do not pose risks to human health or the environment. Additionally, the Clean Water Act (CWA) in the U.S. regulates the discharge of pollutants, including cutting fluids, into water bodies, requiring facilities to obtain permits and adhere to discharge limits to protect water quality.

8.2. Social and safety regulations

Regulations focusing on worker safety and social responsibility include the Occupational Safety and Health Administration (OSHA) Standards, which require employers to implement safety measures to protect workers from hazards associated with cutting fluids, such as dermatitis and respiratory issues, by providing personal protective equipment (PPE) and ensuring proper ventilation. Additionally, the European Union's Directive 2004/37/EC addresses the protection of workers from the risks associated with exposure to carcinogens and mutagens, including certain chemicals found in cutting fluids.

8.3. ESG strategies and governance

ESG strategies reflect a commitment to sustainable and responsible practices. Companies are increasingly required to conduct Environmental Impact Assessments (EIAs) to evaluate the impact of their use of CFs and to explore alternatives that minimize ecological damage. Additionally, adhering to the United Nations SDGs encourages companies to adopt more sustainable practices, including reducing hazardous chemicals in cutting fluids. Certain industries, such as automotive and aerospace, face additional regulations tailored to their specific needs. These sectors often have stringent requirements regarding the use of CFs, including specific standards for the types of CFs used and their disposal methods, due to the high precision and safety demands.

9. Conclusions and future prospects

This review highlights the significant advancements and challenges in machining processes, with a particular focus on sustainable practices and their impact on both environmental and economic aspects. Key findings emphasize the benefits of dry machining in reducing pollution and waste, while also acknowledging its limitations such as increased tool wear and reduced process stability. The review further discusses the advantages of MQL and hybrid nanofluids in balancing lubrication and cooling, showcasing their superior performance compared to traditional methods. To ensure continued progress in this field, it is crucial for manufacturers to adopt comprehensive strategies that enhance worker safety, optimize cutting fluid usage, and embrace innovative technologies. Ultimately, by integrating these approaches, the industry can achieve more sustainable, cost-effective, and environmentally friendly machining processes, aligning with the broader goals of sustainable manufacturing.

As engineering materials advance and high-speed cutting becomes more prevalent, the role of CF in machining has become increasingly vital. Traditionally, the application of CF has yielded numerous benefits, including reduced cutting temperatures, decreased friction between tools and workpieces, prolonged tool lifespan, and improved machining efficiency and surface quality. These advantages stem from the fundamental functions of CF, namely cooling, lubrication, corrosion protection, and cleaning. However, conventional CFs come with significant drawbacks, such as.

- Environmental Impact: Many traditional metal CFs contain hazardous chemicals, such as chlorinated compounds, petroleum-based oils, and heavy metals. Improper disposal of these fluids can lead to soil contamination, environmental pollution, and water pollution, posing risks to ecosystems and human health.
- Health Hazards: Exposure to metal CFs can pose health risks to machine operators and workers in machining facilities. Inhalation of coolant mists and fumes may cause respiratory problems, skin contact with CFs can lead to dermatitis and irritation, and ingestion of fluids can result in gastrointestinal issues. Long-term exposure to certain chemicals found in CFs has also been linked to more serious health conditions, including cancer.
- Maintenance and Disposal Costs: Metal CFs require regular maintenance, including monitoring fluid concentration levels, filtering out contaminants, and replenishing depleted fluids. Additionally, the disposal of used CFs can be costly and may require compliance with regulations governing hazardous waste disposal.
- Odor and Vapors: Some metal CFs emit strong odors and volatile organic compounds (VOCs) during machining operations, which can create unpleasant working conditions in machining facilities. In addition to causing discomfort for workers, these odors and vapors may also affect indoor air quality and contribute to respiratory issues.
- Chip and Sludge Formation: Metal CFs can accumulate chips, fines, and other solid particles during machining operations, leading to the formation of sludge in coolant tanks and on machine surfaces. This can interfere with coolant circulation, clog filters and nozzles, and increase the risk of bacterial growth and corrosion.
- Compatibility Issues: Certain types of metal CFs may not be compatible with certain materials, coatings, or machining processes. For example, water-based CFs may cause rusting or corrosion on ferrous metals if not properly formulated or applied.
- Regulatory Compliance: There are regulations and guidelines governing the use, handling, and disposal of metal-CFs to protect worker health and safety and minimize environmental impact. Compliance with these regulations requires additional resources and may limit the options for selecting CFs in some cases.

Despite these challenges, ongoing research and development endeavors aim to enhance the environmental sustainability, health and safety aspects, and performance of metal-CFs. Sustainable machining and metal-cutting technologies aim to minimize the environmental impact, conserve resources, and improve the overall efficiency of machining processes. Strategies include the adoption of green biodegradable oils, the development of advanced recycling technologies, and the implementation of efficient machining technologies such as.

- Minimum Quantity Lubrication: MQL systems deliver small amounts of CF directly to the cutting zone, reducing fluid consumption, waste generation, and environmental pollution. Benefits include improved health and safety for workers, cost savings, and reduced environmental impact.
- Dry Machining: Dry machining eliminates the use of CFs altogether, relying on optimized tool geometries, coatings, and machining parameters to minimize heat generation and tool wear. This approach conserves resources, reduces waste, and eliminates the need for fluid disposal, but it requires careful process optimization to avoid overheating and tool damage.
- Mist cooling: Near-dry machining uses minimal amounts of CF mixed with compressed air to provide lubrication and cooling during machining. This approach combines the benefits of dry machining with improved tool life and surface finish compared to traditional flood coolant systems.
- High-Pressure Coolant (HPC): High-pressure coolant systems deliver coolant at elevated pressures to the cutting zone, improving heat dissipation, chip evacuation, and surface finish. HPC systems reduce fluid consumption, extend tool life, and enhance machining efficiency, especially in high-speed and high-temperature machining applications.
- Cryogenic Machining: Cryogenic machining involves using extremely cold temperatures, typically through the application of liquid nitrogen or carbon dioxide, to cool the cutting zone and reduce heat generation during machining. This approach can improve tool life, surface finish, and dimensional accuracy, particularly when machining heat-sensitive materials.

Sustainable machining and metal-cutting technologies offer numerous benefits, including reduced resource consumption, improved environmental performance, enhanced worker health and safety, and cost savings for manufacturers. By adopting these technologies and practices, machining operations can become more environmentally friendly, economically viable, and socially responsible.

