CIRP Annals - Manufacturing Technology 73 (2024) 483–508

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: https://www.editorialmanager.com/CIRP/default.aspx

Sustainable machining: Recent technological advances

A. Shokrani (2)[a,*], P.J. Arrazola (1)[b], D. Biermann (1)[c], P. Mativenga (2)[d], I.S. Jawahir (1)[e]

[a] University of Bath, Bath, United Kingdom
[b] University of Mondragon, Mondragon, Spain
[c] TU Dortmund University, Dortmund, Germany
[d] University of Manchester, Manchester, United Kingdom
[e] University of Kentucky, Lexington, KY, United States

ARTICLE INFO

Article history:
Available online 22 July 2024

Keywords:
Machining
Sustainable machining
Cutting tool

ABSTRACT

Multiple international organizations and many governments around the world have declared climate emergency. There is a pressing need to minimize the environmental impacts of human activities including manufacturing processes. Machining by mechanical cutting is a fundamental manufacturing process and minimizing and eliminating its environmental impacts is vital. In this keynote paper, sustainability in the context of machining is identified. The resources used in machining have been categorized and the social and environmental impacts and potential methods to reduce them have been identified. The findings are critically discussed and the gaps and challenges for future research direction are highlighted.

1. Introduction

Manufacturing of products and goods has driven economic growth and prosperity to many regions of the world. However, the world is in a state of climate emergency. The CO_2 emissions due to human activities in the past 50 years have been higher than the total over the entire human history. The issue is not limited to greenhouse gas (GHG) emissions. Natural resources have been extracted at an alarming rate over the past 60 years and the list of critical raw materials (CRMs) have been increasing in the past decade [84]. The linear concept of extraction-production-consumption-disposal is no longer sustainable.

Machining is a fundamental manufacturing process for producing precision mechanical parts used across different industries. The global metal machining market is estimated at ~$378 billion in 2023 [210] supported by a ~$73 billion cutting tools market [90]. Fig. 1 illustrates the inputs and outputs of a machining system consisting of the machine tool, workpiece material, cutting tools, coolant/lubricants (CLs) and tooling such as tool holders and fixtures. Each of these affects the impacts of a machining system on the environment. Energy is used for operating machine tools and a small portion of this energy is used for material cutting.

1.1. What is sustainability?

In 1987, the UN Commission on Environment and Development set out Sustainable Development as meeting "*the needs of today without compromising the ability of future generations to meet their own needs*" [297]. This led to the concept of eco-efficiency: environmental impact per unit output. Despite improvements in eco-efficiency of products and services over the years, total global environmental impact has continued to increase due to the rise in consumption driven by effluence and population. Rockstrom et al. [229] proposed a framework based on nine "*planetary boundaries*" associated with the Earth's biophysical subsystems and defined a safe operating zone within the planet's system. By 2023, six out of these nine planetary boundaries were violated.

Kara et al. [131] provided a detailed analysis of the definitions for sustainability and sustainable development, and highlighted their shortcomings. Based on the work of Nykvist et al. [184] on translating planetary boundaries to national limits, Hasuchild [109] proposed the concept of absolute sustainability. They [111] noted that whilst sustainable manufacturing aims to satisfy the needs of present and future generations, it should not violate the planetary boundaries. It is argued that environmental sustainability takes precedence and planetary

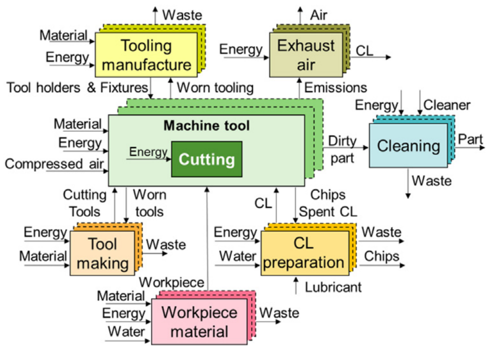

Fig. 1. Inputs and outputs of a machining system.

* Corresponding author.
E-mail address: a.shokrani@bath.ac.uk (A. Shokrani).

https://doi.org/10.1016/j.cirp.2024.06.001

boundaries should be used instead of the triple bottom model (environmental, economic and social) [110]. Achieving environmental sustainability however, must not be used as a means to sacrifice human rights. Instead, efforts should focus on equitable division of the limited resources and not exceeding the planetary boundaries.

To meet the needs of the society, the resource consumption remains high but never beyond the planetary boundaries [223]. However, an analysis by O'Neill et al. [185] indicated that whilst basic physical needs of the world population can be met without significant breach of the planetary boundaries, reaching more qualitative goals (life satisfaction, equality, life expectancy, etc.) requires a fundamental change. One such change is achieving two to six times increased efficiency in resource consumption including in manufacturing. Additionally, circular economy strategies such as extending the life of products, repairing, reusing, remanufacturing and upcycling them, and recycling at the end of their life can reduce the demand on extracting materials, reduce energy consumption for manufacturing and reduce waste generation. Kara et al. [131] provided a detailed review of circular economy strategies and their potential to increase material efficiency and reduce environmental impacts.

1.2. Sustainability in machining

Sustainable machining entails reduction and elimination of the negative environmental and social impacts of a machining system without transgressing the planetary boundaries to meet the needs of the present and future generations, and improve the quality of life. The machining system includes the material cutting and machining itself as well as the production and procurement of the machine tool, cutting tools and the CLs. The societal impacts of machining are often overlooked. Beyond direct impacts on the workers' health and wellbeing, the supply chains of the materials and products used in a machining system can have a profound impact on the societies that they operate in. The principles of sustainability should not be limited to the processes but also products, systems and supply chains must be considered.

Sustainable manufacturing was defined by the US Department of Commerce as "processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound" [114]. Dornfeld [78] applied this definition to machining. In these definitions, "sustainable" is used in an absolute term [110]. In the absence of meaningful targets or quantifiable measures, sustainability in machining is difficult to assess or verify.

Sustainable machining systems must operate within the planetary boundaries [229]. However, operationalizing planetary boundaries at various levels is ongoing research [50,56]. It is difficult, if not impossible, to assign specific planetary limits for machining on its own without considering the wider implications throughout its value chain. To this end, 'downscaling' and defining specific budgets may be useful for global impacts such as GHG emissions e.g. targeting net-zero GHG emissions from machining. Machining companies that achieve this can be considered climate neutral. However, defining specific budgets for other areas is more complex. Additionally, allocated limits may be seen as targets. Alternatively, the impacts from a machining system can be 'upscaled' to planetary boundaries level [281] to highlight how it is contributing to transgressing the planetary boundaries.

Whilst absolute goals are necessary for achieving environmental sustainability in sustainable machining, relative sustainability is deemed more practical in many scenarios. Relative assessment can help identify and develop opportunities for minimizing the negative impacts paving the transition towards the ultimate goal of sustainable machining. Zero-waste, complete recyclability and reduced energy consumption can be the steppingstones to reach such goals. Hauschild et al. [108] highlighted the potential conflict between absolute and relative sustainability where over-consumption can diminish reduced environmental impacts.

The economy provides the foundation for meeting the social needs. The technology must be affordable for widespread adoption but lower costs may lead to increased consumption which needs to be controlled via other means. As such, the donut economy presented by Raworth [222] has been adapted as shown in Fig. 2.

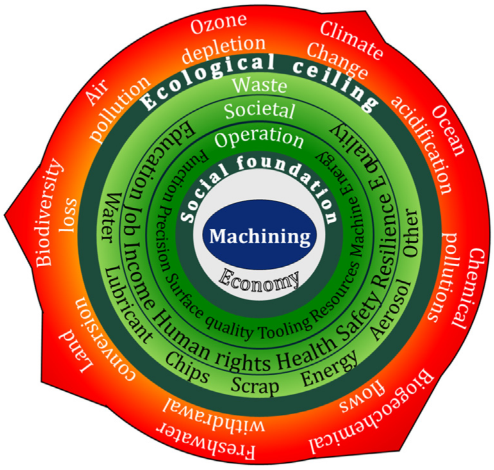

Fig. 2. Donut economy model for machining adapted from [222].

Machining as part of the economy provides a foundation to meet the minimum social needs. The safe operating zone is defined between the inner boundary of the social foundation and the carrying capacity of the planet as the outer boundary. Within this space, the quality of life can be improved if material efficiency is enhanced, and environmental impacts are reduced.

Following this introduction, an overview of the societal and environmental impacts of machining is presented. The efforts are then focused on the environmental impacts of various aspects of a machining system (machine tool, cutting tool, workpiece, cutting chips and CLs) and discussing the technologies for minimizing these impacts. Finally, the cumulative energy consumption for machining including the embodied energy of cutting tools and CLs is presented. An in-depth discussion is provided which lays the future direction for achieving the vision of sustainable machining.

2. Societal and environmental impacts of machining

Machining is a fundamental manufacturing process for producing functional engineering parts and products. The challenge is that in most economic metrics, it is not classified as a standalone industrial sector. Machining is a service provider to a multitude of industrial sectors such as aerospace, automotive, energy, defense, medical implants, consumer goods, etc. Nearly 25 % of the machine tools globally are used in automotive sector whilst 15 % are in aerospace and defense and 13 % are employed in power and energy sectors [133]. In this section, an overview of the major societal and environmental impacts of machining is presented.

2.1. Societal impacts

The ISO 26000 standard provides a framework for social responsibility for business and organizations and defines seven core subjects: human rights, labor practices, the environment, fair operating practices, consumer issues and, community involvement and development. The UNEP/SETAC guidelines [279] introduces social life cycle assessment (S-LCA) as a tool for investigating the social impacts of various activities on five stakeholders: workers, local community, value chain actors, society and children. The impact categories cover health and safety, human rights, working condition, governance, socio-economic impacts, etc. which may consist of multiple indicators. The indicators are assessed against a reference value as a minimum acceptable performance level usually set by the International Labor Organization Convention, ISO 26000, OECD Guidelines, etc.

Sutherland et al. [269] reviewed the major social impacts of manufacturing activities. Wu and Su [298] provided a detailed overview of S-LCA and its application for a manufacturing system. These methods can be applied to manufacturing broadly and machining processes specifically. Indicators specific to manufacturing can be found in [146]. The S-LCA for machining must consider the cradle-to-gate and cradle-to-grave life cycle of machining process and the materials used for the workpiece, cutting tools and CLs. Some of the specific indicators applicable to machining are defined below:

- Health and Safety: Occupational dermatitis and occupational asthma due to the exposure to water-based metalworking fluids (MWFs), a type of CL [258,300].

- Health and safety, equal opportunities: The ergonomics of machine tool and machine interface design [152,157,225]. Hafiz et al. [107] noted the differences in physical dimensions and capabilities of users. They noted that the majority of the machines are designed for an average European/North American worker. A similar issue was explored for female workers by Khan [137].

- Human rights, child labor, forced labor and modern slavery, health and safety, damage to local environment in the value chain: An important social impact of a machining system involves a transparent and responsible supply chain with respect to human rights. In machining, this particularly applies to the supply chain for raw materials for cutting tools (e.g. tungsten, cobalt, etc.), workpiece and CLs (mineral and agricultural-based chemicals, etc.) and their environment and human impacts. Artisanal mining, child labor [36,37,39] and exposure to toxic material [19] can take place in mining and extraction processes. There is a concern that these mining operations in the global south typically work on raw materials with limited economic benefits and the international capital has not been translated into social benefits for the local communities [4].

Haddad et al. [106] performed a S-LCA on manufacturing of aluminum aerospace components including machining and noted that upstream supply chains (mining, raw material production, etc.) have a profound influence on the social impacts of a product. Machining industries have a social responsibility to ensure that they do not inadvertently support human exploitation [35] in their value chain. Digital technologies such as material passports, blockchains, etc. can be implemented to ensure traceability and transparency of tools and materials used in machining.

2.2. Environmental impacts

The environmental aspect of machining is one of the main issues related to sustainability in machining. Direct and indirect energy and raw material consumption, and waste disposal are the main sources of the environmental impacts of machining. Whilst the direct energy and material consumption (Scope 1) are easier to analyze, controlling the sources of energy and raw materials used for machining is more complex.

The UK Department for Environment, Food and Rural Affairs have identified 22 environmental key performance indicators that are categorized into emissions to air, water and land as well as resource use [67]. The main environmental impacts from machining include global warming potential due to GHGs, water acidification as a result of releasing toxic gases, eutrophication by releasing nutrients chemical into water, human toxicity including cancerous and noncancerous, ecotoxicity, land use and abiotic (resource) depletion among others.

2.2.1. Global warming potential, acidification and human toxicity

Machining is widely electrified and generally, there are no direct greenhouse gas (GHG) emissions (Scope 1) from operating a machine tool. However, there are emissions associated with producing electricity (Scope 2) as well as extracting the material for machine tool, tooling and consumables (Scope 3) i.e., workpiece material, cutting tools, coolant/lubricants, etc. Reducing the machine tool's electricity consumption for machining a part can reduce the emissions associated with producing electricity. Using clean electricity from zero-emission sources can further reduce the Scope 2 emissions from a machining system due to the use of electricity.

While reducing machining energy consumption is a major step, the environmental impacts of machining are wider than only GHG emissions from electricity consumption. Energy and specifically fossil fuels are used in the mining and extraction of materials for producing the workpiece, cutting tool and machine tool as well as for operating the machineries used in farming oil seeds for CLs. Carbon, sulfur and nitrogen dioxides released from burning fossil fuels can dissolve in water leading to soil and ocean acidification.

The direct air contaminants from machining are related to solid dust and liquid aerosols generated during material cutting and microbial volatile organic compounds (MVOCs) within the human toxicity category. Dust particles are most common in machining brittle materials where small chips and dust are generated such as during machining of carbon fiber reinforced plastic (CFRP) composites [69]. This can lead to generation of particles smaller than 2.5 µm (PM2.5) which if inhaled can cause serious health issues. Depending on the material, digestion of the particles or skin contact can also result in adverse health effects in workers [105].

Water-based MWFs are widely considered a health and safety hazard [257] which can become aerosolized during machining [290]. Human toxicity can arise from inhaling and exposure to these aerosols leading to occupational asthma, dermatitis and even cancer [197,258]. Water-based MWFs provide a rich environment for fungi and bacterial growth which can generate MVOCs [198]. The health and safety aspects are among the key concerns for the use of MWFs. In the UK, the Health and Safety Executive [58] requires ongoing risk assessment and training to ensure that exposure is prevented or adequately controlled.

Airtight machine tools and local exhaust ventilation (LEV) systems are highly recommended to prevent exposure to aerosolized CLs [58]. In minimum quantity lubrication (MQL) systems, aerosolized lubricants which may or may not contain nanoparticles or chemical additives can become airborne and contaminate the air [162]. Within the research community, the health impacts of inhaling these nanoparticles are rarely considered. Examples of these potentially hazardous nanoparticles are carbon nanotube (CNT), boric acid and aluminum oxide nanoparticles [182].

2.2.2. Land use, resource depletion, eutrophication and ecotoxicity

The materials for cutting tools and workpiece are mined and extracted from ores, consuming energy and resources and generating waste and contaminating waterways and soil [158]. Tungsten and cobalt are extracted for producing cutting tools. Both of these materials are CRMs and enormous waste is generated during their extraction [31]. Depending on the mining and extraction method, they can have a profound impact on the environment. This can be resource depletion, ecotoxicity in the form of releasing chemicals and waste into the environment and land use by deforestation and habitat loss for mining.

Over 10 million cubic meters of cutting fluids are consumed each year [248]. These need to be maintained, treated and disposed. Water, mineral oil, synthetic lubricants and chemical additives are used in producing these fluids.

Ecotoxicity due to water pollution originating from the use of MWFs is one of the major direct impacts of machining. There are strict rules and requirements in various countries on the use, treatment and safe disposal of MWFs [54,172,179,280]. Specifically, water-soluble MWFs can lead to water pollution through leaching of toxic chemicals such as extreme pressure additives, biocides and fungicides, emulsifiers, etc. [197]. Particles of workpiece and tool materials can be washed during cleaning of the parts and chips and be released into the environment.

Contamination of soil by mineral oil based MWFs can lead to oxygen deprivation, resulting in the development of anaerobic microorganisms and making it uninhabitable for aerobic microflora and plants [98]. Water contaminated by spent MWFs in the environment has been shown to damage crop growth [99].

Mineral oil-based CLs are extracted from crude oil leading to resource depletion and land use. Vegetable-based oils are extracted from oil plants. In farming, pesticides and fertilizers can leach into the environment leading to ecotoxicity and eutrophication. Using plant-based derivatives in machining may compete with food production and lead to land use by encouraging deforestation for farmlands [161].

The social and environmental impacts associated with the products used in machining highlight the need for a close collaboration with suppliers and a transparent supply chain to ensure minimal impact on the environment for sourcing the consumables for machining.

3. Classification of resources used in machining

To evaluate the environmental sustainability of machining, the environmental impact of the input material, energy flows and the generated waste flows must be assessed. Dahmus and Gutowski [60] developed a model presenting an overview of the inputs and outputs of a machining system including the waste products for assessing the environmental impacts of machining. Fig. 3 shows an updated system diagram for metal cutting based on [24].

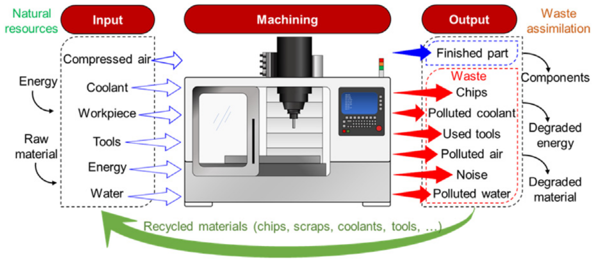

Fig. 3. Inputs and outputs for the environmental assessment of machining based on [24].

In Fig. 4, the effect of various inputs of machining processes on the life cycle stages of a machined part is summarized. Machining has minimal impact on the extraction stage of the raw workpiece material and the end of life stage of a part. The environmental impact of producing non-consumable inputs e.g. the machine tool, clamping system, tool holders, workshop floor, etc. are usually not considered in the Life Cycle Assessment (LCA) of machined parts justified by their relatively long lifespan [60,214]. Nonetheless, the impact of these inputs should also be considered for a holistic LCA of machining. Machine tools have large masses with high material and CO_2 footprint. Diaz et al. [75] demonstrated that the embodied CO_2 of a machine tool from its manufacturing can be as high as 55 % of its emissions due to the use of electricity over its lifetime.

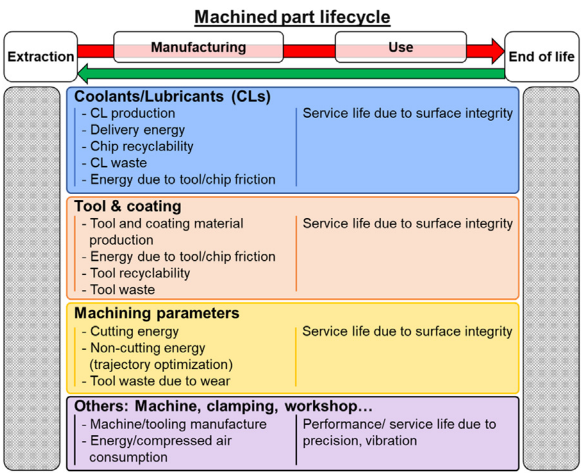

Fig. 4. Impact of machining inputs on lifecycle phases of a machined part.

LCA is widely used to investigate the environmental impact in the design phase of products. Most studies that carry out a LCA for machining make a comparison of the impact generated by employing different CLs [86,203]. In most cases, they only consider the CLs and the machine's energy consumption. Energy consumption of a machine tool is an important contributor to the direct environmental impact of machining [88]. However, a comprehensive analysis should also consider the wider impacts of the production, use and end of life treatment of the cutting tools, CLs, tooling and the machine tool.

4. Cutting tools

Cutting tools are one of the major consumables in machining processes and minimizing the environmental impacts of machining necessitates innovation and optimization of all aspects regarding the tools' life cycle shown in Fig. 5. Reducing the environmental impacts of machining through cutting tools can be achieved by reducing the resource and energy footprint of the tool, extending the tool life and its time in circulation through reconditioning and remanufacturing. The cutting tool performance can also directly affect the energy consumption during machining.

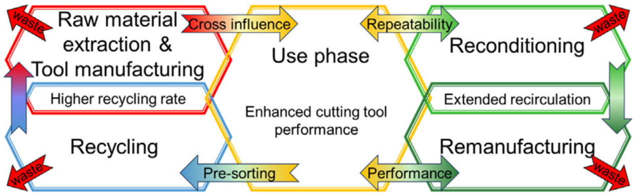

Fig. 5. Circularity of cutting tool materials.

Starting with tool manufacturing, factors such as the percentage of recycled material, use of alternative environmentally friendly materials and reducing the total energy consumption in the process chain represent opportunities to minimize and eliminate the environmental impacts of machining.

The second category comprises the tool's use phase. Improved tool performance through extended tool life and enhanced wear resistance reduces secondary process times leading to increased productivity. At the end-of-life, deciding whether to recondition, recycle or dispose of the tools becomes crucial. Reconditioning and remanufacturing of the tools should be prioritized to extend the materials in circulation. However, this requires overcoming technical and logistical challenges and to ensure that the tools are not damaged beyond repair and that reconditioned tools can perform similar to new tools. With the inevitable end of a tool's life, recycling needs to be addressed by implementing organizational concepts to facilitate economic and effective recycling.

4.1. Environmental impact of cutting tool manufacturing

High speed steel (HSS), cemented carbide, ceramics, polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) are the most common materials used for cutting tools [141]. Tungsten carbide with cobalt binder, also known as cemented carbide or WC—Co is one of the most important cutting tool materials used for over 80 % of the cutting tools in industry.

The extraction of tungsten by mining requires large amounts of resources. With a yield of ~0.13 %, only 2.55 kg of tungsten can be extracted from 2000 kg of tungsten ore generating a significant amount of solid waste [45]. Farjana et al. [87] assessed the environmental impact of cobalt extraction and found high electricity demand as the main concern, followed by the particle emitting blasting process and diesel consumption. They recommended using electricity from renewable sources and reducing the amount of particles released during blasting to be prioritized. The WC—Co tool market alone is responsible for an annual consumption of 36,600 tons of tungsten. Producing this amount from primary ores directly translates to 350,000 tCO_2. Increasing the recycling rate from the current 34 % and reducing dissipation and discard losses has the potential to save up to 40 % of CO_2 emissions and up to 70 % of energy demand

[264]. Sandvik Coromant noted a 20 % decrease in their CO_2 emissions through the reported material recycling rates reaching 80 % with an expected future increase to 90 % [234].

Furberg et al., [92] performed a cradle-to-gate Life Cycle Inventory (LCI) for producing 1 kg WC—Co rods in different scenarios as illustrated in Fig. 6. Their analysis was limited to the production of blanks including powder production, forming green compacts and sintering. For a typical ø10 mm x 72 mm solid carbide tool, these equate to 31 MJ-eq energy and 1.25 kg CO_2-eq footprint.

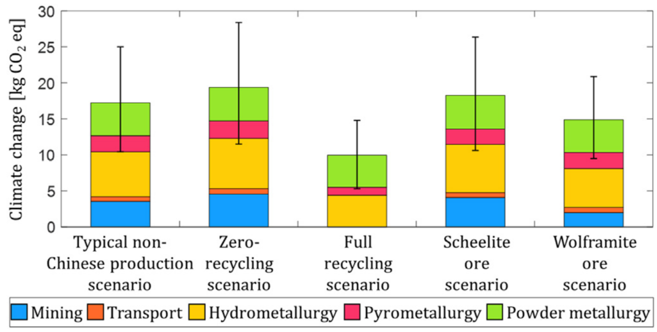

Fig. 6. GHG emissions from producing 1 kg tungsten carbide [92].

For tool manufacturing, the blanks also require grinding, coating, polishing and other finishing processes. Li et al. [154] noted that the carbon footprint of a P10 WC—Co insert with 15 g weight can reach 104.6 kg CO_2/kg which includes the emissions due to material extraction and cutting tool production. However, for their analysis, they only considered 29.6 kg CO_2/kg associated with tool manufacturing from WC—Co blanks. A similar value was used by [128]. For producing a WC—Co blank for a ø10 mm x 73 mm solid end mill, Kirsch et al. [140] defined a 9.01 MJ embodied energy, significantly lower than the aforementioned studies. However, they broke down the tool manufacturing processes and calculated that 8.75 MJ energy is required for making an AlTiN coated tool from the blanks. This only included the direct energy for grinding and coating equipment.

Both tungsten and cobalt are CRMs [84]. Apart from scarcity, the production of these metals is concentrated in a few geographical locations which can pose a risk to the global supply as shown in Fig. 7. Reducing the demand for WC—Co can be achieved by deploying alternative cutting tool materials such as HSS, ceramics and other non-metallic materials e.g. PCBN and PCD. Whilst the performance of these alternatives has been well studied [174,245], there is a need for proving their environmental viability in a machining system using LCA. Furberg et al. [93] assessed the environmental and resource impacts of substituting WC—Co tools with synthetic PCD. They found that PCD tools do not provide a viable alternative to WC—Co tools in order to reduce the environmental impact or resource consumption in machining Ti6Al4V alloy. The high energy consumption and the use of WC—Co and molybdenum in the production of PCD resulted in high environmental and resource impacts. Additionally, higher costs and recyclability of alternative tool materials may pose challenges in their wide adoption [243]. PCD has an embodied energy of 10 MJ/g and 0.9 kg CO_2-eq/g. Catalano et al. [42] investigated the embodied energy and carbon intensity of producing 10 mm diameter HSS tapping tools. They noted 128.5 MJ energy and 9.25 kg CO_2-eq/kg for a HSS bar from primary sources. Additional processes include turning, heat treatment, grinding, cleaning and coating leading to

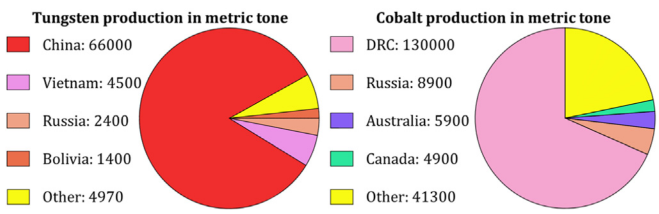

Fig. 7. Cobalt and tungsten production by country [94,134].

