Sustainable Machining Practices during Milling Process: A Review

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Abstract: Milling is a crucial manufacturing process for precision components in industries like aerospace and automobiles. This review delves into the past, present, and future of milling. It highlights that limited research exists on the historical context, current state, and future prospects of milling. In today's era of information and environmental consciousness, sustainability is a growing concern in all research domains, including milling. Research in milling is increasingly focused on ecological aspects such as reducing cutting fluid consumption through automatic flood cooling, minimum quantity lubrication, cryogenics, hybrid lubrication, and enhancing tool life via critical tool modifications. Notable findings include cutting tool enhancements (coating/texturing), advanced cooling techniques (e.g., MQL, Nano MQL, Cryogenic cooling), automatic flood cooling with on/off control, and versatile coolant supply methods, all poised to be pivotal research areas.

Keywords: sustainable manufacturing, sustainable machining practices, sustainable milling

1. INTRODUCTION

Sustainable manufacturing (SM) practices have gained prominence due to global market competition and rising carbon emissions. Industries are increasingly recognizing the urgent need to address environmental impacts and resource depletion. SM aligns with the idea of "sustainable development" outlined in the Brundtland report, aiming to meet present needs without compromising those of future generations [1]. Sustainability encompasses three dimensions: environmental, economic, and societal aspects [2], prompting governments to enact robust legislation to combat pollution and health issues stemming from modern manufacturing. The core principle of triple bottom line sustainability underscores the interconnectedness of the economy, society, and environment. The U.S. Department of Commerce defines sustainable manufacturing as producing goods with processes that minimize environmental harm, conserve resources, ensure safety for all stakeholders, and remain economically viable [3]. Essentially, it involves efficient resource use, seeking renewable alternatives, and potentially delivering both environmental and financial advantages [4]. As consumer preferences and environmental regulations intensify, industries increasingly focus on reducing their environmental footprint while complying with stringent rules. Sustainable machining, situated within the broader context of sustainable manufacturing, represents a critical frontier in modern industrial practices [5]. This paradigm shift in machining processes is fueled by the urgent need to minimize the environmental footprint of Sustainable machining transcends conventional approaches by prioritizing resource efficiency, reducing energy consumption, curbing emissions, and incorporating innovative cooling and lubrication techniques [6]. As industries worldwide grapple with mounting ecological concerns and heightened regulatory scrutiny, the integration of sustainable machining practices has become not just a choice but a necessity [7]. Machining processes entail the precision shaping of parts through cutting operations in machine tools, aiming for predetermined dimensions and surface quality [8]. Techniques like turning, milling, drilling, and grinding are common for achieving high precision and intricate geometries. However, challenges arise when machining difficult-to-machine alloys, such as heat-assisted alloys and composites, due to their superior thermo-mechanical properties [9]. Modern alloys with low thermal conductivity often result in excess heat and cutting force, limiting surface quality and tool life, leading to higher machining costs [10]. Sustainable manufacturing aims to mitigate these issues, striving for environmentally friendly, cost-effective, and health-conscious production practices, addressing economic, environmental, and health concerns associated with conventional cooling methods. Fundamentally, the integration of sustainable practices into machining processes is crucial [11]. This requires a thorough exploration to clarify the methodologies used to comprehensively determine sustainable aspects in machining. To achieve this, the review aims to precisely define machining processes, sustainability aspects, and the various means of attaining sustainability. The review extensively examines past sustainability assessments in the machining industry, evaluates the current landscape, and identifies primary challenges. Starting with technical insights into the significance of machining in production, sustainability pillars, and the roles of cutting tool modifications and cooling/lubrication conditions.

Additionally, the article seeks to explore how these techniques impact on various factors such as cutting tool wear, cutting forces, surface roughness, chip morphology, and other sustainable factors, particularly in the context of machining hard metals, widely employed in sectors such as automotive, aerospace, and machinery due to their unique properties.

This review pursues following key objectives:

- Identification of machinability/ sustainability concerns in machining of metals during milling process.
- Exploration of potential sustainable alternatives to replace/ improve conventional machining techniques.
- Documentation of published research on sustainable alternatives like modified cutting tools and reduced cutting fluid usage in machining hard metals.
- Investigation of research gaps in this review and potential alternative solutions.