The future of sustainable machining and metal cutting is promising, with ongoing research, innovation, and technological advancements driving the development of more environmentally friendly and resource-efficient manufacturing processes. Some prospects in sustainable machining and metal cutting include.

- Advancements in CF Technology: Researchers are working on developing CFs with improved lubrication, cooling, and environmental properties. This includes the use of bio-based and renewable fluids, nanofluids, and additives that enhance performance while minimizing environmental impact.
- Integration of Smart Manufacturing Technologies: The integration of sensors, data analytics, and artificial intelligence (AI) in machining processes enables real-time monitoring, optimization, and predictive maintenance, leading to more efficient use of resources, reduced waste, and improved sustainability.
- Development of Green Machining Processes: Researchers are exploring alternative machining processes that minimize material waste, energy consumption, and environmental pollution. This includes additive manufacturing (3D printing), laser machining, and abrasive water jet cutting, which offer more sustainable alternatives to traditional subtractive machining methods.
- Energy-Efficient Machine Tools: Future machine tools will continue to incorporate energy-efficient features and technologies to minimize energy consumption and reduce carbon emissions. This includes the use of lightweight materials, regenerative braking systems, and energy recovery mechanisms to improve overall efficiency.
- Circular Economy Practices: Manufacturers are increasingly adopting circular economy practices, such as remanufacturing, refurbishment, and recycling of machine components and CTs, to extend product lifecycles, reduce waste, and conserve resources.
- Hybrid Machining Systems: Hybrid machining systems that combine different machining processes, such as additive manufacturing with traditional machining or laser-assisted machining with milling, offer opportunities for optimizing material utilization, reducing energy consumption, and improving process flexibility.
- Collaborative Research and Innovation: Collaboration between academia, industry, and government organizations will play a crucial role in driving innovation and advancing sustainable machining and metal-cutting technologies. This includes joint research initiatives, technology transfer programs, and public-private partnerships focused on sustainability and resource efficiency.
- Regulatory and Policy Initiatives: Continued regulatory and policy initiatives aimed at promoting sustainability and reducing environmental impact in manufacturing will influence the adoption of sustainable machining practices. This includes incentives for green technology adoption, carbon pricing mechanisms, and stricter environmental regulations.
- Concisely, the future of sustainable machining and metal cutting lies in embracing technological innovation, adopting circular economy principles, fostering collaboration, and aligning with regulatory and policy frameworks to create more sustainable and environmentally friendly manufacturing processes. These efforts will not only benefit the environment but also contribute to economic growth, resource conservation, and societal well-being.

CRediT authorship contribution statement

Ammar Elsheikh: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Ali B.M. Ali:** Writing – original draft, Methodology, Investigation. **Amal Saba:** Writing – review & editing, Writing – original draft, Investigation. **Hosam Faqeha:** Writing – original draft, Investigation. **Albraa A. Alsaati:** Writing – original draft, Visualization. **Abdullah M. Maghfuri:** Writing – original draft. **Walaa Abd-Elaziem:** Writing – review & editing, Visualization. **Ahmed A. El Ashmawy:** Writing – review & editing. **Ninshu Ma:** Writing – review & editing.

Declaration of competing interest

The authors of the submitted manuscript "**A Review on Sustainable Machining: Technological Advancements, Health and Safety Considerations, and Related Environmental Impacts**" declared that there is no conflict of interest. All authors mutually agree this manuscript to be submitted to **Results in Engineering,** which was not previously submitted to this journal. Moreover, this paper is not being submitted to any other journals.

Data availability

No data was used for the research described in the article.

Acknowledgement

This work was partially supported by "Osaka University promotion program of cutting-edge multilateral international collaboration related to joining and materials science" and "JWRI International Joint Research Collaborators (JIJReC) program.".

References

[1] R. S, N. R.J.H, J. S.K, G.M. Krolczyk, A comprehensive review on research developments of vegetable-oil based cutting fluids for sustainable machining challenges, J. Manuf. Process. 67 (2021) 286–313, https://doi.org/10.1016/j.jmapro.2021.05.002.

[2] V. D'Angelo, F. Cappa, E. Peruffo, Green manufacturing for sustainable development: the positive effects of green activities, green investments, and non-green products on economic performance, Bus. Strat. Environ. 32 (2023) 1900–1913, https://doi.org/10.1002/bse.3226.

[3] M. Osama, A. Singh, R. Walvekar, M. Khalid, T.C.S.M. Gupta, W.W. Yin, Recent developments and performance review of metal working fluids, Tribol. Int. 114 (2017) 389–401, https://doi.org/10.1016/j.triboint.2017.04.050.

[4] S. Ravi, P. Gurusamy, V. Mohanavel, A review and assessment of effect of cutting fluids, Mater. Today Proc. 37 (2021) 220–222, https://doi.org/10.1016/j.matpr.2020.05.054.

[5] E. Brinksmeier, D. Meyer, A.G. Huesmann-Cordes, C. Herrmann, Metalworking fluids—mechanisms and performance, CIRP Ann 64 (2015) 605–628, https://doi.org/10.1016/j.cirp.2015.05.003.

[6] S.J. Skerlos, in: Q.J. Wang, Y.-W. Chung (Eds.), Cutting Fluids and Their Environmental Impact BT - Encyclopedia of Tribology, Springer US, Boston, MA, 2013, pp. 655–660, https://doi.org/10.1007/978-0-387-92897-5_614.

[7] G. Sur, A.R. Motorcu, S. Nohutçu, Single and multi-objective optimization for cutting force and surface roughness in peripheral milling of Ti6Al4V using fixed and variable helix angle tools, J. Manuf. Process. 80 (2022) 529–545, https://doi.org/10.1016/j.jmapro.2022.06.016.

[8] N.K. Wagri, N.K. Jain, A. Petare, S.R. Das, M.Y. Tharwan, A. Alansari, B. Alqahtani, M. Fattouh, A. Elsheikh, Investigation on the performance of coated carbide tool during dry turning of AISI 4340 alloy steel, Materials 16 (2023), https://doi.org/10.3390/ma16020668.

[9] A.H. Elsheikh, T. Muthuramalingam, S. Shanmugan, A.M. Mahmoud Ibrahim, B. Ramesh, A.B. Khoshaim, E.B. Moustafa, B. Bedairi, H. Panchal, R. Sathyamurthy, Fine-tuned artificial intelligence model using pigeon optimizer for prediction of residual stresses during turning of Inconel 718, J. Mater. Res. Technol. 15 (2021) 3622–3634, https://doi.org/10.1016/j.jmrt.2021.09.119.