36.1 MJ energy and 1.5 kg CO_2-eq emissions per tool which can be reduced to 31.2 MJ and 1.17 kg CO_2-eq if 80 % recycled material is used.

The data for energy demand and CO_2 footprint of various cutting tool materials is sparse. There is a need for cradle-to-gate and cradle-to-grave analysis of cutting tools of different materials considering their embodied energy and CO_2 footprint balanced against their machining performance e.g. tool life.

4.2. Enhanced tool performance

Increasing tool life, while reducing material consumption and specifically CRMs, can reduce the environmental impacts associated with production and use of cutting tools [228].

4.2.1. Micro- and macro- geometries

The magnitude and distribution of the thermomechanical stresses during machining can be controlled by modifying the geometry of the cutting edge. Friction represents ~20 % of the total energy in cutting process and can be reduced using cutting edge preparation techniques [3]. The most common techniques are grinding, brushing, abrasive jet machining or laser machining [70]. Particularly, laser machining has gained in importance, as customized cutting edge geometries in super-hard cutting materials, e.g. PCD or PCBN can be realized [315]. Basset et al. [21] stated that when using coated tools, a significant increase in tool life of more than 100 % can be realized through cutting edge preparation.

Modifying the contact surfaces of the cutting tools through texturing functional surfaces and macro geometries can be used to control the friction and/or contact area at the cutting zone to reduce cutting forces and energy consumption and, enhance tool life [3]. Increased tool life by improving wear resistance and machining performance, can also reduce the use of CRMs [194,205]. Texturing the cutting tools parallel to the cutting edge has shown to reduce cutting forces by 7.7 % in turning AISI 316 [283]. A reduction in the chip-tool effective contact area can also be achieved by macroscopic alterations on the tool. Using an insert with serrated edges was shown to reduce cutting power by 17 % [177]. Whilst additional processing of the cutting edge and tool surfaces can improve tool performance and reduce cutting forces, the viability of these methods needs further assessment in terms of resource and energy efficiency. In this case, these methods are only viable if the additional energy and materials used for processing the tools are offset by a reduction in machine tool's energy consumption or significantly increased tool life.

4.2.2. Protective coatings

Coatings are a viable and cost-effective method for extending tool life whilst reducing friction and energy consumption. Albeit only a few microns in thickness, coatings feature abrasion resistance, thermal insulation, friction reduction and chemical inertia. Thus, the substrate is protected against thermomechanical and thermochemical wear resulting in increased tool life and reduced CRM consumption [32,228]. For instance, in milling of hardened steel, Bouzakis et al. [33] summarized that coatings significantly reduced both stresses and temperatures in the substrate. This can lead to 200 % and up to 500 % increase in tool life compared to uncoated tools at the same cutting speed [228]. To permanently resist the thermomechanical and chemical loads acting on the tool, coatings with different properties are required depending on the application and as depicted in Fig. 8.

Since a compromise must be achieved among various requirements, different coating materials have been integrated as in multi-nanolayer and nanocomposite coatings in place of a single layer coating whilst also enhancing crack resistance as shown in Fig. 8 [228,311]. In addition to the architecture and deposition technologies, the coating materials and compounds also affect the coating's performance during machining [32].

Besides performance, the energy consumption of a coating process is of central importance. There are multiple technologies to apply coating on cutting tools. Among these, physical vapor

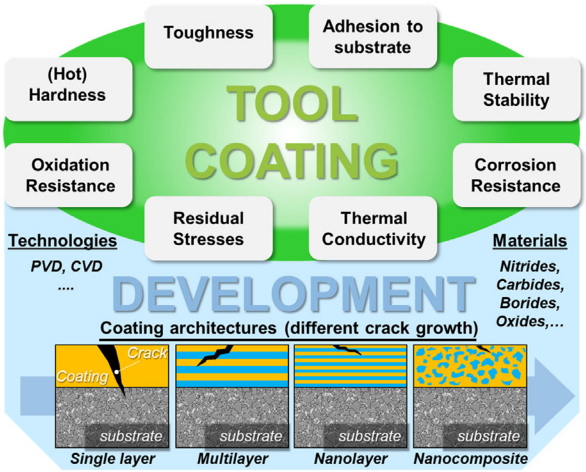

Fig. 8. Criteria required for effective of cutting tool coatings and development of hard coating, based on [228,311].

deposition (PVD) and chemical vapor deposition (CVD) are the most common methods. It has been reported that CVD has a higher energy consumption than PVD coating [21].

According to Kirsch et al. [140], the energy for PVD AlTiN coating process was 2.64 MJ, which is ~15 % of the total embodied energy for a milling tool. Bauer et al. [22] summarized the cumulative energy demand for coating 100,000 drilling tools. They showed that PVD process requires 108,000 MJ for TiN coating, which is about half the energy required for Ti+TiAlN coating. However, considering the material consumption for coating cutting tools, the analysis shows that Ti+TiAlN coating, which requires less material, has significantly lower environmental impact, especially for climate change, resource depletion, and acidification. Moreover, they reported that in PVD plants, a large amount of material does not reach the tools, resulting in waste. Considering that the materials used for coating have a large impact on the tool's environmental impact, there is still a potential for improvement in coating technologies. Coatings affect the recyclability of WC—Co and make reconditioning of worn tools more complex indicating a need for further research. For instance, Oerlikon presented a very hard Ta-C coating for the machining of non-ferrous metals, plastics or CFRP/GFRP. In addition to improved tool life and surface quality, this coating can be reapplied multiple times, allowing the tool to remain in use for longer and go through reconditioning phases before the need for recycling [186].

4.3. Exchangeable pieces and combination tools

An effective approach to minimize the consumption of CRMs is the adaptation of a ratio between the tool's effective cutting section and its total volume leading to a reduction in tool size, use of exchangeable pieces, combination tools or increased number of cutting edges. Exchangeable inserts have been utilized in turning operations for decades, primarily in order to reduce tool costs. About 75 % of all turning operations are performed with a depth of cut in the range of a_p = 1–3 mm. Hence, using smaller tools, without sacrificing tool life, can save costs and reduce the required amount of hard materials such as WC—Co [119], see Fig. 9.

In drilling, primarily, only the cutting edge is subject to wear providing an opportunity for using alternative materials for the body of the tool. This has led to the development of various concepts [205]. Exchangeable head systems are a prime example of efficient resource utilization as only the drilling head is made of CRMs and the body can be used over and over again. Moreover, there is the possibility of reconditioning such tools [167].

Sandvik Coromant have produced inserts with seven cutting edges, shown in Fig. 10a, allowing for using different sides of the same insert and reducing the material consumption for tools [233].

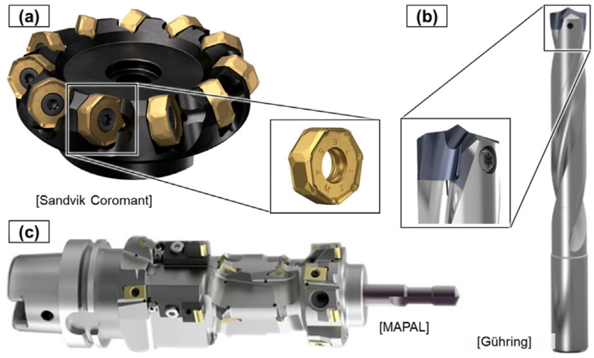

Fig. 10. Overview of industrial tool concepts with reduced material footprint in machining processes.

The HT 800 WP drilling system by Gühring [101] has exchangeable tips with micro-machined cutting edges and a screw lock mounted orthogonally to the drilling axis as shown in Fig. 10b.

Ceratizit [44] relies on replaceable head drills with Hirth toothing, allowing for reconditioning with reduced grinding effort. However, due to the precision required for producing multiple components, these systems can be expensive, limiting their large-scale use in industry. Wider industrial adoption requires further developments to make the manufacturing process more economical.

Besides the reduction of WC—Co consumption for cutting tools, the industry is also concerned with developing combination tools. Mapal [165] reported that by using combination tools such as the one shown in Fig. 10c, the total manufacturing time can be minimized. Unproductive times, tool change and traverse paths as well as material consumption are reduced this way.

Another approach to improve cutting tool performance was initially presented by Iscar to address the need for increasing number of cutting edges (up to 16 per insert). This increases the material removal rate (MRR) and tool life. Coupled with an increased number of insert seats, a symbiosis of elevated productivity and less amount of unused WC—Co is achieved [120,233]. In cooperation with Audi AG and Institute of Machining Technology (ISF), Emuge-Franken has reduced production time and energy consumption for making internal threads through helical thread forming "punch tapping" [307,308].

4.4. Additive manufacturing (AM) of cutting tools and chucks

AM allows for producing cutting tools with specific properties (natural frequency, resonance, etc.), complex geometries and internal cooling channels using less material [57,121]. The specialist designs can improve process stability, tool life and part surface quality and reduce energy consumption [176,224]. Internal coolant channels with optimized geometries can also enhance cooling and lubrication during machining (Fig. 11a).

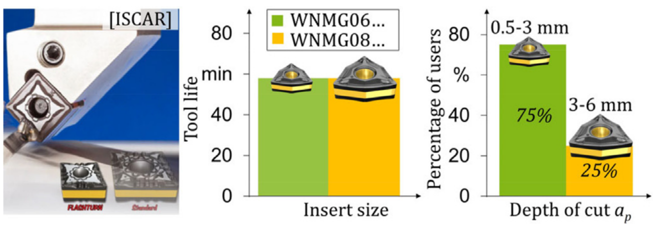

Fig. 9. Smaller inserts to reduce WC—Co consumption by Iscar [119].

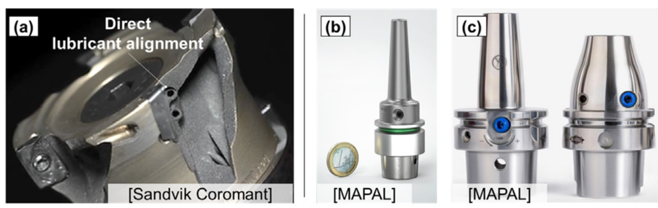

Fig. 11. AM tool holder: a) Sandvik lightweight CoroMill® 390; b) Mapal UNIQ hydraulic expansion chucks overview; c) Chucks in miniature format with HSK-E25 connection.

Lakner et al. [148] demonstrated that using an AM tool with modified cooling channels can lead to a 67 % increased tool life in milling AISI 4140+QT.

Mapal has produced an AM miniature hydraulic chuck with decentralized coolant outlets and negligible radial run-out error [166] as shown in Fig. 11b. They also developed hydraulic expansion chucks, UNIQ, with an equally slim design as shrink fit chucks, see Fig. 11c. In addition to the advantage of smaller dimensions, the use of hydraulic chucks provides the benefit of energy savings, decreased material consumption and a longer service life. These chucks can complete up to 15,000 clamping cycles. A convincing argument for switching to hydraulic clamping is the high amount of energy required for heating shrink fit chucks. A shrink fit tool holder requires about 12 MW of energy during its lifetime and is able to clamp only approximately 500 cycles [76].

By combining CFRP and AM, Kennametal were able to reduce the weight of a stator boring tool by 50 % shown in Fig. 12 [135]. Möhring et al. [176] developed a hybrid milling tool combining a damped steel body and CFRP. Application tests showed that the lightweight design reduced both vibrations and energy consumption while simultaneously increasing productivity.

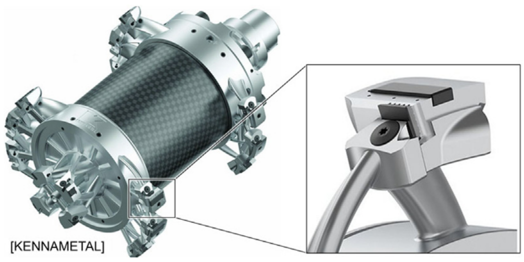

Fig. 12. Kennametal 3D-printed RIQ reaming tool – Stator Drilling Tool with 3 diameter steps for Electric Vehicles, based on [135].

Yang et al. [301] highlighted achieving a homogeneous grain size as the major challenge in AM of WC—Co. Wolfe et al. [296] and Hyperion Materials & Technologies [224] developed WC—Co inserts using Binder Jetting 3D Printing in various grades, with performance equivalent to conventionally produced carbides. Despite the many advantages of AM for producing cutting tools, higher production costs and lower productivity must be considered [145]. The low productivity in current AM technologies, limits the application to high end specialist tools.

4.5. Reconditioning and reusing cutting tools

Tools deployed in machining processes are subject to wear which affects their performance. Whilst advances in wear resistant materials and coatings with optimized tool geometries are targeted to delay the wear progression, the cutting tools will inevitably wear and need replacement.

Upon reaching the end of service life, tool reconditioning can be considered to extend the lifespan of the cutting tool material by resharpening the cutting edges without going through the complete recycling process. Many cutting tool suppliers offer a reconditioning service beyond limiting themselves to regrinding. SECO Tools has reported a continuous increase in demand for their reconditioning service, claiming most carbide tools can be renewed two to three times [241]. Reground tools often fail to perform the same as the original tools; something that customers reportedly expect specifically in production lines where statistical process control is used for deciding tool change frequency. Some coatings can affect the WC—Co substrate and referencing worn tools for regrinding can be challenging. In order to pave the way for a simplified and widespread circulation of used tools, the performance of the reconditioned tools needs to be on par with new tools. Additionally, the perception of the industrial users must change to confide in the products allowing for circularity of cutting tools. Automated real time tool condition monitoring (TCM) systems can facilitate the issues related to the unpredictable wear behavior of cutting tools [77]. Investigations of machining steel with new and reground WC—Co drills indicated that the best results can be achieved by regrinding and removing the coating preceding the recoating step [263]. Research on substrate-sparing methods for de-coating using an excimer laser was published by Marimuthu et al. [168]. TiN coatings were shown to be effectively removed from WC—Co tools without the need for chemical treatments as depicted in Fig. 13a.

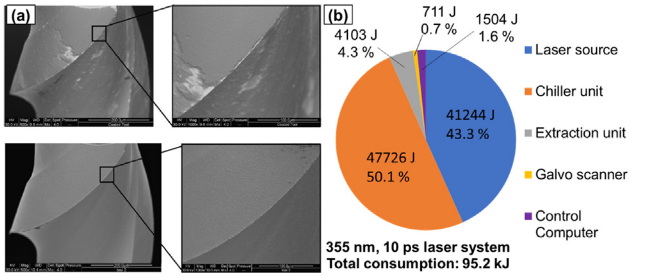

Fig. 13. a) Laser de-coating of cutting tools and b) a picosecond laser system's energy demand based on [168,193].

Further research was focused on laser de-coating TiN and TiAlN layers. Moving closer towards the goal of a circular economy, the authors identified auxiliary equipment of the laser systems being as energy intensive as the laser source itself as shown in Fig. 13b. The highly effective shorter wavelength laser system has the potential to become more efficient with further optimization [193]. The ever-increasing attention to environmental sustainability in all production sectors encourages scrutinizing procedures that were never fully optimized. The regrinding of tools is an example of a task that was reconsidered by Denkena et al. [68]. It demonstrated that by analyzing required grinding allowances and using more suitable grinding wheels, significant amounts of energy and resources could be conserved.

Li et al. [153], assessed the CO_2 footprint of gear hobs with different substrates and coatings considering that they can be repeatedly reground and recoated. Attributing the reconditioning efforts to the use phase, the total CO_2 emissions over the tools' lifetime rise in an approximately linear way, reflected by an increasing efficiency due to the extension of its service life as shown in Fig. 14. Polvorosa et al. [209] investigated the practicality of resharpening tapping tools for the aerospace industry noting that these are usually being discarded at the end of their service life. The results indicated a potential increase in service life when resharpening and recoating the tools for tapping Inconel 718 and advised monitoring the cutting forces and edge geometries to anticipate failure.

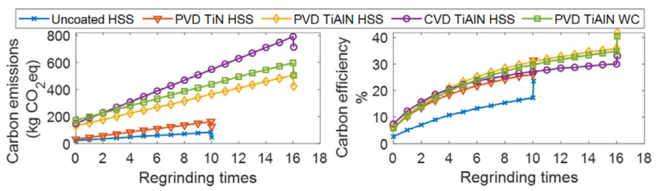

Fig. 14. Carbon emissions and efficiency over the service life of gear hobs including multiple regrinding cycles [153].

4.6. Tool recycling

Cutting tools can only be reconditioned a certain number of times before being scrapped. Recycling cutting tool materials such as WC—Co provides an opportunity to ensure future availability of critical materials, reduce resource depletion and minimize waste generation. As shown in Fig. 15, the demand for WC—Co is expected to grow in the medium term [247], further emphasizing the call for action to increase the material's recycling rate.

A considerable share of the recycled tungsten stems from processing scraps, the byproducts of manufacturing tungsten goods. On the

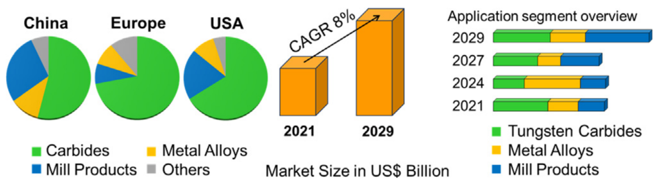

Fig. 15. Current and future tungsten demand based on [175,247].

contrary, a large amount of tungsten is lost at the end of use stage and the recycling rate of end of life tungsten products must be increased [306]. The material flow for tungsten is illustrated in Fig. 16, breaking down the share of recycling input rate, end-use in applications and the overall losses.

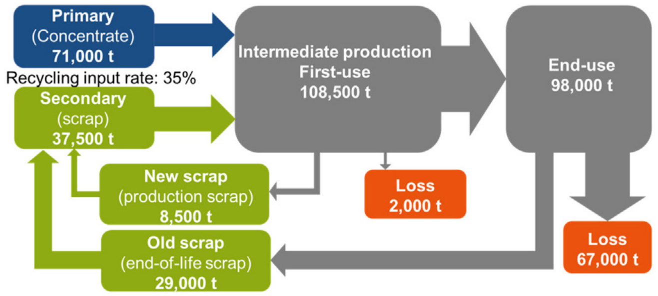

Fig. 16. Global flow of tungsten based on [306].

Different methods have been developed for recycling tungsten. They can be categorized into direct recycling (zinc process and crushing/milling), chemical recycling (indirect recycling) and melting metallurgy, where scrap WC is used as an alloying element [264]. Direct processing is known to have the lowest recycling cost, energy consumption and chemical waste [239]. However, the composition of the scrap should be the same as the final product. This necessitates minimal contamination and pre-sorting the scrap in terms of composition and grade.

In contrast, chemical recycling can recover mixed grades of WC and other carbides into their original form indistinguishable from virgin powder [306]. WC produced through chemical recycling has 75 % lower CO_2 emissions than virgin WC. However, direct recycling by zinc process outperforms chemical recycling by an order of magnitude as illustrated in Fig. 17 [43].

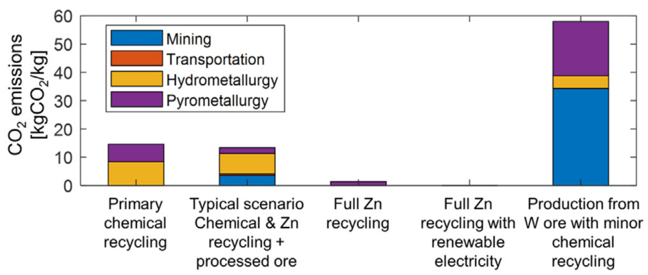

Fig. 17. Benefits of recycling WC—Co in different scenarios [43].

Faga et al. [85] noted that WC—Co produced by direct recycling has higher porosity than that of primary WC—Co which can affect its machining performance. However, when coated tools are used, the difference between recycled and primary WC—Co substrates was negligible. Major tool manufacturers such as Ceratizit [46], Sandvik Coromant [232] and Seco Tools [242] among others offer recycling services for most types of WC—Co using direct and indirect methods. Given the lower energy requirements and chemical waste generation, direct methods are preferred. This requires sorting of collected scraps by composition and grade necessitating a closer collaboration and joint efforts by tool manufacturers and end users alike [47,239].

5. Parts and chips

The ratio between the weight of the initial workpiece material to the final product is referred to as buy-to-fly ratio in aerospace industry and can be as high as 90 %. In machining, this means that cutting chips can be as much as 90 % of the output of the process. The primary transformation of the material, its manufacturing, life span and end of life treatment affects the environmental sustainability of a product. Up to 98 % of the energy footprint of a machined product is due to the embodied energy in the workpiece material [11,214]. Most metals can be recovered by recycling. However, contamination and mixing different grades pose significant challenges in achieving complete recyclability and recycled alloys may have different mechanical properties. Nonetheless, using recycled materials allows for significantly reduced primary material and energy consumption as well as GHG emissions and they can be used for less demanding applications. Fig. 18 illustrates the carbon emissions of example primary materials compared to partially recycled and fully recycled equivalents.

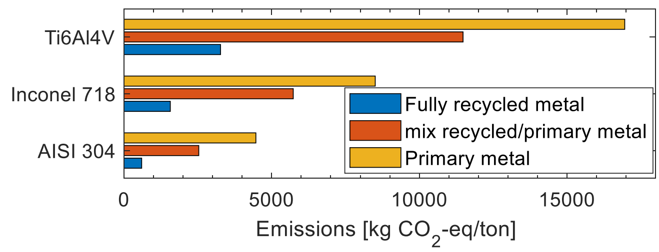

Fig. 18. GHG emissions of producing example alloys through extraction (primary), full recycling and a mixture of recycled and primary metal [82].

Globally, metal recycling rates are dictated by their value and availability of the material in large quantities [117]. However, prior to recycling, every effort should be made to reuse, repair and remanufacture parts to extend the life of materials in circulation before recovering the materials through recycling.

Reduced environmental impacts may be achieved by i) reducing the amount of material used for producing a part by using near-net shape processes, ii) extending the lifespan of the products through improved surface integrity and iii) reusing/ recycling of the inevitable chips produced during machining.

5.1. Near-net shape manufacturing

Manufacturing a part with a geometry close to the final dimensions or near-net manufacturing directly affects the amount of chips and scraps generated in the finishing or semi-finishing machining operations. Additionally, achieving dimensions close to the final tolerances in the material transformation stages, before finishing operations, reduces the environmental impact generated by the transportation of the bulk material [159].

Fig. 19 compares three example scenarios for fabricating a turbine blade using investment casting, AM, and conventional machining. Conventional machining requires the least number of processes but generates more chips since the bulk material is the furthest from the final shape of the turbine blade. More sub-processes are involved in investment casting and AM but near-net shape parts are obtained before finishing machining.

Several studies have compared AM and machining from the energy consumption point of view, for a wide range of components with different cavity to material ratios. Priarone et al. [212,213] highlighted that AM allows creating lightweight workpiece bulks before finish machining. This greatly reduces the energy demand and GHG emissions generated by transportation. Other studies noted that the main machining scenario where AM has a clear advantage over machining is when high complexity shapes, with significant weight reduction need to be manufactured in small batches [116]. These requirements make AM a good candidate for manufacturing parts with a high buy-to-fly ratio used in aerospace applications. Even

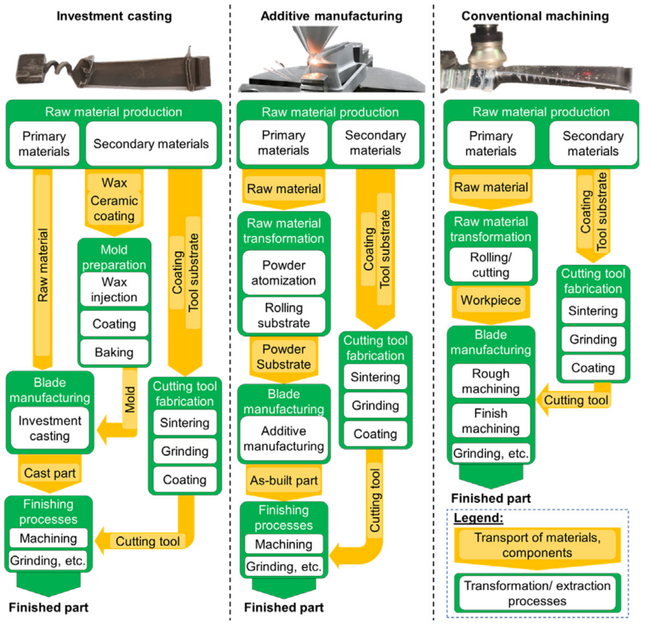

Fig. 19. Process steps for manufacturing turbine blades using different manufacturing processes based on [278].

though the workpiece material from AM has a greater embodied energy than the blank employed for machining, the amount of material used for producing a part is smaller [211]. Volke et al. [286] demonstrated chip-less finishing of AM parts by equipping a CNC lathe with high pressure pumps and burnishing tools, emphasizing the sustainability gains due to reduced wear, allowances and compressive residual stresses in the workpiece contributing to a potentially prolonged product lifespan.

Torres-Carrillo et al. [278] performed a detailed LCA comparing three manufacturing process plans for a case study of an aircraft engine turbine blade: i) machining from a block, ii) investment casting followed by finishing machining and iii) AM with finish machining. A buy-to-fly ratio of 8:1 was assumed to provide a quantitative comparison of the energy consumption and global warming potential associated with the three manufacturing methods summarized in Fig. 19 [112]. The mechanical properties and performance of parts manufactured through different routes is ongoing research which should be considered.