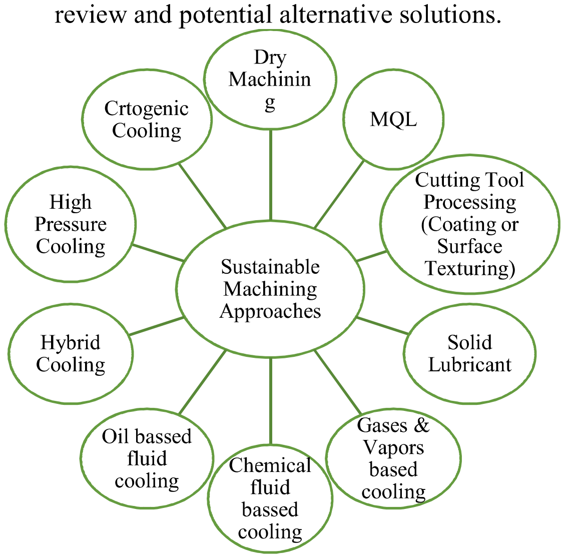

Fig. 7: Sustainable machining approaches

The literature reviewed in this paper critically assesses relevant research work within a focused research zone. To select pertinent studies, a search was conducted on the Scopus database.

2. Results and Discussions

Because there's more production and competition globally, people are trying to reduce resource use and nature pollution. They're doing this by promoting "sustainable production," which means making things in a way that's good for the environment. The machining industry, a big part of production, is strongly affected. To make machining more sustainable, we can improve performance, choose the right cutting tools, cooling techniques, and use biodegradable coolants/ lubricants. Researchers use different methods to understand how to make machining better for the environment. In this part, we'll look at different machining practices with their effects on machinability and sustainability.

3. Dry Machining (DM)

The exploration of dry machining in various studies focused on understanding its effects on tool wear, surface finish, and overall machining performance. Researchers investigated challenges associated with dry machining, such as elevated temperatures and increased friction, proposing strategies to mitigate these issues [12], [11]. Dry machining not only addressed environmental concerns related to coolant disposal but also contributed to energy savings and operational efficiency [13]. Dry machining emerged as a sustainable option to reduce environmental impact and costs associated with cutting fluids, involving cutting or machining without using any fluids [14]. However, dry cutting had drawbacks, such as high temperatures leading to poor performance and tool wear. Researchers explored ways to improve this technique, focusing on tool surface enhancements [15]. Two approaches were tool coating and surface texturing [16]. Tool coating involved adding a thin layer of materials like titanium or ceramics to improve properties. Ceramic coatings, like alumina, offered good chemical and mechanical properties. Super hard coatings, such as CVD, diamond and CBN, provided high hardness and wear resistance [17]. Solid lubricant coatings reduced friction [18], while soft coatings, like MoS_2, enhanced hard coatings' properties [19] . Researchers even explored new coating materials from quarry dust. Textures came in two main types: dimple and strip arrays, created on either the tool's rake face or flank face [20]. Various techniques like electron discharge machining (EDM) and laser surface technology (LST) were used to create micro-textures [21]. The effectiveness of textured tools depended on the shape and dimensions of the textures. Researchers used a trial-and-error approach to find effective texture designs. Experiments were conducted to evaluate different texture designs during milling processes. Results indicated reduced cutting forces, improved lubrication, and enhanced performance with textured tools [22] . Different studies compared textured tools with conventional ones, considering factors like friction, cutting forces, and tool life [21]. Overall, surface texturing proved to be a promising method to improve machining efficiency and sustainability. Improving cutting tools through coating and surface texture was considered sustainable and environmentally friendly. Some explore the cost-effectiveness of coated inserts during milling [23] [24]. More research is needed to compare different coatings and substrates, especially under various cutting conditions. Evaluating diverse surface textures and their sustainability on difficult-to-cut materials is crucial.

a. Minimum Quantity Lubrication (MQL):

Traditional machining heavily relied on cutting fluids for cooling and lubrication during the process. These fluids were crucial for removing heat generated from friction and shear heating, reducing friction coefficients at tool–chip and tool–work interfaces, and aiding in chip disposal [25]. However, machining produced various waste products, including metal chips, spent cutting fluid, oil mist, and unnecessary energy usage. Common cutting fluids, such as petroleum-based mineral oils, were effective but resulted in detrimental waste by-products. Researchers explored MQL as a sustainable cutting fluid [26]. MQL was environmentally friendly, with reduced environmental impact and successful applications [27]. Its advantages included decreased fluid consumption [28], cost efficiency [29], environmental friendliness, improved cutting performance [15], and enhanced surface quality [30]. The principle of MQL involved applying a fine mist of a compressed air mixture with a minimal amount of cutting fluid to the cutting zone. This resulted in high lubrication, reducing the friction coefficient [31]. At high cutting speeds, the lubricating fluid tended to evaporate, impacting its effectiveness [32]. To enhance MQL, researchers explored nanofluid containing nanoparticles like Al2O3, MoS2, SiO2, CuO, and diamond, aiming to increase cutting performance and productivity [22]. Researchers also explored mist-assisted lubri-cooling, a modern strategy that gained popularity in achieving better outcomes in cutting forces, surface roughness, temperatures, tool wear, and tool life [33], [12]. This strategy involved using a minimal amount of lubricant mixed with air from an air compressor, leading to cost reduction and environmental safety [34]. Experiments in milling operations on AISI 4340 steel using MQL showed improvements in tool life and positive environmental and energy benefits [18]. Studies consistently showed that MQL had the least environmental impact in comparisons with dry cutting and flood cooling [7]. [12] examined Hastelloy C276 machining, this study assesses dry, MQL, Cryo CO2, and N-MQL with nano carbon dots (CDs) in soybean oil. Optimizing CDs concentration at 0.8 wt%, N-MQL significantly improves surface roughness by 56–69% as shown in Fig. 2, showcasing its potential for efficient and sustainable machining.