[10] K. Zheng Yang, A. Pramanik, A.K. Basak, Y. Dong, C. Prakash, S. Shankar, S. Dixit, K. Kumar, N. Ivanovich Vatin, Application of coolants during tool-based machining – a review, Ain Shams Eng. J. 14 (2023) 101830, https://doi.org/10.1016/j.asej.2022.101830.

[11] D.P. Adler, W.W.-S. Hii, D.J. Michalek, J.W. Sutherland, Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns, Mach. Sci. Technol. 10 (2006) 23–58, https://doi.org/10.1080/10910340500534282.

[12] M.A. Farooq, R. Kirchain, H. Novoa, A. Araujo, Cost of quality: evaluating cost-quality trade-offs for inspection strategies of manufacturing processes, Int. J. Prod. Econ. 188 (2017) 156–166, https://doi.org/10.1016/j.ijpe.2017.03.019.

[13] A.B. Khoshaim, A.H. Elsheikh, E.B. Moustafa, M. Basha, A.O. Mosleh, Prediction of residual stresses in turning of pure iron using artificial intelligence-based methods, J. Mater. Res. Technol. 11 (2021) 2181–2194, https://doi.org/10.1016/j.jmrt.2021.02.042.

[14] S.N. Phokobye, D.A. Desai, I. Tlhabadira, R.E. Sadiku, I.A. Daniyan, Comparative analysis of the cutting performances of SiAlON ceramic, cubic boron nitride and carbide cutting tools for titanium machining, Int. J. Adv. Manuf. Technol. 128 (2023) 3775–3786, https://doi.org/10.1007/s00170-023-12132-3.

[15] A.H. Elsheikh, J. Guo, Y. Huang, J. Ji, K.-M. Lee, Temperature field sensing of a thin-wall component during machining: numerical and experimental investigations, Int. J. Heat Mass Tran. 126 (2018), https://doi.org/10.1016/j.ijheatmasstransfer.2018.06.006.

[16] A.H. Elsheikh, S. Shanmugan, T. Muthuramalingam, A.K. Thakur, F.A. Essa, A.M. M. Ibrahim, A.O. Mosleh, A comprehensive review on residual stresses in turning, Adv. Manuf. 10 (2022) 287–312, https://doi.org/10.1007/s40436-021-00371-0.

[17] Z. Jiang, F. Zhou, H. Zhang, Y. Wang, J.W. Sutherland, Optimization of machining parameters considering minimum cutting fluid consumption, J. Clean. Prod. 108 (2015) 183–191, https://doi.org/10.1016/j.jclepro.2015.06.007.

[18] X. Wu, C. Li, Z. Zhou, X. Nie, Y. Chen, Y. Zhang, H. Cao, B. Liu, N. Zhang, Z. Said, Circulating purification of cutting fluid: an overview, Int. J. Adv. Manuf. Technol. 117 (2021) 2565–2600.

[19] M.M. Key, E.J. Ritter, K.A. Arndt, Cutting and grinding fluids and their effects on the skin, Am. Ind. Hyg. Assoc. J. 27 (1966) 423–427, https://doi.org/10.1080/00028896609342447.

[20] K. Li, F. Aghazadeh, S. Hatipkarasulu, T.G. Ray, Health risks from exposure to metal-working fluids in machining and grinding operations, Int. J. Occup. Saf. Ergon. 9 (2003) 75–95.

[21] A. Alomar, Occupational skin disease from cutting fluids, dermatol, Clin. 12 (1994) 537–546, https://doi.org/10.1016/S0733-8635(18)30158-X.

[22] B. Järvholm, K. Fast, B. Lavenius, P. Tomsic, Exposure to cutting oils and its relation to skin tumors and premalignant skin lesions on the hands and forearms, Scand. J. Work. Environ. Health (1985) 365–369.

[23] S.A. Lawal, I.A. Choudhury, Y. Nukman, Application of vegetable oil-based metalworking fluids in machining ferrous metals—a review, Int. J. Mach. Tool Manufact. 52 (2012) 1–12, https://doi.org/10.1016/j.ijmachtools.2011.09.003.

[24] E. Salur, M. Kuntoğlu, A. Aslan, D.Y. Pimenov, The effects of MQL and dry environments on tool wear, cutting temperature, and power consumption during end milling of AISI 1040 steel, Metals 11 (2021) 1674.

[25] Q. An, J. Dang, Cooling effects of cold mist jet with transient heat transfer on high-speed cutting of titanium alloy, Int. J. Precis. Eng. Manuf. Technol. 7 (2020) 271–282.

[26] F. Wang, Y. Wang, Comparison of cryogenic cooling strategy effects on machinability of milling nickel-based alloy, J. Manuf. Process. 66 (2021) 623–635.

[27] A.H. Elsheikh, M.A. Elaziz, S.R. Das, T. Muthuramalingam, S. Lu, A new optimized predictive model based on political optimizer for eco-friendly MQL-turning of AISI 4340 alloy with nano-lubricants, J. Manuf. Process. 67 (2021) 562–578, https://doi.org/10.1016/j.jmapro.2021.05.014.

[28] A.M.M. Ibrahim, M.A.E. Omer, S.R. Das, W. Li, M.S. Alsoufi, A. Elsheikh, Evaluating the effect of minimum quantity lubrication during hard turning of AISI D3 steel using vegetable oil enriched with nano-additives, Alex. Eng. J. 61 (2022) 10925–10938, https://doi.org/10.1016/j.aej.2022.04.029.

[29] M. Iruj, S. Yaqoob, J.A. Ghani, H. Jaber, N. Saibani, M. Alkhedher, State-of-the-art hybrid lubrication (Cryo-MQL) supply systems, performance evaluation, and optimization studies in various machining processes, Results Eng 22 (2024) 102090, https://doi.org/10.1016/j.rineng.2024.102090.

[30] A. Race, I. Zwierzak, J. Secker, J. Walsh, J. Carrell, T. Slatter, A. Maurotto, Environmentally sustainable cooling strategies in milling of SA516: effects on surface integrity of dry, flood and MQL machining, J. Clean. Prod. 288 (2021) 125580, https://doi.org/10.1016/j.jclepro.2020.125580.

[31] M.J. Jackson, G.M. Robinson, M.D. Whitt, R.B. da Silva, M.B. da Silva, A. R. Machado, Achieving clean production with nanostructured coated milling tools dry machining low carbon steel, J. Clean. Prod. 422 (2023) 138523, https://doi.org/10.1016/j.jclepro.2023.138523.