As demonstrated in Fig. 20, the high buy-to-fly ratio in machining turbine blades makes it far less energy efficient than near-net-shape manufacturing techniques due to the embodied energy of the raw material. The environmental impact due to the raw material is smaller for AM and investment casting. However, for these processes, the energy footprint and GHG emissions associated with manufacturing processes are significantly larger.

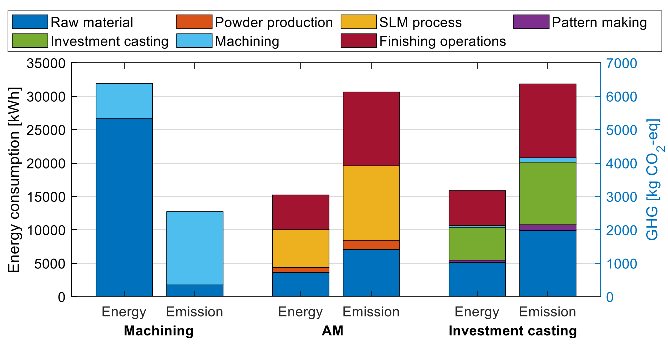

Fig. 20. Energy consumption and global warming potential of manufacturing a turbine blade.

A cost analysis by Allen [10], Fig. 21, shows that AM can replace roughing operations for parts that have a high buy-to-fly ratio, require complex machining operations and are made from expensive materials. Nevertheless, finish machining operations are necessary for producing defect-free precision parts. For instance, for a landing gear rib demonstrator weighing 21 kg, the buy to fly ratio can be reduced from 11.5:1 in machining from a billet to 1.14:1 using wire arc additive manufacturing [5]. Nonetheless, the mechanical properties and performance of parts produced through different routes must still be investigated.

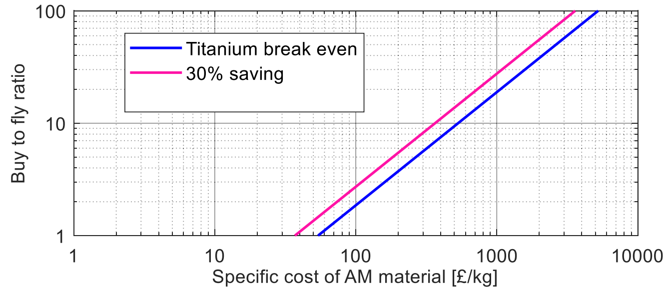

Fig. 21. Specific cost of AM titanium required to compete with machining from solid based on buy-to-fly ratio [10].

5.2. Surface integrity improvement

Machining is one of the most common finishing and semi-finishing operations. Surface integrity after machining can affect fatigue life, corrosion resistance and tribology of products. The most important effects of surface integrity parameters on the mechanical properties of a part are summarized in Table 1.

Table 1
Effect of surface integrity on the performance of a component.

	Part property		
	Fatigue strength	Corrosion resistance	Wear behavior
Topographic parameters	Rough surfaces act as microcracks that nucleate fatigue cracking [147].	Oxygen can accumulate in surface grooves and create pitting corrosion [317].	Fretting fatigue can appear from rubbing two rough surfaces [191].
Mechanical parameters	Tensile stresses can initiate cracks [125].	Stress corrosion cracking [48].	No significant effect [147].
Micro-structural damage	White layer induces tensile stresses [147]. Finer grain size stops crack propagation. Recrystallization can induce tensile stresses [125].	Recrystallization can induce stress corrosion cracking [147].	Fine grain size can improve wear resistance [125].

Novovic et al. [183], demonstrated that up to 90 % of high cycle fatigue life involves crack initiation underlining the importance of low surface roughness values to enhance fatigue resistance. Arola and Williams [16] developed analytical models to predict fatigue strength depending on three main surface roughness parameters: Ra, Rt and Rz. Therefore, improving the surface roughness and surface integrity of a component by careful selection of cutting parameters, cutting tools and machining environment can effectively increase the service life of a component.

Childerhouse et al. [53] reported that hot isostatic pressing (HIP) of electron beam melted-AM Ti-6Al-4 V followed by finish machining at 1 mm depth of cut led to 69 % increase in fatigue life compared to as built and HIPed samples. Suarez Fernandez et al. [266] decoupled the impact of forging and machining on fatigue life of Ti-6Al-2Sn-4Zr-6Mo aeroengine compressor disk components. They noted that machining induced compressive residual stresses resulted in 2–3 times increased fatigue life compared to as-forged test pieces. They also acknowledged that there will be variation in baseline fatigue data between forged parts.

5.3. Chip recycling

The energy that goes into the process of extracting raw materials is generally higher than the energy used for material cutting during machining. For instance, the embodied energy for primary aluminum and steel are about 390 kJ/cm^3 and 185 kJ/cm^3 respectively, whilst their specific cutting energies are ~1 kJ/cm^3 and 2–9 kJ/cm^3 [129,199,221]. Using recycled materials, where technically possible, can reduce the energy and material footprint of the workpiece.

Metal wastes generated during manufacturing have a higher chance of collection and recycling. There is a great opportunity for recycling cutting chips that are generated in large quantities before they are mixed with other materials. This reduces the need for extracting and using virgin materials for producing metal alloys.

Chips are typically compacted into briquettes and are transported for melting and casting. Whilst recycling of metal chips should be encouraged in lieu of landfill disposal, this process has major disadvantages in the form of metal loss during transportation and due to oxidation as well as increased labor and energy costs [293]. Chips of different alloys from different sources can be mixed prior to melting which will need mixing with additional primary metals to ensure viability of the outputs. The high area to volume ratio in the case of the scrapped chips results in a high amount of waste in conventional melting. In recycling aluminum, no more than 54 % of the initial material volume can be recovered due to the casting losses [100]. Contamination by CLs reduces metal recovery during melting. Grayson [96] noted that incinerating one unit of MWFs during melting leads to production of two units of dross. To enhance recovery of highly fragmented materials, new methods of recycling need to be explored.

Solid state recycling through hot extrusion [151], screw extrusion [80], equal channel angular pressing [249] and friction stir welding [150] can bypass smelting in recycling of metals. Solid state recycling has been applied to aluminum [240], titanium [249] and magnesium [14] alloys. Hot extrusion has been reported to achieve 95 % recycling rate, requires 96 % less energy and reduces the environmental impact of recycling by a factor of 3–4 compared to recycling by smelting [80,219]. Schulze et al. [240] experimentally proved that aluminum chips can be recycled into metal sheets without remelting, by using a hot extrusion process. They showed that after hot extrusion, forming processes such as air bending to V-shaped profiles or deep drawing of cups can be achieved as with primary aluminum. The direct use of chips without remelting introduces additional challenges due to the oxide layers covering each individual chip, that can prevent effective welding of the chips [151]. This can reduce the ultimate tensile strength and ductility of the material [219,292]. However, when carried out successfully, solid state recycling enables reduced energy consumption and CO_2 emissions as shown in Fig. 22 and the material can be used in downstream applications.

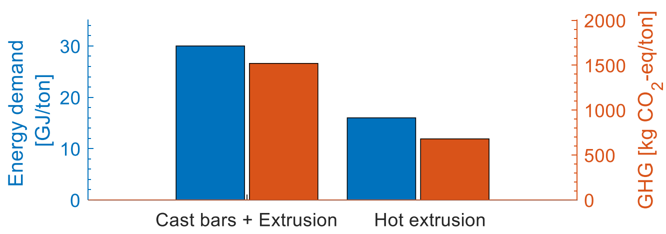

Fig. 22. Energy demand and greenhouse gas emissions for producing one ton aluminum profile by casting and hot extrusion [240].

Converting scrap chips into powder feedstock for AM is another solution with great potential, since it requires less energy than creating forged, cast, or rolled ingots. Dhiman et al. [74] carried out an in-depth literature review of all metal atomization processes and proposed ball milling as a viable and low energy demanding solution for powder production. The stages of different processes employed to recycle chips produced in machining are shown in Fig. 23.

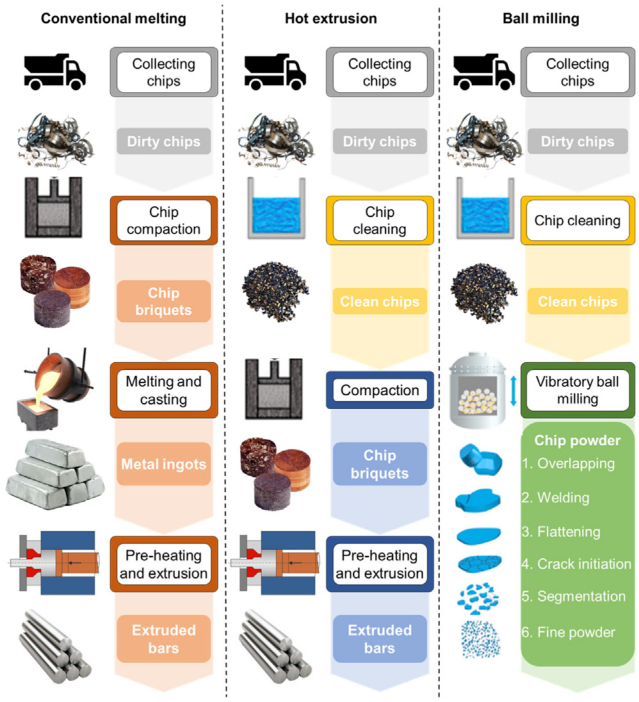

Fig. 23. Process steps for different chip recycling methods, adapted from [74,288].

Denkena et al. [73] proposed a method consisting of compaction, HIPing and Electrode Induction Melting Inert Gas Atomization (EIGA) for producing AM powder from Ti-6Al-4 V chips generated in roughing and finish machining operations. As shown in Fig. 24, they reported a maximum of 72 % reduced energy consumption compared with AM powder from primary titanium alloy. This is mainly due to the elimination of the energy for producing primary titanium. However, no comparison was made for AM powder production from recycled titanium.

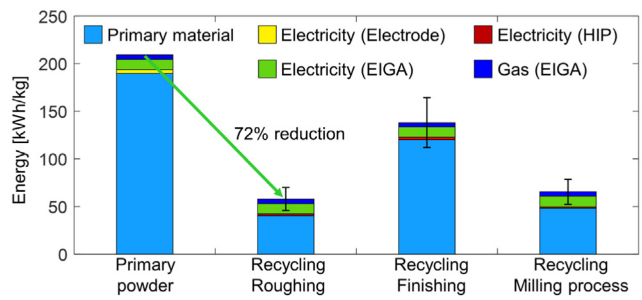

Fig. 24. Energy consumption for producing Ti-6Al-4 V AM powder from primary materials and cutting chips from roughing and finishing machining operations [73].

The cutting chips are commonly contaminated by MWFs posing an issue in both remelting and solid recycling methods. Recovering the MWFs from the chips provides an opportunity for cost saving and reducing the need for replenishing them on machine tools. It also has the added benefit of reducing the emissions and energy consumption for recycling of metal scraps since less MWFs residues need to be incinerated. Impurities on cutting chips increase the energy consumption in recycling [72]. The oils and emulsions are usually eliminated by centrifugation and evaporation of the cutting oils by heating up the chips up to 450 °C for 2–5 h [293]. These additional cleaning processes require energy and resources, increasing the environmental impact of the manufactured part. In contrast, clean chips produced in dry and cryogenic machining require 70 % and 74 % less energy for recycling, respectively [72]. It has also been reported that dry chips have a higher purchase value allowing for recovering the investment costs for additional equipment [113].

6. Coolants and lubricants

Coolant and lubricants (CLs) have been used for their ability to dissipate heat (cooling) and to reduce friction (lubrication). In addition, they may provide thermal stability, chip removal and protection against corrosion [257]. Brinksmeier et al. [34] presented a thorough overview of the development and use of CLs and highlighted regulatory requirements and energy and resource efficiency as the main drivers for future developments in CLs.

Until now, the research has focused on development and evaluation of CLs for enhancing the efficiency and productivity in machining of various materials by extending tool life, improving geometrical accuracy and surface integrity of parts and enabling higher MRR. These also potentially have the capability of improving the environmental sustainability of machining by reducing energy and resource consumption. However, the impact of additional resource and energy consumption for using CLs needs further investigation.

Depending on the type of CLs and method of application, different machining environments have been proposed.

These are i) flood cooling at various pressures and flow rate including High Pressure Cooling (HPC); ii) dry and compressed air cutting; iii) variations of Minimum Quantity Lubrication (MQL); and iv) super cold and liquid gas cooling such as cryogenic machining [64,143,295]. The main challenges in assessing the environmental impact of CLs are the multifaceted and interdisciplinary nature of CLs, their impact on machining performance and part quality and complex formulation of the chemicals used.

6.1. Flood cooling with Metalworking fluids (MWFs)

Flood cooling is the most dominant method for applying MWFs in machining within industry and most machine tool manufacturers supply flood cooling as standard on machine tools. It is considered the baseline for most investigations into alternative cooling and lubrication strategies in terms of machining performance and environmental impact assessment.

MWFs, also known as cutting fluids, are a category of CLs. They are classified into neat/straight oils and water-based MWFs. The latter can be an emulsion of oil in water or solutions of different chemicals in water also known as soluble oils or synthetic MWFs [34]. Water-based MWFs with varying concentrations are the most common cutting fluids used in machining. They are prepared in large quantities and a coolant pump is used for recirculating and delivering them at varying flowrates and pressures into the cutting zone covering the cutting tool and the workpiece. Depending on the system, the coolant preparation and delivery pump can have a power rating as high as the machine tool itself [68].

The formulation of MWFs is usually proprietary material of the manufacturers, commonly in the oil and lubricant industries, and the exact compositions are not disclosed. There is a growing regulatory requirement to eliminate or minimize specific substances in MWFs due to their health and/or environmental impacts [83,285]. The choice and use of biocides is regulated for example by the Biocidal Products Regulation (EU 528/2012 – BPR) in the EU and the Biocidal Products Regulations 2001 in the UK. In the US, a biocide formulation must be registered with EPA. There are calls for restricting the use of medium and long chain chlorinated paraffins (MCCP and LCCP) [59,81]. In the EU, there are new regulations restricting or prohibiting the use of substances that are persistent, bio-accumulative and/or toxic [59,285]. Table 2 shows a summary of common composition of MWFs. Further details of the chemistry of MWFs can be found in [41].

In order to deliver the required function during machining, the performance of MWFs in machining needs to be better understood through additional knowledge of their chemistry, microbial state, tribochemistry at the cutting zone and the physical conditions during manufacturing processes [34]. The wide range of additives used in formulation of MWFs highlights the key challenges in evaluating the environmental and societal impacts of the use of MWFs throughout their lifecycle. The compounded effects of all these additives are relatively unknown and a more accurate evaluation of the overall impact requires full cooperation of MWF producers. Additionally, the material, energy and GHG footprint of the MWF should be investigated at the development phase and declared. This calls for an interdisciplinary approach to the development of future MWFs. The selection and application of MWFs in machining is still not well understood and empirical knowledge and non-scientific practices remain the dominant factors for such selection and use.

Table 2
Examples ingredients of MWFs, adapted from [34].

Compound class	Example compound
Base	Mineral oil, water
Boundary lubricity additives	Glycerol mono oleate, whale oil, natural fats, oils, synthetic ester
Extreme-pressure additives	Chlorinated paraffine, sulphurous ester, phosphoric acid ester, polysulphide
Corrosion inhibitors	Sulfonate, organic boron compounds, amine, aminphosphate, zinc dialkyldithiophosphate, tall oil fatty acids
Emulsifiers	Anionic: sulfonates, potassium-soap, alkanol-amine-soap; Nonionic: fatty alcohol ethoxylate, fatty acid amide; Cationic: quaternary ammonium salts
Coupling agents	fatty alcohol ethoxylates and fatty acid esters
pH buffer	Hydrophobic amines with high pKa are used as an alkalinity booster
Biocides	Nipacide, BIT, BBIT, TMAD, NaPy, etc.
Antioxidants	phenolic and aminic varieties

Whilst there are some studies on the embodied energy and CO_2 footprint of cutting fluids, the exact impacts of production, maintenance and disposal of MWFs are not well understood and the few existing studies focus on soluble oils [11,77]. In most studies, the impacts of chemical additives, fluid maintenance, recirculation and disposal are neglected or overly simplified. Anionic and non-ionic surfactants typically have a large energy and CO_2 footprint [238]. Researchers [77,262] have identified surfactants as the dominant contributors to the overall emissions related to formulation of MWFs. Various grades of base oil are used for different MWFs [180]. However, the energy and emissions from mixing the formulation have not been considered.

6.1.1. Minimizing the impacts of water-based MWFs

One of the major issues related to recirculating flood cooling is the bacterial and fungi growth in the water-based MWFs. Bacterial growth is commonly controlled by using biocides and monitoring the pH of the fluid. An alternative method is to deprive the harmful bacteria from nutrients in the MWFs by encouraging the growth of "good" microorganisms and saturating the fluid. Kuenzi et al. [144] reported the early adoption of this concept by employing Pseudomonas oleovorans waterborne bacteria. Their investigation showed that the harmless bacteria is capable of eliminating human pathogenic bacteria over time [144,198]. Instead of biological control, Meyer et al. [173] and Teti et al. [274] focused on the lubricating properties of microorganisms as a substitute for oil. Meyer et al. [173] tested two yeast and three bacterial species that can survive higher pH values required in machining conditions. Milling tests on AISI 52100 steel showed improved surface roughness and reduced tool wear. Damm et al. [62] incorporated micro-organisms in MWFs. They reported reduced cutting forces and tool-wear leading to improved tool life due to the presence of higher fatty acids and organic deposits in yeast cells. It is important to ensure that the biological balance of the harmless microorganisms is maintained throughout their life to minimize the risk of harmful bacterial growth.

Another development towards minimizing the environmental impacts of cutting fluids has focused on fully synthetic MWF replacing mineral oils with other renewable synthetic alternative compounds derived from vegetable oils referred to as bio-based MWFs. It has been reported that these cutting fluids are more stable and have a longer lifespan. They have the advantage of lower human toxicity and biotoxicity compared to mineral oil. The compounds can also be extracted from algae to reduce competition with food production [102]. However, a comprehensive LCA investigation by Guiton et al. [102] highlighted that mineral oil MWFs have lower environmental impact than algae and rapeseed oil based MWFs except for climate change and fossil fuel use (abiotic depletion). The main contributors to the impact of algae-based oils are the electricity consumption and nutrient input. In this regard, producing rapeseed oil based MWFs has a slightly lower impact on climate change but the highest impact on land use. Using electricity from renewable resources, recycling of water and choosing efficient algae species can significantly reduce the environmental impact of algae-based MWFs in the future.

6.1.2. High pressure cooling (HPC)

HPC falls under the category of flood cooling but at significantly higher pressures. It was first reported in 1950s by Pigott [207] as a method to increase tool life followed on by Mazurkiewicz et al. [171] indicating reduced friction and cutting forces. The effectiveness of HPC in machining has been demonstrated for achieving improved machining performance including enhanced chip-form and chip breakability, reduced tool-chip contact, cutting forces and tool-wear rates as well as increased MRR and tool life and, improved surface integrity [156,244,270]. The HPC has been developed to address the limitations of flood cooling in penetrating the tool-chip and tool-workpiece contact area to enhance cooling and lubrication at the cutting zone. However, the enhanced machining performance is achieved at the expense of increased power consumption for producing high pressure, the generation of cutting fluid mist and potentially increased coolant loss. There is a lack of holistic analyses on the energy consumption and CO_2 emissions related to HPC. The improved tool life and higher MRR may offset the increased energy consumption of the coolant pump. Nevertheless, there is not enough evidence to support that HPC has lower environmental impact than conventional flood cooling. Additionally, the issues related to the maintenance, treatment and disposal of MWFs and their associated health and safety concerns remain valid for HPC.

6.1.3. Recycling and end of life treatment of cutting fluids

Water-based MWFs typically have a lifespan of 6–12 months. In order to minimize the impacts of MWFs, their lifespan should be extended and at the end of their life, they should be recycled into new products or given a new life as new MWFs. Whilst there are efforts in extending the lifespan of cutting fluids, there is no evidence of recovering the oil and chemicals from spent MWFs and in most cases, primary materials are used. Instead, they are incinerated as an energy source adding to the CO_2 emissions from machining processes.

All MWFs should be disposed of in accordance with national and local legislations using approved waste disposal contractors [280]. The treatment of spent MWFs goes through typically three stages of i) removal of tramp oil and suspended solids, ii) separation of emulsified oil and iii) reducing contaminants in water. In some MWF treatment processes, these stages are combined. After separating and treating the water, the discharge to surface waters is subject to the Environmental Permitting Regulations.

Mang et al. [163] provided a comprehensive overview of treatment and disposal of MWFs. There are multiple potential methods for separating water-miscible cutting fluids: i) electrolyte separation by salt or acid splitting, ii) release, stirring or electro- flotation, iii) adsorption, iv) thermal methods and v) ultrafiltration or a combination of these. Among these, ultrafiltration has the lowest direct energy consumption and environmental impact. There are also other methods under development such as ultrafiltration coupled with chemical oxidation or electrochemical oxidation and mechanical vapor recompression. Cheng et al. [52] reviewed the biological treatment of spent MWFs and suggested that a combined process of reverse osmosis and solvent extraction would be the next-generation technology for treating MWFs. The process chain for treating MWF waste highlights the challenges of reusing MWFs as the fluid is contaminated and degrades with machining.

Only a few researchers attempted to quantify the environmental impacts of MWF disposal and provide a holistic solution to reduce the wastage of lubricants during machining. A review of the LCA studies for recycling waste lubricant oil by regeneration suggested that recycling has lower environmental impact than producing base oil from virgin crude [208]. This requires the development of enabling technologies for reusing MWFs.

6.2. Dry cutting

The best way to avoid the direct environmental and health issues related to MWFs is to entirely eliminate them as in dry cutting [86]. Dry cutting is typically associated with higher cutting forces and specific cutting energy. However, this might be offset with the elimination of the power consumption for CLs systems. Usually, the tool life is also shorter in dry machining compared with when CLs are used. However, this is not always the case and there are successful scenarios where dry cutting is recommended usually when hard cutting tools such as CBN, PCD or ceramic tools are used [17]. Surface integrity however, remains a major issue in dry cutting which should be controlled through appropriate selection of cutting tool materials and cutting parameters. A 65 % reduction in machining time has been reported in dry cutting Inconel 718 using SiAlON cutting tools [316]. Finkeldei et al. [89] highlighted the possibility of using high cutting speeds with solid Si3N4 ceramic tools for roughing operations in milling Inconel 718. They noted poor surface integrity up to 75 µm depth which needs to be improved through subsequent finishing operations.

6.3. Minimum quantity lubricants (MQL)/ minimum quantity cooling liquids (MQCL)/ nano-lubricants

In 2004, a major CIRP keynote paper by Weinert et al. [294] reviewed developments in MQL/MQCL with comparison of machining performance with dry machining. In minimum quantity lubrication (MQL) or near-dry machining, a small amount of lubricant oil, typically between 30 and 200 ml/h, is sprayed through compressed air. Conventionally, the aim is to reduce heat generation by lubricating the cutting zone and the cooling is achieved by forced convection of compressed air. Poor cooling capacity of air is a drawback of MQL in comparison with flood cooling. Typically, vegetable-based oils are used in MQL which are renewable and biodegradable making them advantageous over petroleum oil based MWFs. Since the lubricant oil in MQL is not recirculating, there is no health risk associated with bacterial or fungi growth. However, the oil in MQL is consumed. Whilst in the short-term, the oil consumption in MQL appears small compared to flood cooling, over the lifespan of the MWFs in flood cooling, it can become significant. Additionally, the power consumption for generating compressed air is comparable to that of the coolant pump in flood cooling [77].

Whilst MQL almost always provides improved machining performance compared to dry cutting, this is not always the case in comparison with flood cooling. Zhang et al. [309] found that MQL reduced tool-chip contact length compared to dry machining leading to reduced cutting forces and increased tool life. However, the impact was more profound in short engagement times indicating the limited cooling capability of MQL [273]. Biermann et al. [27,28] highlighted that due to the low cooling capacity of MQL, the heat generated during cutting results in thermally induced deformation of the workpiece. In machining titanium alloys, MQL generally provided comparable or improved machining performance to that of flood cooling in terms of surface roughness and tool life [204,250]. In machining Inconel 718, however, Pereira et al. [201] and Okafor et al. [188] noted shorter tool life and higher cutting forces in MQL than in flood cooling. de Paula Oliveira et al. [66] identified that compared to MQL, flood cooling resulted in improved compressive residual stresses but no significant difference was found regarding surface roughness. Kamata et al. [130] noted that certain cutting tool coatings perform better in MQL than in flood cooling indicating the need for optimizing the tool coating for specific machining environments.

In order to address the limited cooling/lubricating capacity of MQL, four different approaches have been identified namely, i) minimum quantity cooling lubrication, ii) chilled air at sub-room temperatures [103], iii) nanofluid lubricants [304] and iv) electrostatic charging [65].

An et al. [13] used water mist at 0 °C as a coolant which was delivered through chilled air at −20 °C. They observed that with an increment in cutting speed from 30 m/min to 150 m/min, the cold-water mist jet cooling process effectively reduces the temperature even at high cutting speeds and extends the tool life in comparison with flood cooling. Wang et al. [289] reported that spraying oil on water on the flank face resulted in the lowest tool wear in turning cast iron. Using a vortex tube to generate chilled air at sub-zero temperatures for MQL has shown to reduce tool wear and improve surface roughness in machining Ni-Ti alloy [305].