[32] S.H. Ali, Y. Yao, B. Wu, B. Zhao, W. Ding, M. Jamil, A. Khan, A. Baig, Q. Liu, D. Xu, Recent developments in MQL machining of aeronautical materials: a comparative review, Chin. J. Aeronaut. (2024), https://doi.org/10.1016/j.cja.2024.01.018.

[33] N.M. Tuan, T.M. Duc, T.T. Long, V.L. Hoang, T.B. Ngoc, Investigation of machining performance of MQL and MQCL hard turning using nano cutting fluids, Fluid 7 (2022), https://doi.org/10.3390/fluids7050143.

[34] P. Yan, Y. Rong, G. Wang, The effect of cutting fluids applied in metal cutting process, Proc. Inst. Mech. Eng. Part B J. Eng. Manuf. 230 (2016) 19–37.

[35] I. Bencheikh, F. Bilteryst, M. Nouari, H. Makich, Wear estimation of coated tools using XFEM/level set function, Procedia CIRP 58 (2017) 428–433.

[36] M. Dragičević, The application of alternative techniques for cooling, flushing and lubrication to improve efficiency of machining processes, Teh. Vjesn. 25 (2018) 1561–1568.

[37] E. Benedicto, E.M. Rubio, D. Carou, C. Santacruz, The role of surfactant structure on the development of a sustainable and effective cutting fluid for machining titanium alloys, Metals 10 (2020) 1388.

[38] M. Sarıkaya, M.K. Gupta, I. Tomaz, D.Y. Pimenov, M. Kuntoğlu, N. Khanna, Ç. V. Yıldırım, G.M. Krolczyk, A state-of-the-art review on tool wear and surface integrity characteristics in machining of superalloys, CIRP J. Manuf. Sci. Technol. 35 (2021) 624–658, https://doi.org/10.1016/j.cirpj.2021.08.005.

[39] M. Soori, F.K.G. Jough, R. Dastres, B. Arezoo, Sustainable CNC machining operations, a review, Sustain. Oper. Comput. 5 (2024) 73–87.

[40] K.h. Salman, A.H. Elsheikh, M. Ashham, M.K.A. Ali, M. Rashad, Z. Haiou, Effect of cutting parameters on surface residual stresses in dry turning of AISI 1035 alloy, J. Brazilian Soc. Mech. Sci. Eng. 41 (2019), https://doi.org/10.1007/s40430-019-1846-0.

[41] S. Padhan, S.R. Das, A. Das, M.S. Alsoufi, A.M. Ibrahim, A. Elsheikh, Machinability investigation of nitronic 60 steel turning using SiAlON ceramic tools under different cooling/lubrication conditions, Mater 15 (2022), https://doi.org/10.3390/ma15072368.

[42] N.N.N. Hamran, J.A. Ghani, R. Ramli, C.H.C. Haron, A review on recent development of minimum quantity lubrication for sustainable machining, J. Clean. Prod. 268 (2020) 122165.

[43] M.A. Khan, S.H. Imran Jaffery, M. Khan, M. Alruqi, Machinability analysis of Ti-6Al-4V under cryogenic condition, J. Mater. Res. Technol. 25 (2023) 2204–2226, https://doi.org/10.1016/j.jmrt.2023.06.022.

[44] D.Y. Pimenov, M. Mia, M.K. Gupta, Á.R. Machado, G. Pintaude, D.R. Unune, N. Khanna, A.M. Khan, Í. Tomaz, S. Wojciechowski, M. Kuntoğlu, Resource saving by optimization and machining environments for sustainable manufacturing: a review and future prospects, Renew. Sustain. Energy Rev. 166 (2022) 112660, https://doi.org/10.1016/j.rser.2022.112660.

[45] G.M. Krolczyk, P. Nieslony, R.W. Maruda, S. Wojciechowski, Dry cutting effect in turning of a duplex stainless steel as a key factor in clean production, J. Clean. Prod. 142 (2017) 3343–3354, https://doi.org/10.1016/j.jclepro.2016.10.136.

[46] J. Singh, S.S. Gill, M. Dogra, R. Singh, M. Singh, S. Sharma, G. Singh, C. Li, S. Rajkumar, State of the art review on the sustainable dry machining of advanced materials for multifaceted engineering applications: progressive advancements and directions for future prospects, Mater. Res. Express 9 (2022) 64003, https://doi.org/10.1088/2053-1591/ac6fba.

[47] I.B. Babe, K. Gupta, S.K. Chaubey, Sustainable dry machining of stainless steel with microwave-treated tungsten carbide cutting tools, Micromachines 14 (2023), https://doi.org/10.3390/mi14061148.

[48] W. Fang, J. Wang, F. Cai, J. Chen, G. Gyawali, S. Zhang, Effects of multilayer structure on impacting fatigue resistance and high-speed dry cutting performance against Ti-6Al-4 V of AlTiN/AlTiBN multilayer coatings, Tribol. Int. 192 (2024) 109258, https://doi.org/10.1016/j.triboint.2024.109258.

[49] H.N. Abu Bakar, J.A. Ghani, C.H.C. Haron, M.J. Ghazali, M.S. Kasim, S. Al-Zubaidi, N. Jouini, Wear mechanisms of solid carbide cutting tools in dry and cryogenic machining of AISI H13 steel with varying cutting-edge radius, Wear 523 (2023) 204758, https://doi.org/10.1016/j.wear.2023.204758.

[50] R. Bibeye Jahaziel, V. Krishnaraj, S. Sudhagar, B. Geetha Priyadarshini, Improving dry machining performance of surface modified cutting tools through combined effect of texture and TiN-WS2 coating, J. Manuf. Process. 85 (2023) 101–108, https://doi.org/10.1016/j.jmapro.2022.11.033.

[51] H. Patel, H. Patil, Tribological performance based machinability investigations of Al2O3-ZrO2 ceramic cutting tool in dry machining of Ti-6Al-4V alloy, Tribol. Int. 176 (2022) 107776, https://doi.org/10.1016/j.triboint.2022.107776.