The addition of micro and nano solid particles into base MQL oil has gained popularity in recent years. The aim is to improve the lubrication and cooling performance of MQL.

Liquid lubricants generally have a limited service temperature of below 350 °C and cannot withstand the high temperatures generated at the cutting zone [314]. In contrast, solid lubricants such as tungsten disulfide, molybdenum disulfide and hexagonal boron nitride can withstand significantly higher temperatures.

The addition of solid nanoparticles to the oil also enhances heat transfer and cooling capacity of MQL [251,252]. Various micro and nano particles have been tested in various vegetable-based oils in machining of different materials with varying degrees of success [295,304]. The nanoparticles used in MQL include metal oxide and carbides: Al_2O_3, TiO_2, ZnO, SiC, CuO, SiO_2; Carbon-based materials: graphite, diamond, carbon nanotubes, graphene and graphene oxide; Solid lubricants such as WS_2, MoS_2, hBN and even boric acid. Typically, 1–4 wt% nanoparticles are mixed with a vegetable oil [182,304].

Sen et al. [246] used a 1 % mixture of SiO_2 nanoparticles in pure palm oil for machining Inconel. They reported improved thermal conductivity and heat transfer leading to lower cutting forces, and tool temperature compared to palm oil alone. Pal et al. [195] investigated the drilling performance of stainless steel in different CL environments such as dry, flood, pure MQL, and nanofluid MQL with Al_2O_3 and sunflower oil. They found that 44 %, 67 % and 56 % reduction in thrust force, torque and surface roughness can be achieved, respectively, compared to flood cooling. The enhancements were attributed to improved cooling and lubrication. Shokrani and Betts [251] designed a nozzle for spraying WS_2 microparticles and rapeseed oil in milling Ti6Al4V. As shown in Fig. 25, they reported over 8 times increased tool life compared to flood cooling at 150 m/min cutting speed.

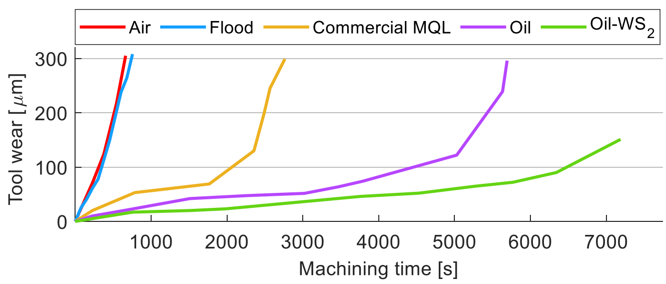

Fig. 25. Tool life using various cooling and lubrication methods in end milling Ti-6Al-4 V at 150 m/min [251].

The majority of the studies using nanoparticles for MQL claimed improved environmental sustainability and the potential adverse impacts of nanoparticles on health and the environment have been widely overlooked. Some of the nanoparticles used in MQL machining have been known as potentially hazardous or carcinogenic. Examples are boric acid, carbon nanotubes (CNT) and Al_2O_3. Nouzil et al. [181,182] investigated the human toxicity levels of nanoparticles used in MQL. Tungsten disulfide and molybdenum disulfide were identified as the least harmful nanoparticles. Further studies are required to establish the safety of nanofluids and appropriate health and safety measures for machining need to be established. There is a lack of knowledge on the impact of various nanoparticles on machining performance. The selection, combination and composition of nanofluids and the base oil are ad-hoc and based on limited experiments.

Electrostatic charging of the lubricant in MQL is a recent development in improving the performance of MQL. As in electrostatic painting, electrostatic charging enhances adhesion of oil droplets to the cutting tool. It can also reduce the liquid surface tension and finer droplets can be generated [65]. Typically, direct current electrical potential larger than 5 kV at micro and nano ampere currents are applied. A combination of WS_2 nanofluid and electrostatic charging has shown to improve machining performance in terms of tool life and surface integrity in end milling Inconel 718 [253].

6.4. Super cold gas, liquid gas and cryogenic cooling

Using liquid gases has been recognized as an effective cooling method for improving machining performance of a range of materials. The majority of research is focused on using liquid nitrogen (LN_2) in cryogenic machining and carbon dioxide in supercritical ($scCO_2$) or liquid (LCO_2) form whilst there is a handful of studies on oxygen, helium and argon [254]. Nitrogen is an inert gas abundant in the atmosphere. The emissions related to LN_2 are associated with the electricity use for liquefying the gas and transportation. Extremely low temperatures related to LN_2 require further health and safety assessment and oxygen monitoring is highly recommended. LN_2 is stored at atmospheric pressure and at low temperatures (∼−196 °C) posing a challenge for delivery, use and application during machining. In contrast, CO_2 is cheaper and stored at room temperature but at high pressures (6 MPa). This makes the delivery of LCO_2 into the cutting zone easier. $scCO_2$ systems operate at higher pressures and $scCO_2$ has the properties of both gas and liquid in this state. CO_2 is heavier than air and there is a risk of oxygen depletion. Unlike other machining processes, machining using CO_2-based CLs is the only machining condition with direct GHG emissions.

Significant research has been conducted on the use of LN_2 for machining various metals ranging from different types of steels, titanium, aluminum, nickel and magnesium alloys as well as composites. Most of these studies reported improved surface integrity and enhanced machining performance, including increased tool life and higher machining productivity. However, there are also conflicting results depending on the mode of delivery and the machining operation. In milling Ti-6Al-4 V, Tapoglou et al. [272] reported shorter tool life using $scCO_2$ than flood cooling. However, An et al. [12] found $scCO_2$ performs better than dry machining. $scCO_2$ has excellent solvent properties and various lubricants can readily be dissolved into $scCO_2$. This has provided an opportunity for lubricated $scCO_2$ machining. It has been shown that lubricated $scCO_2$ with various types of lubricants can enhance the tool life and surface integrity [25,97,272]. However, this is achieved at the expense of increased material and energy footprint. Jawahir et al. [124] thoroughly discussed the research on cryogenic machining under the following key areas: material behavior in terms of thermo-mechanical interactions and tribological behavior, delivery of liquid or cooled gas into the cutting zone, cryogenic applications, surface integrity, and product quality. This was further updated by analyzing the recent developments in cryogenic machining including changes in the microstructure of the workpiece material and recrystallization and formation of nanostructures due to cryogenic and hybrid machining [126].

Cryogenic cooling has a very limited capability in minimizing heat generation [26]. This has led to the development of hybrid cryogenic +MQL machining environment [250]. Unlike lubricated $scCO_2$, in hybrid cryogenic+MQL, the lubricant oil is not dissolved into the gas but delivered as droplets often through separate nozzles. In this method, MQL is used to provide additional lubrication in cryogenic machining. Rodriguez et al. [230] demonstrated that oil droplets in

LCO_2 resulted in improved surface integrity in drilling aeronautical Ti6Al4V/CFRP stacks where conventional CLs cannot be deployed. Hybrid cryogenic+MQL systems with LN_2 has shown improved performance compared with LN_2 or MQL alone in machining of titanium and Inconel alloys [63,196,250,259].

6.5. Environmental assessment of machining environments

The majority of the claims regarding the environmental sustainability of one CL method over another are based on limited information. Often the large quantities of recirculating MWFs are compared with the small amounts used in alternative methods and used as a supporting argument. Other times, the potential health risks of exposure to water-based MWFs are used to justify the viability of alternatives. Evaluation of the environmental impact of machining with machining environments involves numerous interacting and often conflicting, difficult to measure or quantify, and rather complex parameters. For instance, Fig. 26 shows a comparison of effectiveness of various machining environments and their direct environmental impacts compared to flood cooling. However, it does not show the interacting effects of the machining environment for example reduced tool consumption due to the enhanced tool life or reduced specific machining energy by allowing higher MRR. In isolation, dry cutting may appear to have the lowest environmental impact. However, higher tool wear and low MRR may result in significantly larger environmental impacts.

Function of CLs		Flood	HP Flood	Dry	MQL	Cryogenic	Hybrid
Primary	Cooling	0	1	-2	-1	1	1
	Lubrication	0	-2	0	-1	0	0
	Chip removal	0	1	0	-1	0	0
Secondary	Machine cooling	0	0	-2	-2	-1	-1
	Workpiece cooling	0	0	-2	-2	0	0
	Particle control	0	-1	-2	-1	-1	0
	Product quality	0	0	-2	-1	1	1
Sustainability concerns	Water pollution	0	0	2	-1	1	-1
	Air pollution	0	-1	1	-1	2	0
	Operator health and safety	0	0	2	0	2	1
	Energy consumption	0	-1	1	0	-1	-2

Fig. 26. Relative effectiveness and environmental impact of various cooling and lubricating strategies updated from [126,124].

In machining Ti-6Al-4 V alloy using various CLs, Faga et al. [86] concluded that dry machining is the best approach when environmental and human health are concerned. In their study, they used different sets of cutting parameters for each machining environment to achieve a similar tool life. However, low MRR and productivity in dry cutting sacrifices the machining economics. They noted using MQL with ester or vegetable oil lubricant as an alternative to enable higher productivity. Singh et al. [261] highlighted high PM2.5 particulate in the air when MQL is used. Pusavec et al. [216] performed a LCA of flood, HPC and cryogenic cooling with LN_2. They noted the significantly higher energy requirement for producing LN_2 since it is not recirculated. Even after including the energy consumption of the coolant pump in flood and HPC, the overall energy consumption for producing LN_2 was higher. However, the environmental impact of LN_2 is due to electricity and water consumption whilst flood and HPC are also associated with resource depletion, acidification and land use.

Damir et al. [61] performed a similar study comparing flood with cryogenic cooling and concluded that the production of one kilogram synthetic oil for the emulsion consumes 55 times more energy than producing the same amount of LN_2 and therefore cryogenic machining is more environmentally friendly. However, they assumed 337 kg of water-based cutting fluid was used for one hour of machining. Khanna et al. [138] compared the environmental impact of flood, MQL with canola oil and cryogenic machining with LCO_2 and concluded MQL has the lowest impact compared to flood and cryogenic machining. However, they assumed negative CO_2 emissions from producing canola oil and zero emissions from releasing CO_2 during the process. Pereira et al. [202] reviewed the environmental impact of cutting fluids from the published literature, and made a quantitative comparison of mineral oil, ECO-350 oil, canola oil and high oleic sunflower oil. They also used a negative global warming impact in terms of GHG emissions for canola and sunflower oil based on the values from the literature. They recommended sunflower oil as an eco-friendly alternative. However, recent analysis of the CO_2 emissions from vegetable oils [9] casts doubt on these conclusions. A large amount of CO_2 is emitted in the current farming practices through the use of diesel-powered machineries, petrochemical fertilizers and pesticides. The latest update on the emissions from producing sunflower oil ranges from 1.1 to 4.2 $kgCO_2/kg$ [8] rather than -3.76 $kgCO_2/kg$ used by Pereira et al. based on Bart et al. [20]. This potentially puts the emissions from sunflower oil on par with mineral oil, a distillate of petroleum. Farming practices and their yields vary greatly across the globe and vegetable oils from various countries and regions have different amounts of GHG emissions and environmental impacts. This highlights the need for taking supply chains into consideration.

Salem et al. [231] performed a cradle-to-gate single score impact LCA of different cutting fluids including pure soybean and rapeseed oils and with various nanoparticles i.e. MoS_2, TiO_2, CNT, Al_2O_3 compared with flood using petroleum oil and water soluble oil consisting of petroleum and surfactants from [55] as shown in Fig. 27. The analysis shows that the impacts from producing various vegetable-based oils is higher than that of water-based MWFs. This excludes the impacts from the use, maintenance and disposal of cutting fluids. Nevertheless, it raises a question about the claims related to sustainability of various vegetable-based CLs which need more detailed investigations.

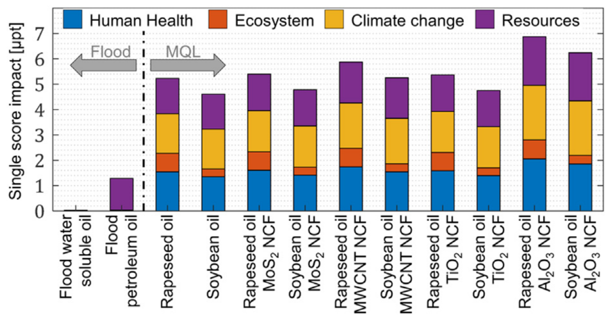

Fig. 27. Single score impact for various cutting fluids [231].

Campitelli et al. [40] performed a gate-to-gate LCI analysis excluding the workpiece for drilling and milling a range of materials and identified electrical energy, compressed air and flood cooling oil as the main drivers of environmental impacts for machining. It was found that flood cooling has a higher environmental impact than MQL due to the energy consumption of the coolant pump [40]. Abba et al. [1] proposed an alternative method for lubrication using crystalline deep eutectic solvents based on citric acid and choline chloride which is solid at room temperatures but becomes liquid at high cutting temperatures.

There is a lack of holistic analyses on the environmental impact of CLs taking cutting tools and tool life, part cleaning, CL production, use, maintenance and disposal into account.

There is no conclusive answer to which machining environment and CLs are most environmentally-friendly. There is minimal or no information available on recycling and disposal of lubricants and nanoparticles from MQL and hybrid cryogenic+MQL.

Similar to flood and HPC, the CL residues from MQL on the final product need to be removed. Amongst the methods discussed, dry and cryogenic machining are the only processes that do not need specific fluid disposal or part cleaning apart from chip removal.

7. Energy consumption

The share of renewable sources for electricity has been growing in recent years due to the growth in wind and solar energy generation [115]. Achieving global zero-emission electricity by 2050 requires significant growth in renewable energy production, twice as much as the current growth rate [118]. Nonetheless, a significant portion of the energy used for manufacturing is generated using fossil fuels. Therefore, quantifying and minimizing the cumulative energy consumption for machining can translate to reduced GHG emissions [220].

Within a machining system, cumulative energy consumption includes the energy used for operating the machine tool as well as the energy used for producing, maintaining, recycling and disposal of the consumables: cutting tools, workpiece material, CLs and tooling. As illustrated in Fig. 28, in the United States, industrial manufacturing accounts for a quarter of the total energy consumption, with metal fabrication and manufacturing of machineries and transportation accounting for over 220 TWh [187]. In 2003, Byrne et al. [38] foresaw that energy consumption will become a focal point in manufacturing. Twenty years later, this discussion is in full swing related to various energy approaches such as management, technology and policy [2]. In 2012, Duflou et al. [79] investigated the developments in energy efficiency for various manufacturing processes and systems including machining. There is still a significant gap for energy strategies within manufacturing companies, meaning that over one third do not define energy targets at all [169]. Similarly, there is a research gap related to energy management for manufacturing [170].

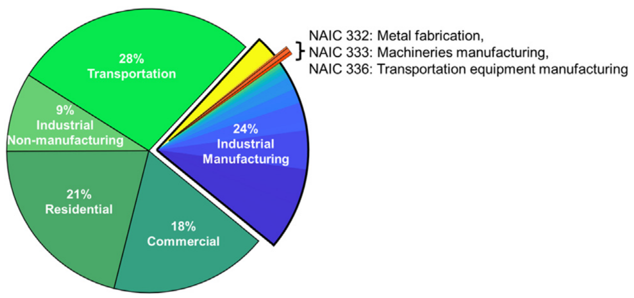

Fig. 28. Distribution of energy consumption by sector in the United States, based on [187].

When dealing with industrial energy consumption, the scale as well as the associated system boundaries must be considered. The scale of a machining system lies somewhere between the global supply chain and the process on a single machine tool [303].

Even within a single scale size, the system boundaries of research studies can differ significantly due to the complexity of energy consumption evaluation [312]. Although the share of actual cutting in the total energy consumed in production of a machined component is only about 15 % [29] and measures can have the greatest effect at the global level, international overarching activities are very dilatory. Accordingly, reducing energy consumption at single machine level is of great importance in order to contribute to energy savings on a globally cumulated basis [303]. At the single machine tool level, six different types of energy saving strategies are defined, which all are conducted with different system boundaries. As demonstrated in Fig. 29, the six types of strategies can be assigned with fluent boundaries to the three categories: i) machine design level, ii) macro process planning level, and iii) micro process planning level [79,303].

In the context of this paper, the measures from the two process planning levels will be considered. A comprehensive overview of the developments in machine tool design to improve energy efficiency have been provided in Denkena et al. [68].

For the analysis of energy-saving measures in metal cutting at the individual machine level, it is necessary to decompose the overall energy consumption into smaller independent elements. Four

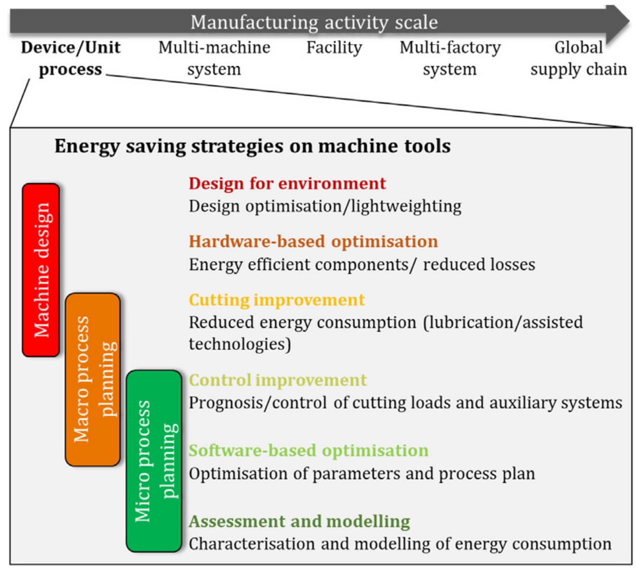

Fig. 29. Scales of energy consumption evaluation and energy saving strategies on machine tools adapted from [303].

categories emerge from the literature [205,303], which are listed below and outlined in Fig. 30:

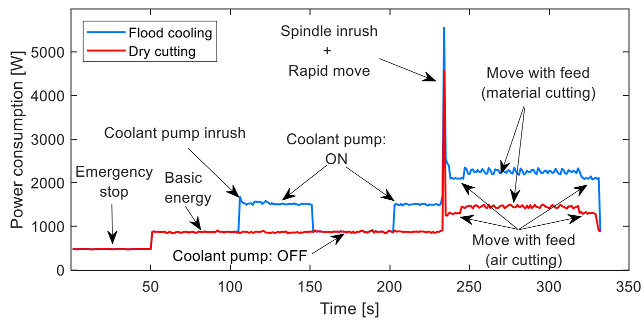

Fig. 30. Energy decomposition in a typical milling process with flood cooling illustrated by a power recording, based on [256].

1. Basic Energy: The energy needed for running the machine tool and its auxiliary systems without running the process
2. Stage energy: The energy for moving the machine's axes
3. Spindle energy: The energy for rotating the spindle with no load
4. Material cutting energy: Only during the actual cutting process does this portion take effect, which includes the energy for the actual material removal.

In this section, the primary electricity consumption of the machine tools during material cutting is discussed and the need for considering embodied energy in resources and materials used in machining is set out as cumulative machining energy. Energy consumption for category 1, 2 and 3 have been discussed in [68].

7.1. Energy consumption modelling

For the design and optimization of machining processes, modelling and simulation of the system behavior is becoming increasingly important. Theoretical, empirical and discrete event modelling are the most frequently used methods of modelling and predicting energy consumption in machining [79,200,310]. Theoretical models can effectively describe the mechanics of machining and the dependency of energy consumption on various parameters. However, there are multitudes of electronic and electrical components in modern machine tools which need to be considered alongside the movement of the axes, spindle, coolant pump as well as material cutting adding to the complexity of such models.

In contrast, empirical models are easy to implement in practice. However, they require a correspondingly high number of experiments for calibration. Discrete event modelling further allows to consider the machine tool's energy consumption in idle time and non-material cutting moves making it ideal for process plan level optimization [200,265]. Regardless of the choice of model, a fundamental understanding of the real system behavior based on experimental studies is essential [310].

Kara and Li [132] developed an empirical model correlating machining energy consumption with cutting parameters capable of predicting energy consumption with over 90 % accuracy. Shokrani et al. [255] modelled the energy consumption in a milling process depending on the cutting parameters using MQL. Beside the cutting parameters, the developed model takes machine-tool dependent coefficients into account. These coefficients have been calculated for a specific case in this study. In the future, machine tool manufactures could provide such coefficients to support their customers in energy efficient process planning of parts.

Jaeger et al. [122] developed a model for energy consumption within an additive-subtractive process chain. This work is motivated by the high amount of energy needed for such sequences, while providing a potential for light-weight products. For this purpose, a combination of discrete event and geometrical-physical approach was used for the cutting process. The model enables a high accuracy of energy consumption prediction for complex workpiece geometries, which are typically produced with a series of different process parameters.

A novel approach for modelling energy consumption in machining processes is deep learning. Xiao et al. [299] developed a meta-reinforcement learning combining a finite Markov decision process with an actor-critic framework to optimize cutting parameters regarding minimization of energy consumption. In addition to the basic, stage, spindle and machining energy, the model maps energy losses as well as embodied energy of the tools and therefore provides a suitable approach for overarching consideration of energy consumption in machining.

7.2. Reducing energy consumption

The central question in dealing with energy consumption is how it can be reduced with the help of technological measures. Even though this section intends to focus on levels of macro- and micro process planning, the recommendations concerning the design of machine tools should be highlighted: machine tools should not be designed/selected with power more than required for a specific product. This highlights the need for selecting appropriate machine tools with the required spindle and drive power necessary for machining a given part/material [79].

In addition, the integration of sensors in the machine tool for supporting power and energy consumption monitoring should become mandatory [275]. Modern machine tools have means for monitoring power consumption. This capability can be extended to energy consumption for running codes for specific tasks to allow users to monitor their overall energy consumption.

7.2.1. Cutting parameter and process planning

The impact of cutting parameters on machine tool energy consumption has been studied extensively [18,51,104,200,256]. They show that using high MRRs leads to increased power consumption, but reduces energy consumption per unit volume material removed by minimizing the process time [271].

In addition to the influence of the MRR, it should be noted that a reduction in machining energy is possible with the same process time simply by reducing the overall mechanical loads. Using this approach, Newman et al. [178] reduced the energy consumption in an exemplary cutting process by 6 %. Beyond the cutting values, the direct energy consumed is significantly influenced by machining strategy [284] and the tool path [15] which is mainly due to the influence of the sequence of wait and rapid traverse on the energy consumption of drives. Avoiding unnecessary movements and air cutting as well as acceleration and deceleration of the drives can reduce energy consumption [312].

Balogun and Mativenga [18] identified the high proportion of a machine tool power consumption in idle state and recommended minimizing the idle time through appropriate process planning. Moreover, performing emergency stop during setup and removal in job and batch production scenarios can further reduce machine tools' energy consumption. Okuma has integrated "ECO suite plus" energy saving and monitoring system into their machine tools that enable reduced energy consumption when the machine is not cutting material and during idle times [189].

7.2.2. Cooling-lubrication

The role of CLs on improving machining performance was extensively discussed in Section 7. CLs can directly decrease energy consumption by reducing cutting forces and the energy required for non-cutting tasks e.g. tool change through increased tool life. They can also indirectly reduce the energy consumption per unit volume of machined material by extending the tool life and allowing higher MRRs. However, delivering CLs into the cutting zone requires additional power. Moreover, energy is used in producing CLs.

It has been demonstrated that the auxiliary equipment of a machine tool consumes as much as 50 % of the total machining energy. As shown in Fig. 31, more than half of this energy portion is related to the cooling-lubrication system for the case of flood cooling [302]. Accordingly, a lot of energy can be saved through adjusting the CL method. A first step, without changing the CL strategy is to optimize the amount of cutting fluid per time by adjusting the flow rate and pressure [205].

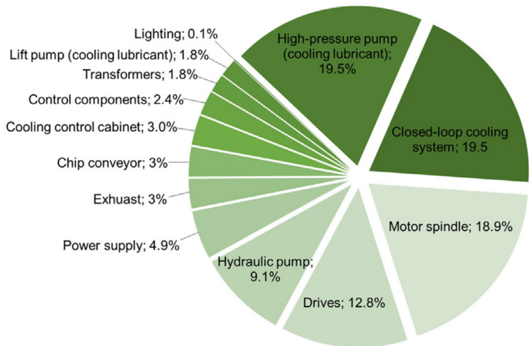

Fig. 31. Share of individual components in power consumption of a machine tool [237].

Further energy savings can potentially be achieved by using alternative CL strategies discussed in Section 7. Klocke at al. [142] conducted experiments on the total energy consumption in producing Inconel 718 symmetrical jet engine parts in turning with HPC compared to flood cooling for two different process chains. HPC brings additional power consumption due to the use of a high-pressure pump. It also allows to double the cutting speed compared to flood cooling and therefore reduces the overall process time. The total energy consumption evaluation showed that in one process chain, using HPC had a lower power consumption and in the other case, energy consumption was more than flood cooling. The benefit of HPC regarding process energy consumption depends on the individual steps of the operation.

When the higher amount of cutting fluids used for high pressure supply and the resulting effort for separating them from the chips is taken into account, it is probably not a suitable approach for machining when direct energy consumption is of concern [267].

As shown in Fig. 31, the power consumption of the HPC pump is equivalent to that of the spindle and the total power consumption for the CL system is higher than the power required for material cutting

[237]. Fujishima et al. [91] reported using a 5.5 kW coolant pump for delivering 7 MPa pressure through spindle coolant. This can reach over 35 kWh for machine tools with HPC.

Another promising approach is cryogenic cooling. Shokrani et al. [256] investigated the power and energy consumption during milling of Ti-6Al-4 V for dry cutting, flood cooling and cryogenic cooling under variation of the cutting parameters. The authors identified flood cooling as the most power and energy intensive cooling method because of the coolant pump. It accounted for 36 % to 44 % of the machine tool's total energy consumption. In contrast, LN_2 coolant is self-propelled, evaporates after application and minimizes the need for part cleaning post machining [215]. Nevertheless, increasing the MRR was found to be more effective in decreasing energy consumption. This was especially enabled using cryogenic cooling due to lower tool wear compared to dry cutting and flood cooling. As an additional effect, as long as the cutting parameters are kept constant, the longer tool life leads to reduced processing times with regard to tool changes resulting in less energy consumption [123]. Pusavec et al. [216] highlighted the high energy consumption for producing LN_2 (0.5 kW/kg) since it is not recirculated.

Fig. 32 demonstrates the energy required for producing and operating various machining environments. It shows the energy intensity of producing and delivering cryogenic and HPC based on [216] in comparison with rapeseed oil-WS_2 nano-lubricant, MQL, Flood and compressed air cooling [77] for a minute of machining excluding the energy required for running the machine tool and material cutting. The analysis shows that ~99 % of the energy footprint in HPC and 96 % in flood is associated with running the coolant pump.

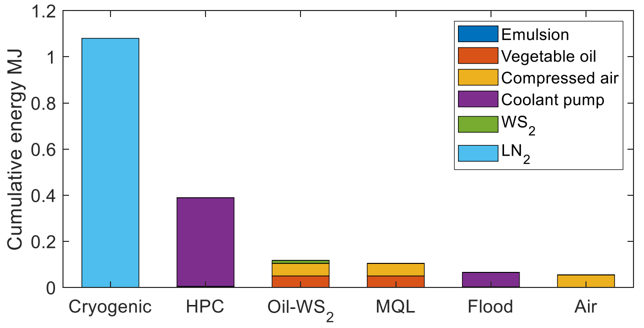

Fig. 32. Energy footprint of various machining environments excluding machine tool energy consumption adapted from [77,216].

The lubrication effect in MQL can reduce the direct machine tool energy consumption [261,267]. However, additional energy is used for producing compressed air. Whether MQL represents a low-consumption approach for cooling/lubrication cannot be conclusively evaluated on the basis of the current literature. Unlike flood cooling, the oil in MQL is not recirculated. Based on Fig. 32, taking the energy required for producing vegetable oil and compressed air results in higher energy requirements for running MQL than flood cooling. The energy consumption of the oil pump and compressed air system depends on many parameters including the air pressure and flowrate, the compressed air system design, controllers, compressors and driers.

Generating compressed air is an energy intensive and low efficiency process often overlooked in machining energy analysis. Further research in this area should focus on optimization of compressed air consumption. As mentioned in Section 7, the embodied energy of coolant/lubricants due to the production, maintenance, treatment and disposal should be considered.

7.2.3. *Assisted machining*

In addition to the use of CL, some concepts of assisted machining have been established to improve machining performance, especially for difficult-to-cut materials. For these to be viable, the improved machining performance and reduced environmental impacts should compensate for the energy consumption and environmental impacts of the assisting technologies. Volkov et al. [287] developed a model for optimizing an ultrasonic-assisted machining (USAM) for turning with the focus on minimizing the cutting forces, which directly affects the energy consumption. Depending on the vibration amplitude and the cutting speed, USAM can reduce the energy demand compared to conventional cutting. However, the study did not take the energy consumption of the ultrasonic device into account.

Airao et al. [6] investigated the power consumption of USAM in turning using different machining environments compared to conventional turning. In the case of MQL and cryogenic cooling, USAM reduced the power consumption by improving CL penetration into the cutting zone resulting in lower friction and tool wear. However, in dry cutting and flood cooling, the power consumption for USAM was higher than the reduction in cutting power consumption due to reduced cutting forces.

Low-frequency vibration [30] or modulation assisted machining (MAM) [164] is another technology which can improve machining efficiency through reduced cutting forces and tool wear specifically in turning and drilling operations. However, currently there is no study indicating if the increased energy consumption due to the MAM is offset by reduced overall process energy consumption.

In thermally assisted machining, Pfefferkorn et al. [206] investigated the impact of preheating 6061 aluminum and AISI 1018 steel workpiece and found that higher pre-heating temperatures reduce specific cutting energy. Nevertheless, the energy required for heating the part was significantly higher than the machining energy. Therefore, the total amount of energy consumption was higher than in conventional machining. This was confirmed by Kim and Lee [139] for laser-assisted and induction-assisted machining of Inconel 718. Even though the cutting forces significantly decreased for both cases compared to conventional machining, overall power consumption was higher for the assisted processes due to the additional energy needed for heating.

It can be concluded that thermally assisted machining will only provide energy savings if the improved machinability is used to improve the energy balance through significantly increased MRR and/or improved tool life. For this purpose, further investigations are necessary to compare the effects of the additional heating energy and the saved energy due to the shortened process times as well as reduced cutting tool consumption.

7.2.4. *Cumulative energy consumption considering the embodied energy of machining resources*

In the previous sections, the focus was on measures that affect the direct energy consumption at the machine tool level which also has been investigated by many researchers. However, energy is also used for producing cutting tools and the CLs. In this regard, cumulative energy consumption is defined as the sum of all direct and indirect energies used for producing and using the tools, CLs and the machine tool itself based on the model in Fig. 1.

Until now, the guiding principle has often been that it makes economic and ecological sense to increase the MRR while accepting a shorter tool life. These calculations, however, do not consider the high amount of energy and resources bound in the cutting tool [51].

Chen et al. [49] conducted a cutting parameter optimization for minimizing energy consumption taking the embodied energy of the tool and CLs into account. As shown in Fig. 33, especially for high

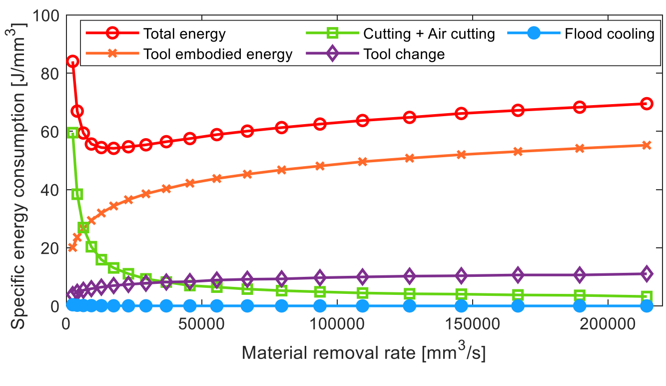

Fig. 33. Specific energy consumption as a function of MRR [49].

MRRs, the embodied energy of the tools dominates the specific cutting energy compared to the energy consumed at the machine tool. Therefore, there is a limit on minimizing the cumulative energy consumption by increasing the MRR.

Liu et al. [160] revealed that the share of the embodied energy in tools is, in addition to the cutting parameters, influenced by CLs due to the differences in tool wear behavior and the embodied energy of the CLs. The optimal MRR therefore differs between dry machining and flood cooling.

Dogan et al. [77], demonstrated that the cumulative energy consumption and specific energy footprint of machining are influenced by machining environment. As shown in Fig. 34, despite higher energy requirements for producing and operating Oil-WS_2 nanofluid MQL, the cumulative energy consumption is lower due to the increased tool life in machining Ti-6Al-4 V at 150 m/min cutting speed. The analysis showed that the cutting tool followed by machine tool energy consumption dominate the cumulative energy consumption of the machining process.

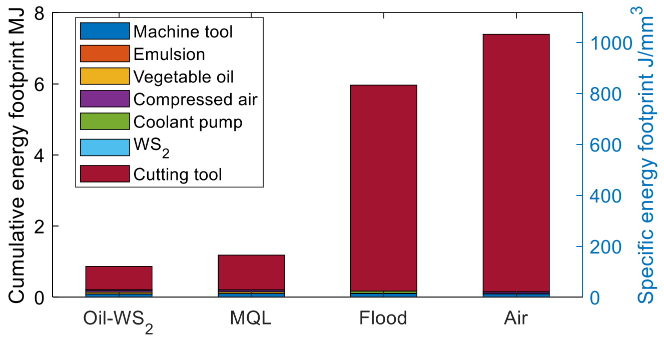

Fig. 34. Cumulative energy footprint using different machining environments in milling Ti6Al4V [77].

Rief et al. [226] included the embodied energy of the tool in a detailed model for energy-efficient process planning. The WC—Co powder mixture for the tool body has an embodied energy of 11.5 MJ/kg. The extruder pressing energy with a representative device sums up to 35.9 MJ/kg. In addition, the authors measured the energy needed for grinding the tool, leading to more than 12 MJ per twist drill with a diameter of 8.5 mm. They highlighted that the embodied energy of the tools is even higher than in their calculation since they did not include coating in their analysis [226]. In comparison, Kirsch et al. [140] reported an average 17.6 MJ embodied energy for a 10 mm diameter coated WC—Co end mill. Dogan et al. [77] estimated the energy footprint of a 12 mm diameter at 84 MJ. Most analyses underestimated the embodied energy of the tools, especially for complex geometries which need several grinding operations.

Cutting tool utilization is in tension between underuse and overuse, leading to either increased cost and environmental impacts or damage to the workpiece and scrap production [268].

Focusing on reducing energy consumption, utilizing the service life of tools increases the efficiency of capitalizing its embodied energy [268]. Being able to detect the exact time that the tools need to be replaced, maximizes the utilization of cutting tools and their embodied energy and material. It also provides an opportunity to replace the tools in a condition that allows for regrinding and remanufacturing as explained in section 5.5.

In practice, physically checking the tool wear is time consuming and requires expertise. Most companies instead opt for predictive methods based on a predefined tool life using statistical process control. In machining of safety critical or high value components, where tool wear induced damage to the workpiece can lead to expensive scrap production, even more conservative measures are taken and tools are discarded prior to their end of life.

About 20–50 % of the tools are discarded early leading to lost value and resources [313]. Being able to precisely detect when a cutting tool needs to be replaced will capitalize on the remaining useful life (RUL) of a cutting tool and unused resources which are currently discarded.

There is a plethora of research dedicated to tool condition monitoring (TCM) using various direct and indirect methods. Teti et al. [276] provided a comprehensive review of tool condition monitoring techniques using various sensors and analysis methods including machine learning. Qin et al. suggested using a feature network dictionary for indirect wear monitoring and on-line RUL estimations [218]. Deep learning processing of sensor signals have also shown potential to increase accuracy to more than 89 % in detecting when a tool change is needed [190].

In addition to the cutting tool, the life cycle perspective can also be extended to the CLs and workpiece. Regarding CLs, it is becoming apparent that the balance of biodegradable oils is significantly better compared to mineral oils [260] and that cryogenic media have a higher embodied energy compared to oil- and water-based MWFs [136]. However, there is minimal information on the in-service and end-of-life energy demand of MWFs. Jansen [127] estimated that 1.98 MJ energy is required for treating a liter of water-based MWF at 5 % concentration whilst Alswat and Mativenga [11] used 17.54 J/l.

Throughout this section, several measures have been explained that have the potential to save energy in the machining process and are summarized in Fig. 35. Some of these measures have already been implemented in parts of the industry. These include optimization of tool paths to reduce non-material cutting moves, increasing MRR and process monitoring to prevent vibration-induced tool breakage. Model-based optimization methods can be used to maximize tool utilization while maintaining a high MRR, and to reduce coolant quantities.

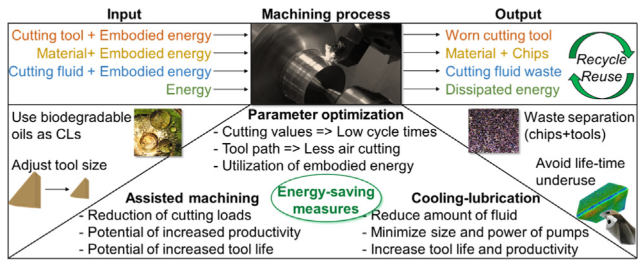

Fig. 35. Overview of energy saving measures in machining processes.

The key knowledge gap identified is the embodied energy of the operating resources. The supplying companies should be required to declare the embodied energy and CO_2 emissions of their products. A holistic approach based on cumulative energy consumption may lead to a completely different assessment of measures that have been positively evaluated so far.

8. Industrial case studies

In this section two industrial case studies from Premium Aerotec and Schaeffler Group are provided indicating their internal environmental assessment.

Premium Aerotec [149] produces ~5 million components per year of 25,000 varieties for various civil aircrafts. They consume 14,800 tons of aluminum and 420 tons of titanium alloys, annually. Nearly 89 % of the total workpiece material procured each year is transformed into chips. Additionally, they consume 21,000 cutting tools of various types and geometries which equates to ~4 tons of tungsten carbide waste each year. They estimated the embodied energy of 388.8 MJ/kg for titanium alloy and 61.2 MJ/kg for aluminum leading to 828 TJ wasted energy through cutting chips [149]. In comparison approximately 2 TJ was used for producing the cutting tools' material excluding the energy consumption for producing the cutting tools.

Schaeffler Group produces high precision components and systems for powertrain and chassis applications in automotive as well as rolling and plain bearing solutions for various industrial sectors mainly through machining. As illustrated in Fig. 36, a recent analysis

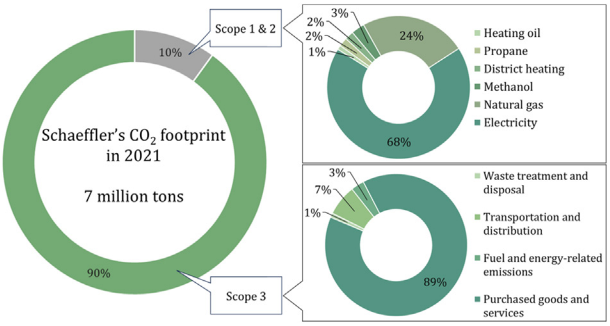

Fig. 36. Schaeffler Group's GHG emissions breakdown in 2021 [236].

of Schaeffler's GHG emissions indicated that 10 % of their emissions are related to Scope 1 and 2 emissions with electricity consumption responsible for 68 % of the impacts [235]. Over 80 % of the emissions were related to the purchased goods and services with purchased steel responsible for 60 % of the emissions. Schaeffler aims to achieve climate neutrality by 2040. They have taken the initiative to minimize the environmental impact of their products through their supply chain by sourcing low GHG emission and recycled steel in the future. However, they noted that the tool life is 2 to 5 times shorter in machining recycled steel than primary steel [23].

This necessitates the need for a system approach to reducing environmental impacts by considering the tradeoffs between using recycled steel and the impact on cutting tool consumption. The case also highlights the importance of taking Scope 3 energy consumption and GHG emissions into consideration. The selection of appropriate supply chains which are transparent and verifiable can affect the overall impact of machining industries on the environment and society.

9. Discussion and future outlook

Machining is a fundamental manufacturing process and minimizing and eventually eliminating the adverse environmental impacts of machining is a necessity. Machining is a major material and energy consumer and there is a need for reducing the resource consumption in machining and their associated GHG emissions. This means making more with less: optimizing, rethinking, redesigning and innovating to extend the life of the products and materials in circulation including the machine tool itself, the cutting tools, CLs and the machined product. The important challenges that require attention to promote sustainability in machining are:

- Whilst there have been many standalone innovations in cutting tools and materials, reducing machine tool energy consumption, various CLs, etc., a supply chain integrated approach is urgently needed. The embodied material, energy, GHG emissions and their wider impacts during their lifecycle should be considered for decision making in machining. It also requires understanding their broader supply chains and their impacts on the environment and society.
- There is a need for a standardized method for manufacturers to declare the environmental and social impacts of their products so that they can be used for decision making in machining in a way that is transparent and verifiable. It will also call for legislation and policy to ensure the availability and accuracy of the information accompanying these products.

  The best possible, and available means for a quantitative evaluation of the environmental impact of machining is life cycle assessment (LCA) following the ISO 14000 series and specifically 14040 and 14044. Availability of data, however, remains a major challenge. The CLs, cutting tool materials and coatings and often their manufacturing technologies as well as the machine tools and tooling are proprietary materials of the manufacturers and are safeguarded as trade secrets.
- It is necessary to model, evaluate, and optimize Scope 1, 2, and 3 emissions. The comparison of existing literature findings is hindered by variations in system boundaries, the scope of analysis, and functional units. The boundaries of the LCA can have a profound impact on the outcome and decisions made. It has become evident that the optimal scenarios are different when different parameters and boundaries are considered.

  For instance, if only machine tool energy consumption is considered, increased MRR can lead to reduced energy consumption at the expense of tool life. However, there are environmental impacts associated with manufacturing of the cutting tools.

  A comprehensive assessment must include the impact of consumables and equipment and their embodied material, energy and GHG emissions. Specifically, Scope 3 environmental impacts, such as extraction and refinement of raw materials, production of bought-in consumables and their life after use must be considered. Additionally, the wider impact on society and economy should be quantified.
- A practical solution is needed to enable machinists to make decisions for day-to-day activities. The complexity of this problem requires adoption of digital technologies and use of advanced modelling and optimization algorithms. However, the additional impacts of digital technologies should also be considered.
- With improving standards of living across the globe and increasing demand for products, continued linear resource consumption and increasing emissions are no longer sustainable. Research efforts should be directed towards maximizing the circularity of materials within machine shops, manufacturing facilities and beyond. Applying circular economy strategies to products, consumables and equipment within a machining system can reduce the demand for extracting raw materials and reduce energy demand and GHG emissions. Kara et al. [131] noted that adopting a circular economy approach can reduce the demand for raw material and reduce the environmental impacts whilst meeting the societal need for prosperity.
- Every effort should be made to extend the lifespan of products and materials in circulation through improved performance, reusing, repairing, remanufacturing and recycling. This applies to the parts produced through machining as well as cutting tools, CLs, machine tools, etc. As shown in Fig. 37, machining is well suited for circularity and specifically recycling as a circular economy strategy. The chips and worn cutting tools generated during machining typically have high value, high concentration, are not mixed and have limited contamination.

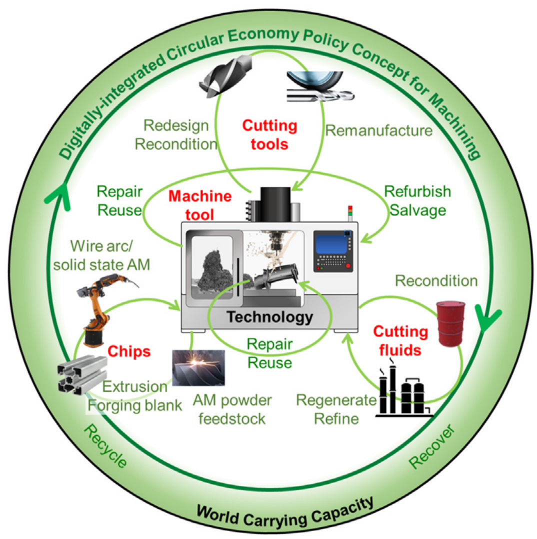

Fig. 37. Vision of circularity in machining with closed-loops in the machining system.

- Enabling and adopting technologies for circular economy is also expected to provide new business opportunities.
- Digital technologies can enable and track circularity of materials. Beside technological advances, circularity needs to be reinforced through appropriate policies, incentives and cultural changes.
- The use of mineral oil is not advocated and obviously, the consumption of non-renewable resources such as mineral oil and materials must be reduced or where possible eliminated. As an alternative, renewable and biodegradable plant-based chemicals and vegetable oils are a possibility. However, the impact of supply chains on the environmental and social sustainability of machining operations is widely overlooked. Sourcing plant-based chemicals and lubricants for fully synthetic fluids and vegetable oils can have a varying impact on the environment and society depending on where they are sourced from.
- Depending on the agricultural practices, the types of fertilizers and pesticides used, and if it contributed to deforestation, they could have a significant and long term impact on the environment for instance through replacing rainforest jungles with soybean farms [161].
- Using arable land for cultivating oil plants for industrial use may compete with food production and add additional stress to the land [7,102]. Algae-based oil in comparison does not require arable land but has high water and energy consumption. Further development in this area and decarbonization of electricity can make algae-based CLs a viable alternative. Technological advancements in CLs and machining environments can further reduce the overall impact of machining by improving tool life and part surface integrity.
- A large portion of the environmental impact of machining a part is related to the workpiece material. The transition to near-net-shape manufacturing as an alternative to roughing operations should increase in the future. This is expected to accelerate with further adoption of AM technologies in lieu of forging and casting and the reduced costs for the AM feedstock. This can also bring new challenges since repair of consolidated AM parts becomes more challenging.
- While materials must be recovered through recycling, research should also focus on remanufacturing and repurposing waste into other products prior to recycling. For instance, reusing and repurposing cutting chips as feedstock for AM can be considered.
- More abundant materials with low environmental impacts, which are readily recyclable, are urgently needed for cutting tools. Both cobalt and tungsten are considered CRMs, have high embodied energy and a large amount of waste is generated in their production. Natural stone and ceramics have been explored as potential alternatives [71,89]. However, their environmental impacts should be assessed within the machining system.
- Alternative business models such as cutting tools as a service can potentially align economic gain with sustainability and worn cutting tools can be collected, remanufactured or recycled. Digital technologies, improved transparency and CAM/machine tool integration can enable these new business models.
- A large number of tools are disposed prematurely each year in order to prevent damage to the workpiece [77]. Others are pushed beyond repair and can only be recycled. Tool condition monitoring and forecasting systems based on sensor systems and digital technologies can determine the right time for replacing the tools so they can be reground or remanufactured [77]. This requires integration into machine tool controllers and the process planning systems. Digital technologies can also bring challenges regarding data security, processing and storage. Additionally, power consumption and other impacts related to data processing and storage should not be overlooked.

9.1. Renewable resources

In 2022, 61 % of the global electricity was from fossil fuels [192]. However, 87.7 % of the global overall energy was still derived from fossil sources [155]. As shown in Fig. 38, in 2021 some renewable sources even took a step backwards in their share of energy production. This shows that the road to carbon-free energy production is still a very long one. Additionally, the share of renewable energy in total electricity production is developed very differently in different countries and regions, and the use of this energy varies greatly from sector to sector [291].

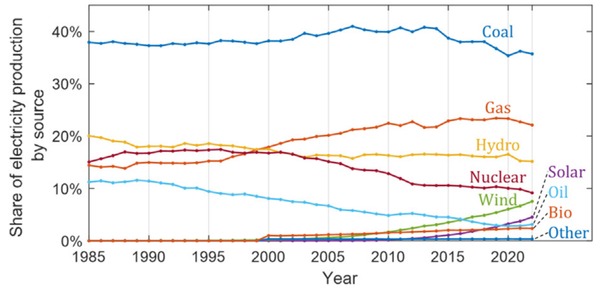

Fig. 38. Development of worldwide energy production share [227].

The path to a broad international use of renewable energy sources is also counteracted by geopolitics [282]. Overall, it can be seen that the development status of renewable energies varies massively around the world and is influenced by technical, political as well as social factors [217]. As such, a generalization of GHG emissions for a given amount of energy is unreliable as the carbon intensity of electricity varies greatly between different regions.

Therefore, raw materials, workpieces, cutting tools, CLs and machined parts may have different associated environmental impacts and embodied GHGs depending on their supply chains and the geographical location that they have been sourced from.

9.2. What if electricity was 100 % GHG emission free?

As shown in Fig. 38, the world's electricity mix is far away from 100 % GHG emission free and renewable electricity. Whilst the authors envisage companies and countries emerge in the near future with access to completely GHG emission free and renewable electricity, there is still a requirement to minimize energy consumption. In this section, a scenario is envisioned when the energy transition has been successfully completed and the electricity is 100 % renewable and GHG emission free.

Thellufsen et al. [277] designed such a scenario for a "GHG free" city. Industry, as part of the city, was also included in the concept. It was suggested to increase the share of electrical energy in industry to minimize direct emissions. The Scope 1 emissions for machining companies are usually limited to site heating and transportation which can be commonly electrified. The starting step would be for machining companies to invest in renewable energies to eliminate their Scope 2 emissions. On site renewable energy production (solar, wind, etc.) can be used to reduce reliance on external electricity from fossil fuels [95].

Even though machining processes are largely electrified, this does not extend to the industries within their supply chain (Scope 3).

The resources and materials used for producing parts in machining are sourced globally. Due to the reliance of machining on global supply chains, clean transportation is needed. Whilst using 100 % renewable sources of electricity for machining may reduce the Scope 2 emissions, it would be naïve to assume a similar scenario for Scope 1 and Scope 3 emissions.

Even zero emission electricity production systems such as wind turbines and solar systems have high embodied energy and CO_2 footprints. Wider environmental impacts beyond GHG emissions should also be considered as explained in Section 2.

In a 100 % GHG emission free electricity world, on site generation of liquefied gases captured from air for cryogenic, thermally assisted machining and vibration/modulation assisted machining may be advantageous. This highlights the potential for LN_2 cryogenic machining to reach minimal environmental impact despite its high energy demand where nitrogen can be directly captured from air using zero GHG emission electricity. Unlike nitrogen, CO_2 concentration in air is low and cannot be efficiently captured from the air.

In a world where clean electricity is abundant, material scarcity is expected to become the upcoming challenge for the workpiece, cutting tools and different components of the machine tools highlighting the immediate need for implementing circular economy and increased recycling rate.

In a GHG emission-free world, there is still a strong need to keep overall energy consumption low, to which each type of consumer should make a particular contribution [282]. The technological concepts presented earlier for reducing energy consumption in machining will continue to be relevant even if electricity production is completely GHG free.

Switching to renewable sources such as vegetable and algae-based oils and chemicals requires improved farming practices and access to clean energy.

Future alternative technologies including assisted machining, CLs and cutting tools which require additional resources and energy to operate are only viable if they reduce the overall impacts of machining systems.