[52] G.S. Goindi, P. Sarkar, Dry machining: a step towards sustainable machining – challenges and future directions, J. Clean. Prod. 165 (2017) 1557–1571, https://doi.org/10.1016/j.jclepro.2017.07.235.
[53] M.K. Gupta, G. Singh, P.K. Sood, Experimental investigation of machining AISI 1040 medium carbon steel under cryogenic machining: a comparison with dry machining, J. Inst. Eng. Ser. C. 96 (2015) 373–379, https://doi.org/10.1007/s40032-015-0178-9.
[54] S.U. Gunjal, S.B. Sanap, in: P.M. Pawar, R. Balasubramaniam, B.P. Ronge, S. B. Salunkhe, A.S. Vibhute, B. Melinamath (Eds.), Performance Evaluation of Molybdenum Disulfide Based Cutting Fluids under Near-Dry Machining as an Environment-Friendly Technique BT - Techno-Societal 2020, Springer International Publishing, Cham, 2021, pp. 675–681.
[55] F.J. Sun, S.G. Qu, Y.X. Pan, X.Q. Li, F.L. Li, Effects of cutting parameters on dry machining Ti-6Al-4V alloy with ultra-hard tools, Int. J. Adv. Manuf. Technol. 79 (2015) 351–360, https://doi.org/10.1007/s00170-014-6717-3.
[56] H.A. Kishawy, H. Hegab, I. Deiab, A. Eltaggaz, Sustainability assessment during machining Ti-6Al-4V with nano-additives-based minimum quantity lubrication, J. Manuf. Mater. Process. 3 (2019), https://doi.org/10.3390/jmmp3030061.
[57] S.M. Alimuzzaman, M.P. Jahan, C.S. Rakurty, N. Rangasamy, J. Ma, Cutting fluids in metal AM: a review of sustainability and efficiency, J. Manuf. Process. 106 (2023) 51–87, https://doi.org/10.1016/j.jmapro.2023.09.075.
[58] D.J. Hiran Gabriel, M. Parthiban, I. Kantharaj, N. Beemkumar, A review on sustainable alternatives for conventional cutting fluid applications for improved machinability, Mach, Sci. Technol. 27 (2023) 157–207, https://doi.org/10.1080/10910344.2023.2194966.
[59] G. Singh, M.K. Gupta, H. Hegab, A.M. Khan, Q. Song, Z. Liu, M. Mia, M. Jamil, V. S. Sharma, M. Sarikaya, C.I. Pruncu, Progress for sustainability in the mist assisted cooling techniques: a critical review, Int. J. Adv. Manuf. Technol. 109 (2020) 345–376, https://doi.org/10.1007/s00170-020-05529-x.
[60] N. Liu, X. Zou, J. Yuan, H. Jiang, Y. Zhang, Y. Chen, Optimization of MQL turning process considering the distribution and control of cutting fluid mist particles, Int. J. Adv. Manuf. Technol. 116 (2021) 1233–1246, https://doi.org/10.1007/s00170-021-07480-x.
[61] S. Nandgaonkar, T.V.K. Gupta, S. Joshi, Effect of water oil mist spray (WOMS) cooling on drilling of Ti6Al4V alloy using ester oil based cutting fluid, Procedia Manuf. 6 (2016) 71–79, https://doi.org/10.1016/j.promfg.2016.11.010.
[62] A. Gautam, Chetan, G. Bartarya, P. Dutta, Environment-friendly machining of aerospace-grade Ti alloy using SiAlON ceramic and AlTiN coated carbide inserts under sustainable biodegradable mist condition, CIRP J. Manuf. Sci. Technol. 39 (2022) 185–198, https://doi.org/10.1016/j.cirpj.2022.08.006.
[63] S. Mane, J. Ramchandani, D. Marla, S.S. Joshi, Experimental investigation of oil mist assisted cooling on orthogonal cutting of Ti6Al4V, Procedia Manuf. 34 (2019) 369–378, https://doi.org/10.1016/j.promfg.2019.06.180.
[64] Z. Said, M. Gupta, H. Hegab, N. Arora, A.M. Khan, M. Jamil, E. Bellos, A comprehensive review on minimum quantity lubrication (MQL) in machining processes using nano-cutting fluids, Int. J. Adv. Manuf. Technol. 105 (2019) 2057–2086, https://doi.org/10.1007/s00170-019-04382-x.
[65] B. Sen, M. Mia, G.M. Krolczyk, U.K. Mandal, S.P. Mondal, Eco-friendly cutting fluids in minimum quantity lubrication assisted machining: a review on the perception of sustainable manufacturing, Int. J. Precis. Eng. Manuf. Technol. 8 (2021) 249–280, https://doi.org/10.1007/s40684-019-00158-6.
[66] V. Vasu, G. Pradeep Kumar Reddy, Effect of minimum quantity lubrication with Al2O3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy, Proc. Inst. Mech. Eng. - Part N J. Nanoeng. Nanosyst. 225 (2011) 3–16, https://doi.org/10.1177/1740349911427520.
[67] Ç.V. Yıldırım, T. Kıvak, M. Sarıkaya, Ş. Şirin, Evaluation of tool wear, surface roughness/topography and chip morphology when machining of Ni-based alloy 625 under MQL, cryogenic cooling and CryoMQL, J. Mater. Res. Technol. 9 (2020) 2079–2092, https://doi.org/10.1016/j.jmrt.2019.12.069.
[68] B. Ramesh, S.R. Vempati, C. Manjunath, A.H. Elsheikh, Examination of minimum quantity lubrication performance in the hard turning of AISI/SAE 1060 high-carbon steel, J. Mater. Eng. Perform. (2024), https://doi.org/10.1007/s11665-024-10070-z.
[69] Y. Wang, C. Liu, State-of-the-art on minimum quantity lubrication in green machining, J. Clean. Prod. 429 (2023) 139613, https://doi.org/10.1016/j.jclepro.2023.139613.
[70] X. Cui, C. Li, Y. Zhang, W. Ding, Q. An, B. Liu, H.N. Li, Z. Said, S. Sharma, R. Li, Comparative assessment of force, temperature, and wheel wear in sustainable grinding aerospace alloy using biolubricant, Front. Mech. Eng. 18 (2023) 3.
[71] Y. Kaynak, Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining, Int. J. Adv. Manuf. Technol. 72 (2014) 919–933.
[72] A.K. Sharma, A.K. Tiwari, A.R. Dixit, Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: a comprehensive review, J. Clean. Prod. 127 (2016) 1–18, https://doi.org/10.1016/j.jclepro.2016.03.146.
[73] A. Das, S. Padhan, S.R. Das, M.S. Alsoufi, A.M.M. Ibrahim, A. Elsheikh, Performance assessment and chip morphology evaluation of austenitic stainless steel under sustainable machining conditions, Metals 11 (2021), https://doi.org/10.3390/met11121931.
[74] A.D.L. Batako, V. Tsiakoumis, An experimental investigation into resonance dry grinding of hardened steel and nickel alloys with element of MQL, Int. J. Adv. Manuf. Technol. 77 (2015) 27–41.
[75] C. Wang, Z. Bao, P. Zhang, W. Ming, M. Chen, Tool wear evaluation under minimum quantity lubrication by clustering energy of acoustic emission burst signals, Measurement 138 (2019) 256–265.
[76] M.J. Bermingham, W.M. Sim, D. Kent, S. Gardiner, M.S. Dargusch, Tool life and wear mechanisms in laser assisted milling Ti–6Al–4V, Wear 322 (2015) 151–163.