10. Concluding remarks

Over the past 50 years, machining has enabled manufacturing of precision parts with complex geometries leading to advancements in science, technology and day-to-day life. Machining has the capacity and capability to support the transformation to a sustainable future.

In this keynote paper, an extended vision for sustainable machining is drawn to meet the needs of the current and future generations. Technological advances in machining with a potential to reduce the environmental impacts of machining have been identified and discussed. The shortcomings in practice and technology have been identified and the path for future research directions have been drawn:

- Future research in machining will be driven by the need to reduce the environmental impacts of machining and specifically the overall GHG emissions and material footprint.
- Whilst there have been isolated efforts in reducing machine tools' energy consumption, new cutting tool geometries, materials and coatings and alternative coolant/lubricants(CLs), there is a need for an integrated system approach taking all aspects of machining into account.
- To date, the focus has been on reducing the energy consumption of machine tools for producing a part. The environmental impacts, embodied energy and GHG emissions for cutting tools and CLs in their production, use, treatment and end-of-life must also be accounted for. This calls for including the Scope 2 and Scope 3 impacts and GHG emissions into consideration.
- The shift towards plant-based products can increase the pressure on the eco-system and the need for more arable land, therefore it should not be seen as a magic solution.
- Technological developments that support assisted machining (i.e. laser assisted, vibration/ultrasonic assisted, induction heating, etc.,), engineered cutting tools with macro- and micro-geometries, coatings and alternative cooling and lubricants can improve machining performance. Their application needs to be accompanied by comprehensive life cycle assessment (LCA) to ensure that the additional resource and energy consumption is offset by the improved machining performance and reduced overall energy consumption and GHG emissions.
- There is a need for a transparent and verifiable material, products and energy supply chain. They can have profound societal and environmental impact on the geographical locations that they are sourced from. Users of machining technology should take additional responsibility for the impacts of their choices of consumables e.g., cutting tools, cutting fluids, etc. and their supply chains.
- The linear use of materials, reliance on non-renewable resources and increasing energy consumption is no longer sustainable. A circular economy model must be implemented including a machining system to maximize the life of materials in circulation followed by material recovery through recycling.

Declaration of competing interest

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

CRediT authorship contribution statement

A. Shokrani: Writing – review & editing, Writing – original draft, Visualization, Supervision, Conceptualization. **P.J. Arrazola:** Writing – review & editing, Writing – original draft, Visualization. **D. Biermann:** Writing – review & editing, Writing – original draft, Visualization. **P. Mativenga:** Writing – review & editing, Writing – original draft. **I.S. Jawahir:** Writing – review & editing, Writing – original draft, Visualization.

Acknowledgements

We gratefully thank the contribution and support from Mr Jannis Saelzer, Mr Gabriel Brock, Mr Pascal Volke, Mr Iñigo Rodriguez, Mr Ishrat Fairoz, Dr Busra Karas and Dr Hakan Dogan. The support from S Melkote (1), V Schulze (1), S Kara (1), B. Denkena (1), P C Priarone (2), T Bergs (2), H C Mohring (2), D Boing, and N He are greatly acknowledged. We are grateful to Dr.-Ing. W Heuer from Schaeffler Group and Dr.-Ing. M Lange from Premium Aerotec for providing case studies.

References

[1] Abbá E, Speidel A, Liao Z, Axinte D, Novovic D (2022) A Bar Of Cutting Fluid: Deep Eutectic Fluids With A Novel Flavour. *Materials Today Advances* :100291. 16/.
[2] Abdelaziz E, Saidur R, Mekhilef S (2011) A Review On Energy Saving Strategies In Industrial Sector. *Renewable and Sustainable Energy Reviews* : 150–168. 15/1.
[3] Abdelrazek AH, Choudhury I, Nukman Y, Kazi S (2020) Metal Cutting Lubricants And Cutting Tools: A Review On The Performance Improvement And Sustainability Assessment. *The International Journal of Advanced Manufacturing Technology* : 4221–4245. 106/.
[4] Abuya WO (2016) Mining Conflicts and Corporate Social Responsibility: Titanium Mining in Kwale, Kenya. *The Extractive Industries and Society* : 485–493. 3/2.
[5] Addison A, Ding J, Martina F, Lockett H, Williams S (2015) *Manufacture of Complex Titanium Parts using Wire+Arc Additive Manufacture, Titanium Europe 2015, International Titanium Association*, .
[6] Airao J, Nirala CK, Khanna N (2022) Novel Use Of Ultrasonic-Assisted Turning In Conjunction With Cryogenic And Lubrication Techniques To Analyze The Machinability Of Inconel 718. *Journal of Manufacturing Processes* . 81/962-975.
[7] Ajanovic A (2011) Biofuels Versus Food Production: Does Biofuels Production Increase Food Prices? *Energy* : 2070–2076. 36/4.
[8] Alcock, T.D., D.E. Salt, S.J. Ramsden, 2020, A Harmonised Systems-Wide Re-Analysis Of Greenhouse Gas Emissions From Sunflower Oil Production, bioRxiv 2020.06. 19.161893.
[9] Alcock TD, Salt DE, Wilson P, Ramsden SJ (2022) More Sustainable Vegetable Oil: Balancing Productivity With Carbon Storage Opportunities. *Science of The Total Environment* . 829/154539.
[10] Allen J (2006) An Investigation Into The Comparative Costs Of Additive Manufacture vs. Machine From Solid For Aero Engine Parts. *Cost Effective Manufacture Via Net-Shape Processing (pp. 17-1 –17-10). Meeting Proceedings RTO-MP-AVT-139, Paper 17. Neuilly-sur-Seine*, RTOFrance.
[11] Alswat HM, Mativenga PT (2022) Modelling The Direct And Embodied Energy Requirements Of Machining. *Journal of Cleaner Production* . 366/132767.
[12] An Q, Cai C, Zou F, Liang X, Chen M (2020) Tool Wear And Machined Surface Characteristics In Side Milling Ti6Al4V Under Dry And Supercritical CO2 with MQL Conditions. *Tribology International* . 151/106511.
[13] An Q, Fu Y, Xu J (2011) Experimental Study On Turning Of TC9 Titanium Alloy With Cold Water Mist Jet Cooling. *International Journal of Machine Tools and Manufacture* : 549–555. 51/6.
[14] Anilchandra AR, Surappa MK (2013) Microstructure And Tensile Properties Of Consolidated Magnesium Chips. *Materials Science and Engineering: A* : 759–766. 560/.
[15] Aramcharoen A, Mativenga PT (2014) Critical Factors In Energy Demand Modelling For CNC Milling And Impact Of Toolpath Strategy. *Journal of Cleaner Production* : 63–74. 78/.
[16] Arola D, Williams CL (2002) Estimating The Fatigue Stress Concentration Factor Of Machined Surfaces. *International Journal of Fatigue* : 923–930. 24/9.
[17] Aspinwall DK, Chen W (1988) Machining of Grey Cast Iron Using Advanced Ceramic Tool Materials. in Davies BJ, (Ed.) *Proceedings of the Twenty-Seventh International Matador Conference*, Macmillan Education UK: London, , 225–230.

[18] Balogun VA, Mativenga PT (2013) Modelling Of Direct Energy Requirements In Mechanical Machining Processes. *Journal of Cleaner Production* : 179–186. 41/.

[19] Banza Lubaba Nkulu C, Casas L, Haufroid V, De Putter T, Saenen ND, Kayembe-Kitenge T, Musa Obadia P, Kyanika Wa Mukoma D, Lunda Ilunga J-M, Nawrot TS, Luboya Numbi O, Smolders E, Nemery B (2018) Sustainability Of Artisanal Mining Of Cobalt In DR Congo. *Nature Sustainability* : 495–504. 1/9.

[20] Bart JCJ, Gucciardi E, Cavallaro S (2013) 11 - Environmental life-Cycle Assessment (LCA) of Lubricants. in Bart JCJ, Gucciardi E, Cavallaro S, (Eds.) *Biolubricants*, Woodhead Publishing, , 527–564.

[21] Bassett E, Köhler J, Denkena B (2012) On The Honed Cutting Edge And Its Side Effects During Orthogonal Turning Operations Of AISI1045 With Coated WC-Co inserts. *CIRP Journal of Manufacturing Science and Technology* : 108–126. 5/2.

[22] Bauer C, Buchgeister J, Hischier R, Poganietz W, Schebek L, Warsen J (2008) Towards A Framework For Life Cycle Thinking In The Assessment Of Nanotechnology. *Journal of Cleaner Production* : 910–926. 16/8-9.

[23] Berger, S., J. Nickel, 2023, Einfluß der Herstellungsroute auf die Zerspanbarkeit von Stahlwerkstoffen am Beispiel des Hartdrehens eines 100CrMnSi6-4, AK ZiS.,

[24] Bergs T, Grünebaum T, Fricke K, Barth S, Ganser P (2021) Life Cycle Assessment For Milling of Ti- and Ni-Based Alloy Aero Engine Components. *Procedia CIRP* : 625–630. 98/.

[25] Bergs T, Pušavec F, Koch M, Grguraš D, Döbbeler B, Klocke F (2019) Investigation of the Solubility of Liquid CO2 and Liquid Oil to Realize an Internal Single Channel Supply in Milling of Ti6Al4V. *Procedia Manufacturing* : 200–207. 33/.

[26] Bermingham MJ, Kirsch J, Sun S, Palanisamy S, Dargusch MS (2011) New Observations On Tool Life, Cutting Forces And Chip Morphology In Cryogenic Machining Ti-6Al-4V. *International Journal of Machine Tools and Manufacture* : 500–511. 51/6.

[27] Biermann D, Iovkov I (2015) Investigations On The Thermal Workpiece Distortion In MQL Deep Hole Drilling Of An Aluminium Cast Alloy. *CIRP Annals* : 85–88. 64/1.

[28] Biermann D, Iovkov I (2013) Modeling and Simulation of Heat Input in Deep-hole Drilling with Twist Drills and MQL. *Procedia CIRP* : 88–93. 8/.

[29] Binali R, Patange AD, Kuntoğlu M, Mikolajczyk T, Salur E (2022) Energy Saving by Parametric Optimization and Advanced Lubri-Cooling Techniques in the Machining of Composites and Superalloys: A Systematic Review. *Energies* : 8313.. 15/21.

[30] Bleicher F, Reiter M, Brier J (2019) Increase Of Chip Removal Rate In Single-Lip Deep Hole Drilling At Small Diameters By Low-Frequency Vibration Support. *CIRP Annals* : 93–96. 68/1.

[31] Blengini GA, Latunussa CE, Eynard U, Matos CTd, Wittmer D, Georgitzikis K, Pavel C, Carrara S, Mancini L, Unguru M, Blagoeva D, Mathieux F, Pennington D (2020) *Study On the EU's List of Critical Raw Materials*, European Commission.

[32] Bobzin K (2017) High-Performance Coatings For Cutting Tools. *CIRP Journal of Manufacturing Science and Technology* : 1–9. 18/.

[33] Bouzakis K-D, Michailidis N, Skordaris G, Bouzakis E, Biermann D, M'Saoubi R (2012) Cutting With Coated Tools: Coating Technologies, Characterization Methods And Performance Optimization. *CIRP annals* : 703–723. 61/2.

[34] Brinksmeier E, Meyer D, Huesmann-Cordes A, Herrmann C (2015) Metalworking Fluids—Mechanisms And Performance. *CIRP Annals* : 605–628. 64/2.

[35] BSR and UN Global Compact. *Supply Chain Sustainability: A Practical Guide for Continuous Improvement, Second Edition*, UN Global Compact Office.

[36] Buss D, Rutherford B (2020) *Gendering Women's Livelihoods in Artisanal and Small-Scale Mining: An Introduction*, 1–16.

[37] Byemba GK (2020) Formalization Of Artisanal And Small-Scale Mining In Eastern Democratic Republic Of The Congo: An Opportunity For Women In The New Tin, Tantalum, Tungsten And Gold (3TG) Supply Chain? *The Extractive Industries and Society* : 420–427. 7/2.

[38] Byrne G, Dornfeld D, Denkena B (2003) Advancing Cutting Technology. *CIRP Annals* : 483–507. 52/2.

[39] Calvão F, McDonald CEA, Bolay M (2021) Cobalt Mining And The Corporate Outsourcing Of Responsibility In The Democratic Republic of Congo. *The Extractive Industries and Society* :100884. 8/4.

[40] Campitelli A, Cristóbal J, Fischer J, Becker B, Schebek L (2019) Resource Efficiency Analysis Of Lubricating Strategies For Machining Processes Using Life Cycle Assessment Methodology. *Journal of Cleaner Production* : 464–475. 222/.

[41] Canter NM (2017) The Chemistry of Metalworking Fluids*, in* Metalworking Fluids, Third Edition, CRC Press, 143–169.

[42] Catalano AR, Debernardi L, Balaso R, Rubbiani F, Priarone PC, Settineri L (2022) An Appraisal Of The Cradle-To-Gate Energy Demand And Carbon Footprint Of High-Speed Steel Cutting Tools. *Procedia CIRP* : 745–750. 105/.

[43] Ceratizit, 2021, CO2 Emissions of WC Powder And The Benefits Of Recycling, Ceratizit.

[44] Ceratizit, 2023, Full Power With Exchangeable Head, Ceratizit. [Online]. Available: https://cuttingtools.ceratizit.com/gb/en/machining-know-how/drilling/product-overview/wtx-change-feed.html. [Accessed: 06-Feb-2023].

[45] Ceratizit, 2023, Passion For Cemented Carbide, Ceratizit. [Online]. Available: https://www.ceratizit.com/int/en/company/passion-for-cemented-carbide-/production.html. [Accessed: 08-Feb-2023].

[46] Ceratizit, Special Operations, Recycling, Ceratizit. [Online]. Available: https://www.ceratizit.com/int/en/offerings/services/special-operations/recycling.html. [Accessed: 08-Feb-2023].

[47] Ceratizit, 2022, Well Supplied In The Future, Ceratizit. [Online]. Available: https://www.ceratizit.com/int/en/company/blog/2022/blogposting-well-supplied-in-the-future-.html. [Accessed: 08-Feb-2023].

[48] Chang L, Volpe L, Wang YL, Burke MG, Maurotto A, Tice D, Lozano-Perez S, Scenini F (2019) Effect of Machining On Stress Corrosion Crack Initiation In Warm-Forged Type 304L Stainless Steel In High Temperature Water. *Acta Materialia* : 203–214. 165/.

[49] Chen X, Li C, Jin Y, Li L (2018) Optimization Of Cutting Parameters With A Sustainable Consideration Of Electrical Energy And Embodied Energy Of Materials. *The International Journal of Advanced Manufacturing Technology* : 775–788. 96/.

[50] Chen X, Li C, Li M, Fang K (2021) Revisiting The Application And Methodological Extensions Of The Planetary Boundaries For Sustainability Assessment. *Science of The Total Environment* . 788/147886.

[51] Chen X, Li C, Tang Y, Li L, Li H (2021) Energy Efficient Cutting Parameter Optimization. *Frontiers of Mechanical Engineering* : 221–248. 16/2.

[52] Cheng C, Phipps D, Alkhaddar RM (2005) Treatment Of Spent Metalworking Fluids. *Water Research* : 4051–4063. 39/17.

[53] Childerhouse T, Hernández-Nava E, Tapoglou N, M'Saoubi R, Franca L, Leahy W, Jackson M (2021) The Influence Of Finish Machining Depth And Hot Isostatic Pressing On Defect Distribution And Fatigue Behaviour Of Selective Electron Beam Melted Ti-6Al-4V. *International Journal of Fatigue* . 147/106169.

[54] Chipasa, K., 2011, Best Practice Guide for the Disposal of Water-mix Metalworking Fluids, United Kingdom Lubricants Association, Available from: https://www.ukla.org.uk/wp-content/uploads/UKLA-PERA-Best-Practice-Guide-for-the-Disposal-of-Water-mix-Metalworking-Fluids.pdf.

[55] Clarens AF, Zimmerman JB, Keoleian GA, Hayes KF, Skerlos SJ (2008) Comparison Of Life Cycle Emissions And Energy Consumption For Environmentally Adapted Metalworking Fluid Systems. *Environmental science & technology* : 8534–8540. 42/22.

[56] Clift R, Sim S, King H, Chenoweth JL, Christie I, Clavreul J, Mueller C, Posthuma L, Boulay A-M, Chaplin-Kramer R (2017) The Challenges Of Applying Planetary Boundaries As A Basis For Strategic Decision-Making In Companies With Global Supply Chains. *Sustainability* : 279.. 9/2.

[57] Colorado HA, Velásquez EIG, Monteiro SN (2020) Sustainability Of Additive Manufacturing: The Circular Economy Of Materials And Environmental Perspectives. *Journal of Materials Research and Technology* : 8221–8234. 9/4.

[58] COSHH. COSHH Essentials For Machining With Metalworking Fluids. *Health & Safety Executive* . UK.

[59] Curtis-Jackson P, van-der-Mescht M, Jones S (2022) *Persistent, Bioaccumulative and Toxic (PBT) Properties of Long Chain Chlorinated Paraffins (LCCPs)*, .

[60] Dahmus JB, Gutowski TG (2004) An Environmental Analysis Of Machining. *ASME International Mechanical Engineering Congress And Exposition*, .

[61] Damir A, Sadek A, Attia H (2018) Characterization Of Machinability And Environmental Impact Of Cryogenic Turning Of Ti-6Al-4V. *Procedia Cirp* : 893–898. 69/.

[62] Damm O, Bezuidenhout M, Uheida E, Dicks L, Hadasha W, Hagedorn-Hansen D (2021) Yeast-Based Metalworking Fluid For Milling Of Titanium Alloy—An Example Of Bio-Integration. *CIRP Journal of Manufacturing Science and Technology* : 47–60. 34/.

[63] Danish M, Gupta MK, Rubaiee S, Ahmed A, Korkmaz ME (2021) Influence Of Hybrid Cryo-MQl Lubri-Cooling Strategy On The Machining And Tribological Characteristics of Inconel 718. *Tribology International* . 163/107178.

[64] De Bartolomeis A, Newman ST, Biermann D, Shokrani A (2020) State-of-The-Art Cooling and Lubrication for Machining Inconel 718. *Journal of Manufacturing Science and Engineering* . 143/5.

[65] De Bartolomeis A, Shokrani A (2020) Electrohydrodynamic Atomization For Minimum Quantity Lubrication (EHDA-MQL) In End Milling Ti6Al4V Titanium Alloy. *Journal of Manufacturing and Materials Processing* : 70.. 4/3.

[66] de Paula Oliveira G, Cindra Fonseca M, Araujo AC (2017) Analysis Of Residual Stress And Cutting Force In End Milling Of Inconel 718 Using Conventional Flood Cooling And Minimum Quantity Lubrication. *The International Journal of Advanced Manufacturing Technology* : 3265–3272. 92/9.

[67] DEFRA, 2012, Environmental Key Performance Indicators: Reporting Guidelines for UK Business Department for Environment, Food and Rural Affairs, Queen's Printer and Controller, London.

[68] Denkena B, Abele E, Brecher C, Dittrich M-A, Kara S, Mori M (2020) Energy Efficient Machine Tools. *CIRP Annals* : 646–667. 69/2.

[69] Denkena B, Bergmann B, Rahner B-H (2018) Energy-Efficient Control Of Dust Extraction For The Machining Of Fibre-Reinforced Plastics. *Procedia CIRP* : 49–54. 78/.

[70] Denkena B, Biermann D (2014) Cutting Edge Geometries. *CIRP Annals* : 631–653. 63/2.

[71] Denkena B, Breidenstein B, Krödel A, Bergmann B, Picker T, Wolters P (2022) Suitability Of Natural Rocks As Materials For Cutting Tools. *SN Applied Sciences* : 1–21. 4/.

[72] Denkena B, Dittrich MA, Uhlich F, Wichmann M (2019) Approaches For An Energy And Resource Efficient Manufacturing In The Aircraft Industry. *Procedia CIRP* : 180–185. 80/.

[73] Denkena B, Krödel A, Pyzcak F, Rackel MW, Kettelmann S, Matthies J (2021) Recycled Titanium Chips As Initial Product For The Atomisation Process Of Powders For Additive Manufacturing To Increase Resource Efficiency. In: *Proceedings of the Machining Innovations Conference for Aerospace Industry (MIC)*, .

[74] Dhiman S, Joshi RS, Singh S, Gill SS, Singh H, Kumar R, Kumar V (2021) A Framework For Effective And Clean Conversion Of Machining Waste Into Metal Powder Feedstock For Additive Manufacturing. *Cleaner Engineering and Technology* . 4/100151.

[75] Diaz N, Helu M, Jayanathan S, Chen Y, Horvath A, Dornfeld D (2010) Environmental Analysis Of Milling Machine Tool Use In Various Manufacturing Environments. In: *Proceedings of the 2010 IEEE International Symposium on Sustainable Systems and Technology*, IEEE, .

[76] Dima digitale maschinelle fertigung, 2022, Warum Hydrodehnspannfutter nachhaltiger sind, Dima-digitale maschinelle fertigung. [Online]. Available: https://dima-magazin.com/werkzeuge-spannmittel/titelstory-warum-hydrodehns-pannfutter-nachhaltiger-sind/. [Accessed: 02-Feb-2023].

[77] Dogan H, Jones L, Hall S, Shokrani A (2023) Towards Sustainable and Intelligent Machining: Energy Footprint and Tool Condition Monitoring for Media-Assisted Processes. *Journal of Machine Engineering* : 16–40. 23/2.

[78] Dornfeld, D., *Sustainability of Machining*, in *CIRP Encyclopedia of Production Engineering*, L. Laperrière and G. Reinhart, 2014, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 1204–1207.

[79] Duflou JR, Sutherland JW, Dornfeld D, Herrmann C, Jeswiet J, Kara S, Hauschild M, Kellens K (2012) Towards Energy And Resource Efficient Manufacturing: A Processes And Systems Approach. *CIRP Annals* : 587–609. 61/2.

[80] Duflou JR, Tekkaya AE, Haase M, Welo T, Vanmeensel K, Kellens K, Dewulf W, Paraskevas D (2015) Environmental Assessment Of Solid State Recycling Routes For Aluminium Alloys: Can Solid State Processes Significantly Reduce The Environmental Impact Of Aluminium Recycling? *CIRP Annals* : 37–40. 64/1.
[81] ECHA, 2021, Call For Evidence For A Restriction Proposal On MCCP, Europeans Chemical Agency
[82] ELG Haniel Group, 2015, Sustainability report, ELG-Haniel-Group. [Online]. Available: https://www.elgmetals.com/site/assets/files/2025/elg_cr_report_2015_online.pdf. [Accessed: 28-Feb-2023].
[83] EU 2019/1021, 2020, Regulation (EU) 2019/1021 On Persistent Organic Pollutants ABl. EC L 169, p. 45 dated 2019-06-20, Last Amended By EU 2021/277, Official Journal of the European Union
[84] EU Commission, 2020, Critical Raw Materials, European Commission, [Online]. Available: https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en. [Accessed: 28-Feb-2023].
[85] Faga MG, Mattioda R, Settineri L (2010) Microstructural And Mechanical Characteristics Of Recycled Hard Metals For Cutting Tools. *CIRP Annals* : 133–136. 59/1.
[86] Faga MG, Priarone PC, Robiglio M, Settineri L, Tebaldo V (2017) Technological And Sustainability Implications Of Dry, Near-Dry, And Wet Turning of Ti-6Al-4V Alloy. *International Journal of Precision Engineering and Manufacturing-Green Technology* : 129–139. 4/.
[87] Farjana SH, Huda N, Mahmud MAP (2019) Life Cycle Assessment Of Cobalt Extraction Process. *Journal of Sustainable Mining* : 150–161. 18/3.
[88] Fernando R, Gamage J, Karunathilake H (2022) Sustainable Machining: Environmental Performance Analysis Of Turning. *International Journal of Sustainable Engineering* : 15–34. 15/1.
[89] Finkeldei D, Sexauer M, Bleicher F (2019) End Milling of Inconel 718 Using Solid Si3N4 Ceramic Cutting Tools. *Procedia CIRP* : 1131–1135. 81/.
[90] FortuneBusinessInsights. *Metal Cutting Tools Market- FBI101751*, Fortune Business Insights.
[91] Fujishima M, Shimanoe H, Mori M (2017) Reducing The Energy Consumption Of Machine Tools. *International Journal of Automation Technology* : 601–607. 11/4.
[92] Furberg A, Arvidsson R, Molander S (2019) Environmental Life Cycle Assessment Of Cemented Carbide (WC-Co) Production. *Journal of cleaner production* : 1126–1138. 209/.
[93] Furberg A, Fransson K, Zackrisson M, Larsson M, Arvidsson R (2020) Environmental And Resource Aspects Of Substituting Cemented Carbide With Polycrystalline Diamond: The Case Of Machining Tools. *Journal of Cleaner Production* . 277/123577.
[94] Garside, M., 2023, Global Tungsten Production Volume 2022, By Country, Statista. [Online]. Available: https://www.statista.com/statistics/1009356/tungsten-production-worldwide-by-country/. [Accessed: 28-Feb-2023].
[95] Ghadimi P, Kara S, Kornfeld B (2015) Renewable Energy Integration Into Factories: Real-Time Control Of On-Site Energy Systems. *CIRP Annals* : 443–446. 64/1.
[96] Grayson J (2017) Reducing Melt Loss and Dross Generation. *Light Metal Age* https://www.lightmetalage.com/news/industry-news/casthouse/article-reducing-melt-loss-dross-generation/.
[97] Grguraš D, Sterle L, Krajnik P, Pušavec F (2019) A Novel Cryogenic Machining Concept Based On A Lubricated Liquid Carbon Dioxide. *International Journal of Machine Tools and Manufacture* . 145/103456.
[98] Grigoriev S, Bobrovskij N, Melnikov P, Bobrovskij I, Levitskih O (2017) Ecological and Toxicological Characteristics of Metalworking Fluids Used in Finishing Processing in Russian Federation. *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, .
[99] Grijalbo L, Fernandez-Pascual M, García-Seco D, Gutierrez-Mañero FJ, Lucas JA (2013) Spent Metal Working Fluids Produced Alterations On Photosynthetic Parameters And Cell-Ultrastructure Of Leaves And Roots Of Maize Plants. *Journal of Hazardous Materials* : 220–230. 260/.
[100] Gronostajski JZ, Kaczmar JW, Marciniak H, Matuszak A (1997) Direct Recycling Of Aluminium Chips Into Extruded Products. *Journal of Materials Processing Technology* : 149–156. 64/1.
[101] Gühring, HT 800 WP - Das Wechselplatten-Bohrsystem, Gühring
[102] Guiton M, Suárez-Montes D, Sánchez R, Baustert P, Soukoulis C, Okan BS, Serchi T, Cambier S, Benetto E (2022) Comparative Life Cycle Assessment Of A Microalgae-Based Oil Metal Working Fluid With Its Petroleum-Based And Vegetable-Based Counterparts. *Journal of Cleaner Production* . 338/130506.
[103] Gupta MK, Song Q, Liu Z, Pruncu CI, Mia M, Singh G, Lozano JA, Carou D, Khan AM, Jamil M (2020) Machining Characteristics Based Life Cycle Assessment In Eco-Benign Turning Of Pure Titanium Alloy. *Journal of Cleaner Production* :119598. 251/.
[104] Gutowski T, Dahmus J, Thiriez A (2006) Electrical Energy Requirements For Manufacturing Processes. *13th CIRP international conference on life cycle engineering*, .
[105] Haddad M, Zitoune R, Eyma F, Castanie B (2014) Study of the surface defects and dust generated during trimming of CFRP: Influence of tool geometry, machining parameters and cutting speed range. *Composites Part A: Applied Science and Manufacturing* : 142–154. 66/.
[106] Haddad Y, Yuksek YA, Jagtap S, Jenkins S, Pagone E, Salonitis K (2023) Eco-social sustainability assessment of manufacturing systems: an LCA-based framework. *Procedia CIRP* : 312–317. 116/.
[107] Hafiz MZ, Isa H, Mohamed MSS (2013) An overview of ergonomics problems related to CNC machining operations. *Advanced Engineering Forum*, Trans Tech Publ.
[108] Hauschild, M., D. Dornfeld, M. Hutchins, S. Kara, F. Jovane, *Sustainable Manufacturing*, in *CIRP Encyclopedia of Production Engineering*, L. Laperrière and G. Reinhart, 2014, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 1208–1214.
[109] Hauschild MZ (2015) Better – But is it Good Enough? On the Need to Consider Both Eco-efficiency and Eco-effectiveness to Gauge Industrial Sustainability. *Procedia CIRP* : 1–7. 29/.
[110] Hauschild MZ, Herrmann C, Kara S (2017) An Integrated Framework for Life Cycle Engineering. *Procedia CIRP* . 61/2-9.
[111] Hauschild MZ, Kara S, Røpke I (2020) Absolute Sustainability: Challenges To Life Cycle Engineering. *CIRP Annals* : 533–553. 69/2.
[112] Herranz S, Campa F, De Lacalle LL, Rivero A, Lamikiz A, Ukar E, Sánchez J, Bravo U (2005) The Milling Of Airframe Components With Low Rigidity: A General Approach To Avoid Static And Dynamic Problems. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* : 789–801. 219/11.
[113] Hook M (2019) *The Surprising Value in Fluid Recovery, Production Machining*, Gardner Business Media Inc.Cincinnati, OH https://www.productionmachining.com/blog/post/the-surprising-value-in-fluid-recovery.
[114] Howard MC (2010) *Sustainable Manufacturing Initiative (SMI): A True Public-Private Dialogue*, US Department of Commerce.
[115] IEA, 2022, Renewable Electricity, IEA, Paris
[116] Ingarao G, Priarone PC, Deng Y, Paraskevas D (2018) Environmental Modelling Of Aluminium Based Components Manufacturing Routes: Additive Manufacturing Versus Machining Versus Forming. *Journal of Cleaner Production* : 261–275. 176/.
[117] International-Resource-Panel, 2011, Recycling Rates Of Metals, UNEP,
[118] IRENA, 2019, Global Energy Transformation, A Roadmap To 2050, International Renewable Energy Agency, Abu Dhabi
[119] Iscar Tools, FLASH-TURN Iscar Tools. [Online]. Available: https://pdf.directindustry.com/pdf/iscar-tools/flash-turn/5692-425389.html. [Accessed: 01-Feb-2023].
[120] Iscar Tools, Milling Product Line, Iscar Tools. [Online]. Available: https://www.iscar.de/products.aspx/countryid/7/productid/12247. [Accessed: 06-Feb-2023].
[121] Iscar Tools, The Philosophy of Technology - Substitutive or Additive?, Iscar Tools. [Online]. Available: https://www.iscar.com/newarticles.aspx/countryid/1/newarticleid/12032. [Accessed: 03-Feb-2023].
[122] Jaeger E, Ravisankar B, Wirtz A, Meißner M, Rehtanz C, Biermann D, Wiederkehr P (2021) Simulation-Based Analysis Of The Energy Demand Within An Additive Subtractive Process Chain. *Procedia CIRP* : 352–357. 99/.
[123] Jamil M, Zhao W, He N, Gupta MK, Sarikaya M, Khan AM, Siengchin S, Pimenov DY (2021) Sustainable Milling of Ti–6Al–4V: A Trade-Off Between Energy Efficiency, Carbon Emissions And Machining Characteristics Under MQL And Cryogenic Environment. *Journal of Cleaner Production* . 281/125374.
[124] Jawahir I, Attia H, Biermann D, Duflou J, Klocke F, Meyer D, Newman S, Pusavec F, Putz M, Rech J (2016) Cryogenic Manufacturing Processes. *CIRP Annals* : 713–736. 65/2.
[125] Jawahir I, Brinksmeier E, M'saoubi R, Aspinwall D, Outeiro J, Meyer D, Umbrello D, Jayal A (2011) Surface Integrity In Material Removal Processes: Recent Advances. *CIRP Annals* : 603–626. 60/2.
[126] Jawahir I, Schoop J, Kaynak Y, Balaji A, Ghosh R, Lu T (2020) Progress Toward Modeling And Optimization Of Sustainable Machining Processes. *Journal of Manufacturing Science and Engineering* . 142/11.
[127] Jensen, M., 2016, Climate Impact From Metalworking Fluids, Wallenius Water Innovation. [Online] https://www.walleniuswater.com/process-fluids/blog/metalworking-fluids-impact-on-the-climate#:~:text=A/20metalworking/20fluid/20doesn't,use/20and/20in/20its/20container. [Accessed: 13-Mar-2023]
[128] Jiang Z, Gao D, Lu Y, Liu X (2019) Optimization of Cutting Parameters for Trade-off Among Carbon Emissions, Surface Roughness, and Processing Time. *Chinese Journal of Mechanical Engineering* : 94.. 32/1.
[129] Kalpakjian S, Schmid S (2022) *Manufacturing Engineering and Technology*, 8th ed. Pearson Publishing CompanyNew Jersey.
[130] Kamata Y, Obikawa T (2007) High Speed MQL Finish-Turning Of Inconel 718 With Different Coated Tools. *Journal of Materials Processing Technology* : 192–193. /281-286.
[131] Kara S, Hauschild M, Sutherland J, McAloone T (2022) Closed-Loop Systems To Circular Economy: A Pathway To Environmental Sustainability? *CIRP Annals* : 505–528. 71/2.
[132] Kara S, Li W (2011) Unit Process Energy Consumption Models For Material Removal Processes. *CIRP Annals* : 37–40. 60/1.
[133] KBV Reserach, 2022, Global Machine Tools Market Size, Share & Industry Trends Analysis Report, https://www.kbvresearch.com/machine-tools-market/
[134] Kelly, L., 2023, Top 10 Cobalt Producers by Country (Updated 2023), Investing News, [Online]. Available: https://investingnews.com/where-is-cobalt-mined/. [Accessed: 28-Feb-2023].
[135] Kennametal, RIQ Reibwerkzeug für Statorbohrungen, Kennametal. [Online]. Available: https://www.kennametal.com/de/de/products/metalworking-tools/holemaking/precision-hole-finishing.html. [Accessed: 02-Feb-2023].
[136] Khan AM, Alkahtani M, Sharma S, Jamil M, Iqbal A, He N (2021) Sustainability-Based Holistic Assessment And Determination Of Optimal Resource Consumption For Energy-Efficient Machining Of Hardened Steel. *Journal of Cleaner Production* . 319/128674.
[137] Khan IA (2014) Multi-Response Ergonomic Evaluation Of Female CNC Machine Operators. *International Journal of Human Factors and Ergonomics* : 32–64. 3/1.
[138] Khanna N, Shah P, de Lacalle LNL, Rodríguez A, Pereira O (2021) In Pursuit Of Sustainable Cutting Fluid Strategy For Machining Ti-6Al-4V Using Life Cycle Analysis. *Sustainable Materials and Technologies* . 29/e00301.
[139] Kim E-J, Lee C-M (2020) Experimental Study On Power Consumption Of Laser And Induction Assisted Machining With Inconel 718. *Journal of Manufacturing Processes* : 411–420. 59/.
[140] Kirsch B, Effgen C, Büchel M, Aurich J (2014) Comparison Of The Embodied Energy Of A Grinding Wheel And An End Mill. *Procedia CIRP* : 74–79. 15/.
[141] Klocke F, Kuchle A (2011) C. in Klocke F, (Ed.) utting Tool Materials and Tools, *in* Manufacturing Processes 1: Cutting, Springer Berlin Heidelberg, Berlin, Heidelberg, 95–196.
[142] Klocke F, Lung D, Cayli T, Döbbeler B, Sangermann H (2014) Evaluation Of Energy Efficiency In Cutting Aerospace Materials With High-Pressure Cooling Lubricant Supply. *International Journal of Precision Engineering and Manufacturing* : 1179–1185. 15/.
[143] Krolczyk GM, Maruda RW, Krolczyk JB, Wojciechowski S, Mia M, Nieslony P, Budzik G (2019) Ecological Trends In Machining As A Key Factor In Sustainable Production–A Review. *Journal of Cleaner Production* : 601–615. 218/.

[144] Kuenzi, P., A. Rufenact, N. Di Maiuta, P. Weber. *Microbiology In Bioconcept Metalworking*. in *Proceedings of the Society of Tribologists and Lubrication Engineers 2014 Annual Meeting and Exhibition*.

[145] Kugaevskii S, Pizhenkov E, Gamberg A (2019) The Effectiveness Of Additive SLM-Technologies In The Manufacture Of Cutting Tools. *Materials Today: Proceedings* . 19/1977-1981.

[146] Kühnen M, Hahn R (2017) Indicators In Social Life Cycle Assessment: A Review Of Frameworks, Theories, And Empirical Experience. *Journal of Industrial Ecology* : 1547–1565. 21/6.

[147] La Monaca A, Murray JW, Liao Z, Speidel A, Robles-Linares JA, Axinte DA, Hardy MC, Clare AT (2021) Surface Integrity In Metal Machining-Part II: Functional Performance. *International Journal of Machine Tools and Manufacture* :103718. 164/.

[148] Lakner T, Bergs T, Döbbeler B (2019) Additively Manufactured Milling Tool With Focused Cutting Fluid Supply. *Procedia CIRP* : 464–469. 81/.

[149] Lange, M., 2022, Sustainable Aviation: Aircraft Concepts And Production, Smart And Networked Manufacturing 24.

[150] Latif A, Ingarao G, Fratini L (2022) Multi-Material Based Functionally Graded Billets Manufacturing Through Friction Stir Consolidation Of Aluminium Alloys Chips. *CIRP Annals* : 261–264. 71/1.

[151] Laurent-Brocq M, Lilensten L, Pinot C, Schulze A, Duchaussoy A, Bourgon J, Leroy E, Tekkaya AE (2023) Solid State Recycling Of Aluminium Chips: Multi-Technique Characterization And Analysis Of Oxidation. *Materialia* . 31/101864.

[152] Levchuk I, Schäfer A, Lang K-H, Gebhardt H, Klussmann A (2012) Needs Of Ergonomic Design At Control Units In Production Industries. *Work 41/Supplement* 1:1594–1598.

[153] Li B, Cao H, Yan J, Jafar S (2017) A Life Cycle Approach To Characterizing Carbon Efficiency Of Cutting Tools. *The International Journal of Advanced Manufacturing Technology* : 3347–3355. 93/.

[154] Li C, Tang Y, Cui L, Li P (2015) A Quantitative Approach To Analyze Carbon Emissions Of CNC-Based Machining Systems. *Journal of Intelligent Manufacturing* : 911–922. 26/5.

[155] Li L, Lin J, Wu N, Xie S, Meng C, Zheng Y, Wang X, Zhao Y (2022) Review And Outlook On The International Renewable Energy Development. *Energy and Built Environment* : 139–157. 3/2.

[156] Liang X, Liu Z, Liu W, Wang B, Yao G (2019) Surface Integrity Analysis For High-Pressure Jet Assisted Machined Ti-6Al-4V Considering Cooling Pressures And Injection Positions. *Journal of Manufacturing Processes* : 149–159. 40/.

[157] Liu L, Li W, Tan Z, Zhang M, Bo M (2019) Model Design And Analysis Improvement Of CNC Lathe Based on Ergonomics. *IOP Conference Series: Materials Science and Engineering* :012045. 573/1:.

[158] Liu Y, Wang P, Gojenko B, Yu J, Wei L, Luo D, Xiao T (2021) A Review Of Water Pollution Arising From Agriculture And Mining Activities In Central Asia: Facts, Causes And Effects. *Environmental Pollution* . 291/118209.

[159] Liu Z, Islam F, Era IZ, Grandhi M (2023) LCA-Based Environmental Sustainability Assessment Of Hybrid Additive Manufacturing Of A Turbine Blade. *Green Manufacturing Open* . 2/1.

[160] Liu Z, Li C, Fang X, Guo Y (2018) Cumulative Energy Demand And Environmental Impact In Sustainable Machining Of Inconel Superalloy. *Journal of Cleaner Production* . 181/329-336.

[161] Lourençoni T, da Silva Junior CA, Lima M, Teodoro PE, Pelissari TD, dos Santos RG, Teodoro LPR, Luz IM, Rossi FS (2021) Advance Of Soy Commodity In The Southern Amazonia With Deforestation Via PRODES And ImazonGeo: A Moratorium-Based Approach. *Scientific Reports* : 21792.. 11/1.

[162] Lv T, Xu X, Yu A, Niu C, Hu X (2021) Ambient Air Quantity And Cutting Performances Of Water-Based Fe3O4 Nanofluid In Magnetic Minimum Quantity Lubrication. *The International Journal of Advanced Manufacturing Technology* : 1711–1722. 115/5.

[163] Mang, T., U. Hanschke, H.G. Theis, *Splitting and Disposal of Metalworking Fluids*, in *Encyclopedia of Lubricants and Lubrication*, T. Mang, 2014, Springer Berlin Heidelberg: Berlin, Heidelberg. p. 1942–1948.

[164] Mann JB, Guo Y, Saldana C, Yeung H, Compton WD, Chandrasekar S (2011) Modulation-Assisted Machining: A New Paradigm In Material Removal Processes. *Advanced Materials Research* : 514–522. 223/.

[165] Mapal, Bore Machining, Mapal. [Online]. Available: https://mapal.com/en-int/media/catalogues/boremachining. [Accessed: 02-Feb-2023].

[166] Mapal, 2018, Miniaturisation In Clamping Technology Thanks To Additive Manufacturing Mapal. [Online]. Available: https://mapal.com/en-int/a/miniSpanntechnik. [Accessed: 02-Feb-2023].

[167] Mapal, 2023, Social Responsibility, MAPAL. [Online]. Available: https://mapal.com/en-int/product-innovations-2023/sustainability. [Accessed: 02-Feb-2023].

[168] Marimuthu S, Kamara A, Whitehead D, Mativenga P, Li L (2010) Laser Removal Of TiN Coatings From WC Micro-Tools And In-Process Monitoring. *Optics & Laser Technology* : 1233–1239. 42/8.

[169] Mawson VJ, Hughes BR (2019) The Development Of Modelling Tools To Improve Energy Efficiency In Manufacturing Processes And Systems. *Journal of Manufacturing Systems* : 95–105. 51/.

[170] May G, Stahl B, Taisch M, Kiritsis D (2017) Energy Management In Manufacturing: From Literature Review To A Conceptual Framework. *Journal of cleaner production* : 1464–1489. 167/.

[171] Mazurkiewicz, M., Z. Kubala, J. Chow, 1989, Metal Machining With High-Pressure Water-Jet Cooling Assistance—A New Possibility,

[172] Metalworking Fluids Standard Advisory Committee (MWFSAC), 2023, Metalworking Fluids: Safety and Health Best Practices Manual, Occupational Safety and Health Administration, https://www.osha.gov/metalworking-fluids/manual

[173] Meyer D, Redetzky M, Brinksmeier E (2017) Microbial-Based Metalworking Fluids In Milling Operations. *CIRP Annals* : 129–132. 66/1.

[174] Mitsubishi Materials, B228A Ceramic End Mills, Ultra High Productivity For Nickel Based Heat Resistant Alloys. [Online]. Available: https://www.mitsubishicarbide.com/mmus/catalog/pdf/b/b228a.pdf. [Accessed: 02-Mar-2023]. Mitsubishi Carbide

[175] MMR, 2022, Tungsten Market - Global Industry Analysis and Forecast (2022-2029), Maximize Market Research. [Online]. Available: https://www.maximizemarketresearch.com/market-report/global-tungsten-market/25066/. [Accessed: 08-Feb-2023].

[176] Möhring H-C, Werkle KT (2022) Lightweight Semi-Actively Damped High Performance Milling Tool. *CIRP Annals* : 353–356. 71/1.

[177] Muthuswamy P (2022) Investigation On Sustainable Machining Characteristics Of Tools With Serrated Cutting Edges In Face Milling Of AISI 304 Stainless Steel. *Procedia CIRP* . 105/865-871.

[178] Newman ST, Nassehi A, Imani-Asrai R, Dhokia V (2012) Energy Efficient Process Planning For CNC Machining. *CIRP Journal of Manufacturing Science and Technology* : 127–136. 5/2.

[179] NIOSH, 1998, What You Need To Know About: Occupational Exposure To Metalworking Fluids, U.S. Department Of Health And Human Services

[180] Norrby T, Wedin P (2017) How Base Oil Selection Determines Metalworking Fluid Emulsion Stability. *Lube-Tech* : 14–17. 139/.

[181] Nouzil I, Eltaggaz A, Deiab I, Pervaiz S (2020) Toxicity of Nanoparticles Used in Minimum Quantity Lubrication (MQL) Machining: A Sustainability Analysis. *ASME International Mechanical Engineering Congress and Exposition*, . American Society of Mechanical Engineers.

[182] Nouzil I, Eltaggaz A, Pervaiz S, Deiab I (2022) Toxicity Analysis of Nano-Minimum Quantity Lubrication Machining—A Review. *Lubricants* : 176.. 10/8.

[183] Novovic D, Dewes R, Aspinwall D, Voice W, Bowen P (2004) The Effect Of Machined Topography And Integrity On Fatigue Life. *International Journal of Machine Tools and Manufacture* : 125–134. 44/2-3.

[184] Nykvist, B., Å. Persson, L. Persson, 2013, National Environmental Performance On Planetary Boundaries - A study For the Swedish Environmental Protection Agency, Report 6576, Stockholm.

[185] O'Neill DW, Fanning AL, Lamb WF, Steinberger JK (2018) A Good Life For All Within Planetary Boundaries. *Nature Sustainability* : 88–95. 1/2.

[186] Oerlikon Balzers, BALINIT MAYURA - Die nächste Schichtgeneration für die Verarbeitung von Nichteisenwerkstoffen, Oerlikon Balzers. [Online]. Available: https://www.oerlikon.com/balzers/de/de/portfolio/balzers-oberflaechenloesungen/pvd-und-pacvd-basierte-beschichtungsloesungen/balinit/kohlenstoff-dlc-basierte/balinit-mayura/. [Accessed: 01-Feb-2023].

[187] Office of Energy Efficiency and Renewable Energy, 2022, Advanced Manufacturing & Industrial Decarbondation: Analysis finds Decrease in U.S. Manufacturing Energy Consumption, [Online]. Available: https://www.energy.gov/eere/amo/articles/analysis-finds-decrease-us-manufacturing-energy-consumption [Accessed: 11-June-2023]

[188] Okafor AC, Nwoguh TO (2020) Comparative Evaluation Of Soybean Oil–Based MQL Flow Rates And Emulsion Flood Cooling Strategy In High-Speed Face Milling Of Inconel 718. *The International Journal of Advanced Manufacturing Technology* : 3779–3793. 107/9.

[189] Okuma, ECO Suite Plus. 2021, Okuma Corporation Marketing Office.

[190] Omole S, Dogan H, Lunt AJG, Kirk S, Shokrani A (2023) Using Machine Learning For Cutting Tool Condition Monitoring And Prediction During Machining Of Tungsten. *International Journal of Computer Integrated Manufacturing* : 1–25.

[191] Ortiz-de-Zarate G, Madariaga A, Childs TH, Arrazola PJ (2022) Surface Topography Irregularities Generated By Broaching. *CIRP Annals* : 105–108. 71/1.

[192] Our World in Data, 2022, Electricity Consumption From Fossil Fuels, Nuclear And Renewables, 2022, Our World in Data. [Online]. Available: https://ourworldindata.org/grapher/elec-mix-bar. [Accessed: 10-Sep-2023].

[193] Ouyang J, Mativenga PT, Liu Z, Li L (2021) Energy Consumption And Process Characteristics Of Picosecond Laser De-Coating Of Cutting Tools. *Journal of Cleaner Production* . 290/125815.

[194] Özel T, Biermann D, Enomoto T, Mativenga P (2021) Structured And Textured Cutting Tool Surfaces For Machining Applications. *CIRP Annals* : 495–518. 70/2.

[195] Pal A, Chatha SS, Sidhu HS (2021) Performance Evaluation Of The Minimum Quantity Lubrication With Al2o3-Mixed Vegetable-Oil-Based Cutting Fluid In Drilling Of AISI 321 Stainless Steel. *Journal of Manufacturing Processes* : 238–249. 66/.

[196] Park K-H, Suhaimi MA, Yang G-D, Lee D-Y, Lee S-W, Kwon P (2017) Milling Of Titanium Alloy With Cryogenic Cooling And Minimum Quantity Lubrication (MQL). *International Journal of Precision Engineering and Manufacturing* : 5–14. 18/1.

[197] Park RM (2018) Risk Assessment For Metalworking Fluids And Cancer Outcomes. *American Journal of Industrial Medicine* : 198–203. 61/3.

[198] Passman FJ, Küenzi P (2020) Microbiology in Water-Miscible Metalworking Fluids. *Tribology Transactions* : 1147–1171. 63/6.

[199] Peng T, Ou X, Yan X, Wang G (2019) Life-Cycle Analysis Of Energy Consumption And GHG Emissions Of Aluminium Production In China. *Energy Procedia* : 3937–3943. 158/.

[200] Peng T, Xu X (2014) Energy-Efficient Machining Systems: A Critical Review. *The International Journal of Advanced Manufacturing Technology* : 1389–1406. 72/.

[201] Pereira O, Celaya A, Urbikaín G, Rodríguez A, Fernández-Valdivielso A, Lacalle LNLd (2020) CO2 Cryogenic Milling Of Inconel 718: Cutting Forces And Tool Wear. *Journal of Materials Research and Technology* : 8459–8468. 9/4.

[202] Pereira O, Martín-Alfonso J, Rodríguez A, Calleja A, Fernández-Valdivielso A, De Lacalle LL (2017) Sustainability Analysis Of Lubricant Oils For Minimum Quantity Lubrication Based On Their Tribo-Rheological Performance. *Journal of Cleaner Production* : 1419–1429. 164/.

[203] Pereira O, Rodríguez A, Fernández-Abia A, Barreiro J, de Lacalle LL (2016) Cryogenic And Minimum Quantity Lubrication For An Eco-Efficiency Turning Of AISI 304. *Journal of Cleaner Production* : 440–449. 139/.

[204] Pervaiz S, Anwar S, Qureshi I, Ahmed N (2019) Recent Advances in the Machining of Titanium Alloys using Minimum Quantity Lubrication (MQL) Based Techniques. *International Journal of Precision Engineering and Manufacturing-Green Technology* : 133–145. 6/1.