[77] M. Hu, W. Ming, Q. An, M. Chen, Tool wear monitoring in milling of titanium alloy Ti–6Al–4 V under MQL conditions based on a new tool wear categorization method, Int. J. Adv. Manuf. Technol. 104 (2019) 4117–4128.
[78] X. Cui, C. Li, M. Yang, M. Liu, T. Gao, X. Wang, Z. Said, S. Sharma, Y. Zhang, Enhanced grindability and mechanism in the magnetic traction nanolubricant grinding of Ti-6Al-4V, Tribol. Int. 186 (2023) 108603.
[79] K. Arul, V. Mohanavel, S. Raj Kumar, T. Maridurai, K. Magesh Kumar, M. Ravichandran, Investigation of machining attributes on machining of alloys under nano fluid MQL environment: a review, Mater. Today Proc. 59 (2022) 1312–1318, https://doi.org/10.1016/j.matpr.2021.11.525.
[80] A. Yücel, Ç.V. Yıldırım, M. Sarıkaya, Ş. Şirin, T. Kıvak, M.K. Gupta, Í. V Tomaz, Influence of MoS2 based nanofluid-MQL on tribological and machining characteristics in turning of AA 2024 T3 aluminum alloy, J. Mater. Res. Technol. 15 (2021) 1688–1704.
[81] T. He, N. Liu, H. Xia, L. Wu, Y. Zhang, D. Li, Y. Chen, Progress and trend of minimum quantity lubrication (MQL): a comprehensive review, J. Clean. Prod. 386 (2023) 135809, https://doi.org/10.1016/j.jclepro.2022.135809.
[82] Ş. Şirin, M. Sarıkaya, Ç.V. Yıldırım, T. Kıvak, Machinability performance of nickel alloy X-750 with SiAlON ceramic cutting tool under dry, MQL and hBN mixed nanofluid-MQL, Tribol. Int. 153 (2021) 106673, https://doi.org/10.1016/j.triboint.2020.106673.
[83] M.A. Makhesana, K.M. Patel, G.M. Krolczyk, M. Danish, A.K. Singla, N. Khanna, Influence of MoS2 and graphite-reinforced nanofluid-MQL on surface roughness, tool wear, cutting temperature and microhardness in machining of Inconel 625, CIRP J. Manuf. Sci. Technol. 41 (2023) 225–238, https://doi.org/10.1016/j.cirpj.2022.12.015.
[84] T. Lv, X. Xu, H. Weng, A. Yu, C. Niu, X. Hu, A study on lubrication and cooling performance and machining characteristics of magnetic field–assisted minimum quantity lubrication using Fe3O4 nanofluid as cutting fluid, Int. J. Adv. Manuf. Technol. 123 (2022) 3857–3869, https://doi.org/10.1007/s00170-022-10500-z.
[85] H. Wang, Q. Bai, S. Chen, P. Wang, W. Guo, Y. Dou, Wear suppression and interface properties of diamond tool in micro-milling of TC4 alloy under graphene nanofluid MQL environment, J. Clean. Prod. 418 (2023) 138180, https://doi.org/10.1016/j.jclepro.2023.138180.
[86] M. Sarıkaya, Ş. Şirin, Ç.V. Yıldırım, T. Kıvak, M.K. Gupta, Performance evaluation of whisker-reinforced ceramic tools under nano-sized solid lubricants assisted MQL turning of Co-based Haynes 25 superalloy, Ceram. Int. 47 (2021) 15542–15560, https://doi.org/10.1016/j.ceramint.2021.02.122.
[87] J. Wang, J. Ge, G. Chen, J. Liu, Z. Wang, C. Ren, Sustainable cooling/lubrication induced thermo-mechanical effects on ultrasonic vibration helical milling of CFRP/Ti–6Al–4V stacks, Int. J. Light. Mater. Manuf. 6 (2023) 311–328, https://doi.org/10.1016/j.ijlmm.2023.02.002.
[88] C. Ni, L. Zhu, Investigation on machining characteristics of TC4 alloy by simultaneous application of ultrasonic vibration assisted milling (UVAM) and economical-environmental MQL technology, J. Mater. Process. Technol. 278 (2020) 116518, https://doi.org/10.1016/j.jmatprotec.2019.116518.
[89] Q. Niu, J. Rong, L. Jing, H. Gao, S. Tang, X. Qiu, L. Liu, X. Wang, F. Dai, Study on force-thermal characteristics and cutting performance of titanium alloy milled by ultrasonic vibration and minimum quantity lubrication, J. Manuf. Process. 95 (2023) 115–130, https://doi.org/10.1016/j.jmapro.2023.04.002.
[90] S.K. Lim, W.H. Azmi, A.S. Jamaludin, A.R. Yusoff, Characteristics of hybrid nanolubricants for MQL cooling lubrication machining application, Lubricants 10 (2022), https://doi.org/10.3390/lubricants10120350.
[91] A.A. Junankar, Y. Yashpal, J.K. Purohit, Experimental investigation to study the effect of synthesized and characterized monotype and hybrid nanofluids in minimum quantity lubrication assisted turning of bearing steel, Proc. Inst. Mech. Eng. Part J J. Eng. Tribol. 236 (2022) 1794–1813.
[92] V.K. Sharma, T. Singh, K. Singh, M. Rana, A. Gehlot, R. Verma, Influence of hybrid nanofluid on tool wear and surface roughness in MQL-assisted face milling of AISI 52100, Adv. Mater. Process. Technol. (n.d) 1–12. https://doi.org/10.1080/2374068X.2023.2179291.
[93] T.B. Ngoc, T.M. Duc, N.M. Tuan, V.L. Hoang, T.T. Long, Machinability assessment of hybrid nano cutting oil for minimum quantity lubrication (MQL) in hard turning of 90CrSi steel, Lubricants 11 (2023), https://doi.org/10.3390/lubricants11020054.
[94] E. Usluer, U. Emiroğlu, Y.F. Yapan, G. Kshitij, N. Khanna, M. Sarıkaya, A. Uysal, Investigation on the effect of hybrid nanofluid in MQL condition in orthogonal turning and a sustainability assessment, Sustain. Mater. Technol. 36 (2023) e00618, https://doi.org/10.1016/j.susmat.2023.e00618.
[95] U. Demir, Y.F. Yapan, M. Uslu Uysal, A. Uysal, Sustainability assessment and optimization for milling of compacted graphite iron using hybrid nanofluid assisted minimum quantity lubrication method, Sustain. Mater. Technol. 38 (2023) e00756, https://doi.org/10.1016/j.susmat.2023.e00756.
[96] N. Khanna, C. Agrawal, D.Y. Pimenov, A.K. Singla, A.R. Machado, L.R.R. da Silva, M.K. Gupta, M. Sarikaya, G.M. Krolczyk, Review on design and development of cryogenic machining setups for heat resistant alloys and composites, J. Manuf. Process. 68 (2021) 398–422, https://doi.org/10.1016/j.jmapro.2021.05.053.
[97] N. Khanna, G. Kshitij, M. Solanki, T. Bhatt, O. Patel, A. Uysal, M. Sarıkaya, In pursuit of sustainability in machining thin walled α-titanium tubes: an industry supported study, Sustain. Mater. Technol. 36 (2023) e00647, https://doi.org/10.1016/j.susmat.2023.e00647.
[98] S. Debnath, M.M. Reddy, Q.S. Yi, Environmental friendly cutting fluids and cooling techniques in machining: a review, J. Clean. Prod. 83 (2014) 33–47, https://doi.org/10.1016/j.jclepro.2014.07.071.

[99] N. Tamil Alagan, P. Hoier, T. Beno, U. Klement, A. Wretland, Coolant boiling and cavitation wear – a new tool wear mechanism on WC tools in machining Alloy 718 with high-pressure coolant, Wear 452–453 (2020) 203284, https://doi.org/10.1016/j.wear.2020.203284.
[100] D. Kramar, J. Kopac, High pressure cooling in the machining of hard-to-machine materials, J. Mech. Eng. 55 (2009) 685–694.
[101] X. Zhang, D. Wang, Z. Peng, Effects of high-pressure coolant on cooling mechanism in high-speed ultrasonic vibration cutting interfaces, Appl. Therm. Eng. 233 (2023) 121125, https://doi.org/10.1016/j.applthermaleng.2023.121125.
[102] I. Tanabe, Y. Yamagami, H. Hoshino, Development of a new high-pressure cooling system for machining of difficulut-to-machine materials, J. Mach. Eng. 20 (2020) 82–97.
[103] Y. Zhang, M. Wu, K. Liu, J. Zhang, Optimization research of machining parameters for cutting GH4169 based on tool vibration and surface roughness under high-pressure cooling, Materials 14 (2021), https://doi.org/10.3390/ma14247861.
[104] Z. Lu, D. Zhang, X. Zhang, Z. Peng, Effects of high-pressure coolant on cutting performance of high-speed ultrasonic vibration cutting titanium alloy, J. Mater. Process. Technol. 279 (2020) 116584.
[105] L. Liu, M. Wu, L. Li, Y. Cheng, FEM simulation and experiment of high-pressure cooling effect on cutting force and machined surface quality during turning Inconel 718, Integrated Ferroelectrics Int. J. 206 (2020) 160–172.
[106] N. Tamil Alagan, P. Zeman, P. Hoier, T. Beno, U. Klement, Investigation of micro-textured cutting tools used for face turning of alloy 718 with high-pressure cooling, J. Manuf. Process. 37 (2019) 606–616, https://doi.org/10.1016/j.jmapro.2018.12.023.
[107] M.N. Sultana, N.R. Dhar, Performance evaluation of high-pressure cooling by using external rotary liquid applicator in milling Ti–6Al–4V alloy, Heliyon 9 (2023) e17671, https://doi.org/10.1016/j.heliyon.2023.e17671.
[108] K.C. Wickramasinghe, H. Sasahara, E.A. Rahim, G.I.P. Perera, Green Metalworking Fluids for sustainable machining applications: a review, J. Clean. Prod. 257 (2020) 120552, https://doi.org/10.1016/j.jclepro.2020.120552.
[109] J. Singh, S.S. Gill, M. Dogra, R. Singh, A review on cutting fluids used in machining processes, Eng. Res. Express. 3 (2021) 12002, https://doi.org/10.1088/2631-8695/abeca0.
[110] L. Tang, Y. Zhang, C. Li, Z. Zhou, X. Nie, Y. Chen, H. Cao, B. Liu, N. Zhang, Z. Said, S. Debnath, M. Jamil, H.M. Ali, S. Sharma, Biological stability of water-based cutting fluids: progress and application, Chin. J. Mech. Eng. 35 (2022) 3, https://doi.org/10.1186/s10033-021-00667-z.
[111] T. Hassan, E.M. Kandeel, M.S. Taher, E.E. Badr, A.S. El-Tabei, Sustainable utilization of the vegetable oil manufacturing waste product in the formulation of eco-friendly emulsifiable cutting fluids, Sci. Rep. 13 (2023) 21406, https://doi.org/10.1038/s41598-023-46768-8.
[112] R. D'Amato, C. Wang, R. Calvo, P. Valášek, A. Ruggiero, Characterization of vegetable oil as cutting fluid, Procedia Manuf. 41 (2019) 145–152, https://doi.org/10.1016/j.promfg.2019.07.040.
[113] Y. Wang, C. Li, Y. Zhang, B. Li, M. Yang, X. Zhang, S. Guo, G. Liu, Experimental evaluation of the lubrication properties of the wheel/workpiece interface in MQL grinding with different nanofluids, Tribol. Int. 99 (2016) 198–210, https://doi.org/10.1016/j.triboint.2016.03.023.
[114] T. Gao, C. Li, D. Jia, Y. Zhang, M. Yang, X. Wang, H. Cao, R. Li, H.M. Ali, X. Xu, Surface morphology assessment of CFRP transverse grinding using CNT nanofluid minimum quantity lubrication, J. Clean. Prod. 277 (2020) 123328, https://doi.org/10.1016/j.jclepro.2020.123328.
[115] S. Koley, Arsenic calamity in India's West Bengal: a critical review of mitigation scenarios, in: Proc. Inst. Civ. Eng. Sustain., Emerald Publishing Limited, 2023, pp. 198–213.
[116] A. Shokrani, P.J. Arrazola, D. Biermann, P. Mativenga, I.S. Jawahir, Sustainable machining: recent technological advances, CIRP Ann 73 (2024) 483–508, https://doi.org/10.1016/j.cirp.2024.06.001.
[117] G. Kshitij, N. Khanna, Ç.V. Yıldırım, S. Dağlı, M. Sarıkaya, Resource conservation and sustainable development in the metal cutting industry within the framework of the green economy concept: an overview and case study, Sustain. Mater. Technol. 34 (2022) e00507, https://doi.org/10.1016/j.susmat.2022.e00507.
[118] N. Eliaz, Corrosion of metallic biomaterials: a review, Materials 12 (2019) 407.