[205] Pervaiz S, Kannan S, Deiab I, Kishawy H (2020) Role Of Energy Consumption, Cutting Tool And Workpiece Materials Towards Environmentally Conscious

Machining: A Comprehensive Review. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* : 335–354. 234/3.
[206] Pfefferkorn FE, Lei S, Jeon Y, Haddad G (2009) A Metric For Defining The Energy Efficiency Of Thermally Assisted Machining. *International Journal of Machine Tools and Manufacture* : 357–365. 49/5.
[207] Pigott R, Colwell A (1952) *Hi-jet System For Increasing Tool Life*, SAE Technical Paper.
[208] Pinheiro CT, Quina MJ, Gando-Ferreira LM (2021) Management Of Waste Lubricant Oil In Europe: A Circular Economy Approach. *Critical Reviews in Environmental Science and Technology* : 2015–2050. 51/18.
[209] Polvorosa R, de Lacalle LL, Egea AS, Fernandez A, Esparta M, Zamakona I (2020) Cutting Edge Control By Monitoring The Tapping Torque Of New And Resharpened Tapping Tools In Inconel 718. *The International Journal of Advanced Manufacturing Technology* : 3799–3808. 106/.
[210] Precedence Research, 2023, Machining Market, Report Number: 2997, Precedence-Research. [Online]. Available: https://www.precedenceresearch.com/machining-market. [Accessed: 09-Sep-2023].
[211] Priarone PC, Campatelli G, Montevecchi F, Venturini G, Settineri L (2019) A Modelling Framework For Comparing The Environmental And Economic Performance of WAAM-Based Integrated Manufacturing And Machining. *CIRP Annals* : 37–40. 68/1.
[212] Priarone PC, Ingarao G (2017) Towards Criteria For Sustainable Process Selection: On The Modelling Of Pure Subtractive Versus Additive/Subtractive Integrated Manufacturing Approaches. *Journal of Cleaner Production* : 57–68. 144/.
[213] Priarone PC, Ingarao G, di Lorenzo R, Settineri L (2017) Influence Of Material-Related Aspects Of Additive And Subtractive Ti-6Al-4V Manufacturing On Energy Demand And Carbon Dioxide Emissions. *Journal of Industrial Ecology* : S191–S202. 21/S1.
[214] Priarone PC, Robiglio M, Settineri L, Tebaldo V (2016) Modelling Of Specific Energy Requirements In Machining As A Function Of Tool And Lubricoolant Usage. *CIRP Annals* : 25–28. 65/1.
[215] Pušavec F, Kopač J (2011) Sustainability Assessment: Cryogenic Machining of Inconel 718. *Strojniški vestnik-Journal of Mechanical Engineering* : 637–647. 57/9.
[216] Pusavec F, Krajnik P, Kopac J (2010) Transitioning To Sustainable Production–Part I: Application On Machining Technologies. *Journal of Cleaner production* : 174–184. 18/2.
[217] Qazi, A., F. Hussain, N.A. Rahim, G. Hardaker, D. Alghazzawi, K. Shaban, K. Haruna, 2019, Towards Sustainable Energy: A Systematic Review Of Renewable Energy Sources, Technologies, And Public Opinions, IEEE Access 7/63 837–63851.
[218] Qin X, Huang W, Wang X, Tang Z, Liu Z (2022) Real-Time Remaining Useful Life Prediction of Cutting Tools Using Sparse Augmented Lagrangian Analysis and Gaussian Process Regression. *Sensors* : 413.. 23/1.
[219] Rahim SNA, Lajis MA, Ariffin S (2015) A Review on Recycling Aluminum Chips by Hot Extrusion Process. *Procedia CIRP* : 761–766. 26/.
[220] Rahimifard S, Seow Y, Childs T (2010) Minimising Embodied Product Energy To Support Energy Efficient Manufacturing. *CIRP Annals* : 25–28. 59/1.
[221] Rankin J (2012) Energy Use in Metal production. In: Proceedings of the High Temperature Processing Symposium, Swinburne University of Technology, .
[222] Raworth K (2017) *Doughnut Economics: Seven Ways to Think Like a 21st-century Economist*, Chelsea Green Publishing.
[223] Raworth K (2012) *A Safe and Just Space For humanity: Can We Live Within the Doughnut?* Oxfam.
[224] Richter, A., 2022, Add To Subtract, Cutting Tool Engineering. [Online]. Available: https://www.ctemag.com/news/articles/add-subtract. [Accessed: 03-Mar-2023].
[225] Riediger D, Hinrichsen S, Schlee A (2015) Ergonomic Design of Graphical Control Elements on Production Machines. *Production Engineering and Management* 1.
[226] Rief M, Karpuschewski B, Kalhoefer E (2017) Evaluation And Modeling Of The Energy Demand During Machining. *CIRP Journal of Manufacturing Science and Technology* . 19/62-71.
[227] Ritchie, H., M. Roser, P. Rosado, 2022, Energy, Published Online at OurWorldInData.org. https://ourworldindata.org/energy [Online Resource] [Accessed: 03-Mar-2023].
[228] Rizzo A, Goel S, Luisa Grilli M, Iglesias R, Jaworska L, Lapkovskis V, Novak P, Postolnyi BO, Valerini D (2020) The Critical Raw Materials In Cutting Tools For Machining Applications: A Review. *Materials* : 1377.. 13/6.
[229] Rockström J, Steffen W, Noone K, Persson Å, Chapin FS, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A Safe Operating Space For Humanity. *Nature* : 472–475. 461/7263.
[230] Rodriguez I, Arrazola PJ, Cuesta M, Sterle L, PuŠAvec F (2023) Improving Surface Integrity When Drilling CFRPs and Ti-6Al-4V Using Sustainable Lubricated Liquid Carbon Dioxide. *Chinese Journal of Aeronautics* : 129–146. 36/7.
[231] Salem A, Hopkins C, Imad M, Hegab H, Darras B, Kishawy HA (2020) Environmental Analysis Of Sustainable And Traditional Cooling And Lubrication Strategies During Machining Processes. *Sustainability* : 8462.. 12/20.
[232] Sandvik Coromant, 2024, Carbide Recycling, Sandvik Coromant. [Online]. Available: https://www.sandvik.coromant.com/en-gb/services/recycling. [Accessed: 26-Mar-2024].
[233] Sandvik Coromant, CoroMill® 745, Sandvik Coromant. [Online]. Available: https://www.sandvik.coromant.com/en-gb/tools/milling-tools/face-milling-tools/coromill-745. [Accessed: 10-Sep-2023].
[234] Sandvik Coromant, 2023, Sustainable Business, Sandvik Coromant. [Online]. Available: https://www.sandvik.coromant.com/en-gb/about-us/sustainable-business. [Accessed: 08-Feb-2023].
[235] Schaeffler Group, 2021, Sustainability Report 2021, [Online]. Available: https://www.schaeffler.com/remotemedien/media/_shared_media_rwd/01_company_1/sustainability/2021_sustainability_report/2021_schaeffler_sustainability_report_en_71zvps.pdf. [Accessed: 02-Aug-2023],
[236] Schaeffler Group, 2022, Sustainability Report 2022, [Online]. Available: https://www.schaeffler-sustainability-report.com/2022/servicepages/downloads/files/entire-schaeffler-sr22.pdf. [Accessed: 02-Aug-2023],
[237] Schischke, K., E. Hohwieler, R. Feitscher, J. König, S. Kreuschner, N.F. Nissen, P. Wilpert, 2012, Energy-Using Product Group Analysis - LOT 5, Machine Tools And Related Machinery, Fraunhofer IZM. [Online]. Available: https://tes.bam.de/Netzwerke/Content/DE/Downloads/Evpg/Industrie/405_vorstudie.pdf?__blob=publicationFile [Accessed: 20-May-2024].
[238] Schowanek D, Borsboom-Patel T, Bouvy A, Colling J, de Ferrer JA, Eggers D, Groenke K, Gruenenwald T, Martinsson J, McKeown P, Miller B, Moons S, Niedermann K, Pérez M, Schneider C, Viot J-F (2018) New And Updated Life Cycle Inventories For Surfactants Used In European Detergents: Summary Of The ERASM Surfactant Life Cycle And Ecofootprinting Project. *The International Journal of Life Cycle Assessment* : 867–886. 23/4.
[239] Schubert, W.-.D., B. Zeiler, I. Secretary-General, 2019, Recycling of Tungsten, Tungsten Newletter August
[240] Schulze A, Hering O, Tekkaya AE (2022) Production and Subsequent Forming of Chip-Based Aluminium Sheets Without Remelting. *International Journal of Precision Engineering and Manufacturing-Green Technology* : 1035–1048. 9/4.
[241] Seco Tools, Recondition Machining Tools: When (And How) Is Right Doing It, Seco Tools. [Online]. Available: https://www.secotools.com/article/538?language=en. [Accessed: 03-Mar-2023].
[242] Seco Tools, 2024, Recycling, Our Commitment To Long-Term Sustainability, Seco Tools. [Online]. Available: https://www.secotools.com/article/539. [Accessed: 26-Mar-2024].
[243] Seco Tools, 2020, Zero Waste For A Low Carbon Future, Seco Tools. [Online]. Available: https://www.secotools.com/article/113119?language=en. [Accessed: 01-Mar-2023].
[244] Seid Ahmed Y, Paiva JM, Veldhuis SC (2019) Characterization And Prediction Of Chip Formation Dynamics In Machining Austenitic Stainless Steel Through Supply Of A High-Pressure Coolant. *The International Journal of Advanced Manufacturing Technology* : 1671–1688. 102/.
[245] Seleznev A, Pinargote NWS, Smirnov A (2021) Ceramic Cutting Materials And Tools Suitable For Machining High-Temperature Nickel-Based Alloys: A Review. *Metals* : 1385.. 11/9.
[246] Sen B, Mia M, Mandal UK, Mondal SP (2020) Synergistic Effect Of Silica And Pure Palm Oil On The Machining Performances Of Inconel 690: A Study For Promoting Minimum Quantity Nano Doped-Green Lubricants. *Journal of Cleaner Production* :120755. 258/.
[247] Shemi A, Magumise A, Ndlovu S, Sacks N (2018) Recycling Of Tungsten Carbide Scrap Metal: A Review Of Recycling Methods And Future Prospects. *Minerals Engineering* : 195–205. 122/.
[248] Shen J, Liu B, Wu J, Chai Y, Cheng C, Liu C, Yan R, Saleem Khan MF (2020) Characterization Of Fluorescent Dissolved Organic Matters In Metalworking Fluid By Fluorescence Excitation-Emission Matrix And High-Performance Liquid Chromatography. *Chemosphere* :124703. 239/.
[249] Shi Q, Tse YY, Higginson RL (2016) Effects of Processing Parameters On Relative Density, Microhardness And Microstructure Of Recycled Ti–6Al–4V From Machining Chips Produced By Equal Channel Angular Pressing. *Materials Science and Engineering: A* : 248–258. 651/.
[250] Shokrani A, Al-Samarrai I, Newman ST (2019) Hybrid Cryogenic MQL For Improving Tool Life In Machining Of Ti-6Al-4V Titanium Alloy. *Journal of Manufacturing Processes* : 229–243. 43/.
[251] Shokrani A, Betts J (2020) A New Hybrid Minimum Quantity Lubrication System For Machining Difficult-To-Cut Materials. *CIRP Annals* : 73–76. 69/1.
[252] Shokrani A, Betts J, Carnevale M (2021) Thermal Analysis In MQL End Milling Operations. *Procedia CIRP* : 358–361. 101/.
[253] Shokrani A, Betts J, Jawahir IS (2022) Improved Performance And Surface Integrity In Finish Machining of Inconel 718 With Electrically Charged Tungsten Disulphide MQL. *CIRP Annals* : 109–112. 71/1.
[254] Shokrani A, Dhokia V, Muñoz-Escalona P, Newman ST (2013) State-Of-The-Art Cryogenic Machining And Processing. *International Journal of Computer Integrated Manufacturing* : 616–648. 26/7.
[255] Shokrani A, Dhokia V, Newman S (2016) Modelling And Verification Of Energy Consumption In CNC Milling. *Sustainable Design and Manufacturing 2016*, Springer.
[256] Shokrani A, Dhokia V, Newman ST (2018) Energy Conscious Cryogenic Machining Of Ti-6Al-4V Titanium Alloy. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* : 1690–1706. 232/10.
[257] Shokrani A, Dhokia V, Newman ST (2012) Environmentally Conscious Machining Of Difficult-To-Machine Materials With Regard To Cutting Fluids. *International Journal of Machine Tools and Manufacture* : 83–101. 57/.
[258] Shokrani, A., V. Dhokia, S.T. Newman, 2014, A Techno-Health Study Of The Use Of Cutting Fluids And Future Alternatives,
[259] Shokrani A, Newman ST (2018) Hybrid Cooling And Lubricating Technology For CNC Milling of Inconel 718 Nickel Alloy. *Procedia CIRP* : 215–218. 77/.
[260] Sílvia R-C, Lauro C, Ana H, Davim J (2022) Development Of FEM-Based Digital Twins For Machining Difficult-To-Cut Materials: A Roadmap For Sustainability. *Journal of Manufacturing Processes* : 739–766. 75/.
[261] Singh R, Dureja JS, Dogra M, Kumar Gupta M, Jamil M, Mia M (2020) Evaluating The Sustainability Pillars Of Energy And Environment Considering Carbon Emissions Under Machining of Ti-3Al-2.5V. *Sustainable Energy Technologies and Assessments* . 42/100806.
[262] Skerlos SJ, Hayes KF, Clarens AF, Zhao F (2008) Current Advances In Sustainable Metalworking Fluids Research. *International journal of sustainable manufacturing* : 180–202. 1/1-2.
[263] Sousa JA, Sousa MN, Jackson MJ, Machado AR (2014) Comparison Of The Steel Machining Performance Of New And Reground Cemented Carbide Drills. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture* : 376–387. 228/3.
[264] Srivastava RR, Lee J-c, Bae M, Kumar V (2019) Reclamation Of Tungsten From Carbide Scraps And Spent Materials. *Journal of Materials Science* : 83–107. 54/.
[265] Stoldt J, Schlegel A, Franz E, Langer T, Putz M (2013) Generic Energy-Enhancement Module For Consumption Analysis of Manufacturing Processes in Discrete

Event Simulation. *in* Re-engineering Manufacturing For Sustainability, Springer SingaporeSingapore.
[266] Suárez Fernández D, Wynne BP, Crawforth P, Fox K, Jackson M (2021) The Effect Of Forging Texture And Machining Parameters On The Fatigue Performance Of Titanium Alloy Disc Components. *International Journal of Fatigue* . 142/105949.
[267] Sultana MN, Dhar NR, Zaman PB (2019) A Review On Different Cooling/Lubrication Techniques In Metal Cutting. *American Journal of Mechanics and Applications* : 71–87. 7/4.
[268] Sun H, Liu Y, Pan J, Zhang J, Ji W (2020) Enhancing Cutting Tool Sustainability Based On Remaining Useful Life Prediction. *Journal of Cleaner Production* . 244/118794.
[269] Sutherland JW, Richter JS, Hutchins MJ, Dornfeld D, Dzombak R, Mangold J, Robinson S, Hauschild MZ, Bonou A, Schönsleben P, Friemann F (2016) The Role Of Manufacturing In Affecting The Social Dimension Of Sustainability. *CIRP Annals* : 689–712. 65/2.
[270] Tanabe I, Yamagami Y, Hoshino H (2020) Development Of A New High-Pressure Cooling System For Machining Of Difficult-To-Machine Materials. *Journal of Machine Engineering* : 82–97. 20/1.
[271] Tao P, Xun X (2012) The State Of The Art In Energy Consumption Model–The Key To Sustainable Machining. *Applied Mechanics and Materials* : 592–599. 232/.
[272] Tapoglou N, Taylor C, Makris C (2021) Milling Of Aerospace Alloys Using Supercritical CO2 Assisted Machining. *Procedia CIRP* : 370–373. 101/.
[273] Tasdelen B, Thordenberg H, Olofsson D (2008) An Experimental Investigation On Contact Length During Minimum Quantity Lubrication (MQL) Machining. *Journal of Materials Processing Technology* : 221–231. 203/1.
[274] Teti R, D'Addona D, Segreto T (2021) Microbial-Based Cutting Fluids As Bio-Integration Manufacturing Solution For Green And Sustainable Machining. *CIRP Journal of Manufacturing Science and Technology* : 16–25. 32/.
[275] Teti R, Jemielniak K, O'Donnell G, Dornfeld D (2010) Advanced Monitoring Of Machining Operations. *CIRP Annals* : 717–739. 59/2.
[276] Teti R, Mourtzis D, D'Addona DM, Caggiano A (2022) Process Monitoring Of Machining. *CIRP Annals* : 529–552. 71/2.
[277] Thellufsen JZ, Lund H, Sorknæs P, Østergaard P, Chang M, Drysdale D, Nielsen S, Djørup S, Sperling K (2020) Smart Energy Cities In A 100% Renewable Energy Context. *Renewable and Sustainable Energy Reviews* . 129/109922.
[278] Torres-Carrillo S, Siller HR, Vila C, López C, Rodríguez CA (2020) Environmental Analysis Of Selective Laser Melting In The Manufacturing Of Aeronautical Turbine Blades. *Journal of Cleaner Production* . 246/119068.
[279] Traverso, M., S. Valdivia, A. Luthin, L. Roche, G. Arcese, S. Neugebauer, L. Petti, M. D'Eusanio, B. Tragnone, R. Mankaa, 2021, Methodological Sheets For Subcategories In Social Life Cycle Assessment (S-LCA) 2021, United Nations Environment Programme (UNEP)
[280] UKLA. *Good Practice Guide for Safe Handling and Disposal of Metalworking Fluids*, United Kingdom Lubricant Association.
[281] University of Cambridge Institute for Sustainability Leadership (CISL). *Linking Planetary Boundaries to business: The first White Paper in Kering's series On Planetary Boundaries For Business*, Cambridge Institute for Sustainability Leadership-Cambridge, UK.
[282] Vakulchuk, R., I. Overland, D. Scholten, 2020, Renewable Energy And Geopolitics: A Review, Renewable And Sustainable Energy Reviews 122/109547.
[283] Vasumathy D, Meena A (2017) Influence Of Micro Scale Textured Tools On Tribological Properties At Tool-Chip Interface In Turning AISI 316 Austenitic Stainless Steel. *Wear* : 1747–1758. 376/.
[284] Vila C, Abellán-Nebot JV, Siller-Carrillo HR (2015) Study of Different Cutting Strategies for Sustainable Machining of Hardened Steels. *Procedia Engineering* : 1120–1127. 132/.
[285] VKIS VSI IGM BGHM, 2022, List of Substances for Metal Working Fluids According To DIN 51385 For Metal Working, VSI. [Online]: Available: https://www.vsi-schmierstoffe.de/fileadmin/user_upload/PDFs/VKIS_Richtlinien/VKIS-VSI-IGM-BGHM-Liste_EN_22_Auflage.pdf. [Accessed: 05-Mar-2023].
[286] Volke P, Brock G, Berger S, Saelzer J, Nickel J, Biermann D (2022) Sustainable Production of Rotationally Symmetrical Components: Approaches to Resource Saving on Tool and Workpiece. *ASME International Mechanical Engineering Congress and Exposition*, . American Society of Mechanical Engineers.
[287] Volkov G, Bratov V, Gruzdkov A, Babitsky V, Petrov YV, Silberschmidt V (2011) Energy-Based Analysis Of Ultrasonically Assisted Turning. *Shock and Vibration* : 333–341. 18/1-2.
[288] Wagiman A, Mustapa MS, Asmawi R, Shamsudin S, Lajis MA, Mutoh Y (2020) A Review On Direct Hot Extrusion Technique In Recycling Of Aluminium Chips. *The International Journal of Advanced Manufacturing Technology* : 641–653. 106/1.
[289] Wang C, Lin H, Wang X, Zheng L, Xiong W (2017) Effect Of Different Oil-On-Water Cooling Conditions On Tool Wear In Turning Of Compacted Graphite Cast Iron. *Journal of Cleaner Production* : 477–489. 148/.
[290] Wang X, Zhou Y, Wang F, Jiang X, Yang Y (2021) Exposure Levels Of Oil Mist Particles Under Different Ventilation Strategies In Industrial Workshops. *Building and Environment* . 206/108264.
[291] Wang Y, Zhang D, Ji Q, Shi X (2020) Regional Renewable Energy Development In China: A Multidimensional Assessment. *Renewable and Sustainable Energy Reviews* . 124/109797.
[292] Watanabe H, Moriwaki K, Mukai T, Ishikawa K, Kohzu M, Higashi K (2001) Consolidation Of Machined Magnesium Alloy Chips By Hot Extrusion Utilizing Superplastic Flow. *Journal of Materials Science* : 5007–5011. 36/20.
[293] Wędrychowicz M, Wzorek Ł, Tokarski T, Noga P, Wiewióra J (2016) Recycling Without Melting: An Alternative Approach To Aluminum Scrap Recovery. *Key Engineering Materials* . Trans Tech Publ.
[294] Weinert K, Inasaki I, Sutherland JW, Wakabayashi T (2004) Dry Machining and Minimum Quantity Lubrication. *CIRP Annals - Manufacturing Technology* : 511–537. 53/2.
[295] Wickramasinghe, K., H. Sasahara, E. Abd Rahim, G. Perera, 2020, Green Metalworking Fluids For Sustainable Machining Applications: A Review, Journal of Cleaner Production 257/120552.
[296] Wolfe T, Shah R, Prough K, Trasorras JL (2023) Coarse Cemented Carbide Produced Via Binder Jetting 3D Printing. *International Journal of Refractory Metals and Hard Materials* . 110/106016.
[297] World Commission on Environment and Development, 1987, Report of the World Commission on Environment and Development: Our Common Future (Brundtland Report), United Nations, Annex to document A/42/427 - Development and International Cooperation: Environment.
[298] Wu Y, Su D (2020) Social Life Cycle Assessment. in Su D, (Ed.) *Sustainable Product Development: Tools, Methods and Examples*, Springer International Publishing, Cham, 127–152.
[299] Xiao Q, Li C, Tang Y, Li L (2019) Meta-Reinforcement Learning Of Machining Parameters For Energy-Efficient Process Control Of Flexible Turning Operations. *IEEE Transactions on Automation Science and Engineering* : 5–18. 18/1.
[300] Yan J, Feng C, Li L (2014) Sustainability Assessment Of Machining Process Based On Extension Theory And Entropy Weight Approach. *The International Journal of Advanced Manufacturing Technology* : 1419–1431. 71/5.
[301] Yang Y, Zhang C, Wang D, Nie L, Wellmann D, Tian Y (2020) Additive Manufacturing Of WC-Co Hardmetals: A Review. *The International Journal of Advanced Manufacturing Technology* : 1653–1673. 108/.
[302] Yingjie Z (2014) Energy Efficiency Techniques In Machining Process: A Review. *The International Journal of Advanced Manufacturing Technology* : 1123–1132. 71/.
[303] Yoon H-S, Kim E-S, Kim M-S, Lee J-Y, Lee G-B, Ahn S-H (2015) Towards Greener Machine Tools–A Review On Energy Saving Strategies And Technologies. *Renewable and Sustainable Energy Reviews* : 870–891. 48/.
[304] Zadafiya K, Shah P, Shokrani A, Khanna N (2021) Recent Advancements In Nano-Lubrication Strategies For Machining Processes Considering Their Health And Environmental Impacts. *Journal of Manufacturing Processes* : 481–511. 68/.
[305] Zailani ZA, Mativenga PT (2016) Effects of Chilled Air on Machinability of NiTi Shape Memory Alloy. *Procedia CIRP* : 207–210. 45/.
[306] Zeiler B, Bartl A, Schubert W-D (2021) Recycling Of Tungsten: Current Share, Economic Limitations, Technologies And Future Potential. *International Journal of Refractory Metals and Hard Materials* . 98/105546.
[307] Zerspanungstechnik, 2014, Punch Tap von Emuge-Franken - Helikal-Gewindeformen, Zerspanungstechnik. [Online]. Available: https://www.zerspanungstechnik.com/bericht/gewindeformer/helikal_gewindeformen-2014-10-14. [Accessed: 06-Feb-2023].
[308] Zerspanungstechnik, 2020, Taptor von Emuge-Franken - Zeit einsparen bei der Innengewindefertigung, Zerspanungstechnik. [Online]. Available: https://www.zerspanungstechnik.com/bericht/gewindebohrer/zeit_einsparen_bei_der_innengewindefertigung_-2020-06-25. [Accessed: 06-Feb-2023].
[309] Zhang S, Li JF, Wang YW (2012) Tool Life And Cutting Forces In End Milling Inconel 718 Under Dry And Minimum Quantity Cooling Lubrication Cutting Conditions. *Journal of Cleaner Production* : 81–87. 32/.
[310] Zhao G, Liu Z, He Y, Cao H, Guo Y (2017) Energy Consumption In Machining: Classification, Prediction, And Reduction Strategy. *Energy* : 142–157. 133/.
[311] Zhao J, Liu Z, Wang B, Hu J, Wan Y (2021) Tool Coating Effects On Cutting Temperature During Metal Cutting Processes: Comprehensive Review And Future Research Directions. *Mechanical Systems and Signal Processing* :107302. 150/.
[312] Zhou L, Li J, Li F, Meng Q, Li J, Xu X (2016) Energy Consumption Model And Energy Efficiency Of Machine Tools: A Comprehensive Literature Review. *Journal of Cleaner Production* : 3721–3734. 112/.
[313] Zhou Y, Xue W (2018) Review Of Tool Condition Monitoring Methods In Milling Processes. *The International Journal of Advanced Manufacturing Technology* : 2509–2523. 96/.
[314] Zhu S, Cheng J, Qiao Z, Yang J (2019) High Temperature Solid-Lubricating Materials: A Review. *Tribology International* : 206–223. 133/.
[315] Zimmermann M, Kirsch B, Kang Y, Herrmann T, Aurich JC (2020) Influence Of The Laser Parameters On The Cutting Edge Preparation And The Performance Of Cemented Carbide Indexable Inserts. *Journal of Manufacturing Processes* : 845–856. 58/.
[316] Zimmermann R, Welling D, Venek T, Ganser P, Bergs T (2021) Tool Wear Progression Of SiAlON Ceramic End Mills In Five-Axis High-Feed Rough Machining Of An Inconel 718 BLISK. *Procedia CIRP* . 101/13-16.
[317] Zupanc U, Grum J (2010) Effect Of Pitting Corrosion On Fatigue Performance Of Shot-Peened Aluminium Alloy 7075-T651. *Journal of Materials Processing Technology* : 1197–1202. 210/9.