[119] C.B. Castells, C. Ràfols, M. Rosés, E. Bosch, Effect of temperature on pH measurements and acid–base equilibria in methanol–water mixtures, J. Chromatogr., A 1002 (2003) 41–53.
[120] J.-K. Kim, C.-H. Jeon, H.W. Lee, Y.-K. Park, K. Min, I. Hwang, Y.-M. Kim, Effect of accelerated high temperature on oxidation and polymerization of biodiesel from vegetable oils, Energies 11 (2018) 3514.
[121] O.E. Agwu, J.U. Akpabio, S.B. Alabi, A. Dosunmu, Artificial intelligence techniques and their applications in drilling fluid engineering: a review, J. Pet. Sci. Eng. 167 (2018) 300–315.
[122] Y.M. Shashidhara, S.R. Jayaram, Vegetable oils as a potential cutting fluid—an evolution, Tribol. Int. 43 (2010) 1073–1081, https://doi.org/10.1016/j.triboint.2009.12.065.
[123] A. Randegger-Vollrath, Determination of chlorinated paraffins in cutting fluids and lubricants, Fresenius' J. Anal. Chem. 360 (1998) 62–68.
[124] A. Shokrani, V. Dhokia, S.T. Newman, Environmentally conscious machining of difficult-to-machine materials with regard to cutting fluids, Int. J. Mach. Tool Manufact. 57 (2012) 83–101, https://doi.org/10.1016/j.ijmachtools.2012.02.002.
[125] S. Kalpakjian, S. Schmid, Manufacturing, engineering and technology SI 6th edition-serope kalpakjian and stephen schmid: manufacturing, engineering and technology, Digit. Des. (2006).
[126] S. Alves, Vegetable Based Cutting Fluid - an Environmental Alternative to Grinding Process, 2008.
[127] E. Kuram, B. Ozcelik, M. Bayramoglu, E. Demirbas, B.T. Simsek, Optimization of cutting fluids and cutting parameters during end milling by using D-optimal design of experiments, J. Clean. Prod. 42 (2013) 159–166, https://doi.org/10.1016/j.jclepro.2012.11.003.
[128] J.Z. Zhang, P.N. Rao, M. Eckman, Experimental evaluation of a bio-based cutting fluid using multiple machining characteristics, Wear 12 (2012) 13–14.
[129] R.A. Kazeem, D.A. Fadare, O.M. Ikumapayi, A.A. Adediran, S.J. Aliyu, S. A. Akinlabi, T.-C. Jen, E.T. Akinlabi, Advances in the application of vegetable-oil-based cutting fluids to sustainable machining operations, A Review, Lubricants 10 (2022), https://doi.org/10.3390/lubricants10040069.
[130] R. Katna, M. Suhaib, N. Agrawal, Nonedible vegetable oil-based cutting fluids for machining processes – a review, Mater. Manuf. Process. 35 (2020) 1–32, https://doi.org/10.1080/10426914.2019.1697446.
[131] R. Park, M. Silverstein, N. Maizlish, F. Mirer, Mortality among workers exposed to cutting fluids and abrasives: bearing plant 1, international union, united automobile, Aerospace and Agricultural Implement (1984).
[132] E.A. Eisen, P.E. Tolbert, R.R. Monson, T.J. Smith, Mortality studies of machining fluid exposure in the automobile industry I: a standardized mortality ratio analysis, Am. J. Ind. Med. 22 (1992) 809–824, https://doi.org/10.1002/ajim.4700220604.
[133] P.E. Tolbert, E.A. Eisen, L.J. Pothier, R.R. Monson, M.F. Hallock, T.J. Smith, Mortality studies of machining-fluid exposure in the automobile industry: II. Risks associated with specific fluid types, Scand. J. Work, Environ. Health. 18 (1992) 351–360.
[134] E.P. on C. in the F.C. (EFSA C. Panel), D. Schrenk, M. Bignami, L. Bodin, J. K. Chipman, J. del Mazo, C. Hogstrand, L. Hoogenboom, J. Leblanc, C.S. Nebbia, Risk assessment of N-nitrosamines in food, EFSA J. 21 (2023) e07884.
[135] A.S. Robertson, D.C. Weir, P.S. Burge, Occupational asthma due to oil mists, Thorax 43 (1988) 200.
[136] B. Purvis, Y. Mao, D. Robinson, Three pillars of sustainability: in search of conceptual origins, Sustain. Sci. 14 (2019) 681–695.
[137] Z. Jiang, D. Gao, Y. Lu, L. Kong, Z. Shang, Quantitative analysis of carbon emissions in precision turning processes and industrial case study, Int. J. Precis. Eng. Manuf. Technol. 8 (2021) 205–216.
[138] A. Uysal, I.S. Jawahir, Optimization of sustainable machining of Ti6Al4V alloy using genetic algorithm for minimized carbon emissions and machining costs, and maximized energy efficiency and human health benefits, in: ASME Int. Mech. Eng. Congr. Expo, American Society of Mechanical Engineers, 2021. V02BT02A061.
[139] H. Yang, J. Wu, F. Chen, Z. Guo, X. Xue, Y. Chen, G. Xu, Life cycle climate performance evaluation of electric vehicle thermal management system under Chinese climate and driving condition, Appl. Therm. Eng. 228 (2023) 120460.
[140] A.M. Khan, M.K. Gupta, H. Hegab, M. Jamil, M. Mia, N. He, Q. Song, Z. Liu, C. I. Pruncu, Energy-based cost integrated modelling and sustainability assessment of Al-GnP hybrid nanofluid assisted turning of AISI52100 steel, J. Clean. Prod. 257 (2020) 120502, https://doi.org/10.1016/j.jclepro.2020.120502.