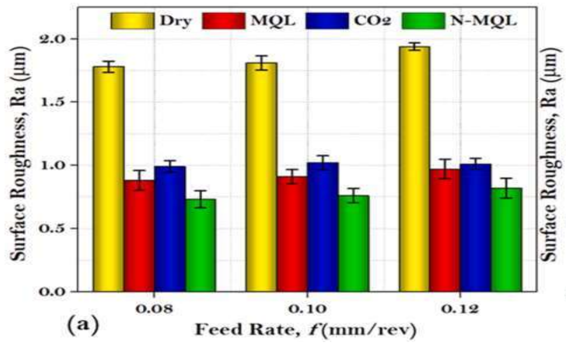

Fig. 8 Sufrace roughness under diverse environment at Ve of 60 m/min [12]

The studies collectively emphasize the importance of transitioning from traditional cooling methods to modern and sustainable strategies like MQL/ NMQL/ SMQL to achieve better outcomes in machining processes.

4. CRYOGENIC COOLING

Cryogenic machining, a cutting-edge technology explored in sustainable machining practices, involved the use of extremely low temperatures to enhance machining processes [35]. The technique typically utilized liquid nitrogen or other cryogenic fluids to cool the workpiece and cutting tool [36]. This innovative approach addressed challenges associated with traditional machining methods, such as high temperatures leading to tool wear and thermal damage to the workpiece. Cryogenic machining offered several benefits, including improved tool life [37], enhanced material removal rates [38], and better surface finish [2]. The cooling effect minimized friction and heat generation, reducing the likelihood of thermal distortion in the workpiece [37]. Additionally, cryogenic machining aligned with sustainability goals by potentially reducing the need for cutting fluids, which could have environmental impacts [34]. As research in this area progressed, the exploration of cryogenic machining held promises for advancing sustainable and efficient metal-cutting practices in various industrial applications [39].

The cryogenic machining represents a promising avenue for sustainable manufacturing. It offers improved machining performance, reduced environmental footprint, and enhanced tool longevity. As evident from the diverse research papers, cryogenic machining is a compelling approach that aligns with the global shift towards more environmentally friendly and efficient machining practices.

HYBRID SUSTAINABLE MACHINING

Hybrid sustainable machining was an advanced approach that combined the benefits of cryogenic cooling and Minimum Quantity Lubrication (MQL) in metal cutting processes [24], incorporating modifications to cutting tools such as tool coating and surface texturing [23]. This method harnessed the effectiveness of cryogenic cooling in managing heat and MQL in reducing friction [32]. By employing these techniques simultaneously and incorporating tool modifications, hybrid machining achieved further reductions in cutting forces, improved surface finish, and prolonged tool life [35]. Cryogenic hybrid machining utilized both liquid nitrogen (LN2) and carbon dioxide (CO2) [36]. CO2, while not meeting the strict definition of cryogenic temperatures, provided technical advantages, delivering cooling media at room temperature and high pressure [40]. Implementing these advanced cooling/lubricating strategies, along with cutting tool modifications, enhanced machining performance compared to conventional flood-cooling methods [23]. CO2-based approaches considered combining MQL lubricant aerosols with "cryogenic" CO2 dry-ice cooling for greater control over application specifics like flow rate, and particle velocity [21]. [41] evaluated sustainable lubricooling methods (MQL, CryoLN2, Flood) in hard milling, considering energy efficiency, economics, and environmental impact shown in Fig. 3. Cryo-MQL showed higher productivity, 50% lower cost, but 44.3% more CO2 emissions, highlighting economic sustainability but environmental concerns.

A concise summary of the sustainability effects, encompassing environmental, economic, and social dimensions, associated with the above discussed machining techniques shown in table 1. These tables aim to provide a comprehensive understanding of the implications and outcomes of employing different machining strategies, aiding in informed decision-making for sustainable manufacturing practices.

The combination of tool modification with Minimum Quantity Lubrication (MQL) represents a cutting-edge approach to machining sustainability and efficiency. Tool modification, such as coatings and geometrical enhancements, enhances tool life and machining performance. Integrating MQL minimizes lubricant usage, addressing environmental concerns and improving health and safety aspects. This synergistic approach not only extends tool longevity but also contributes to sustainable manufacturing by minimizing resource consumption and environmental impact, making it a promising avenue for advanced and eco-friendly machining practices.

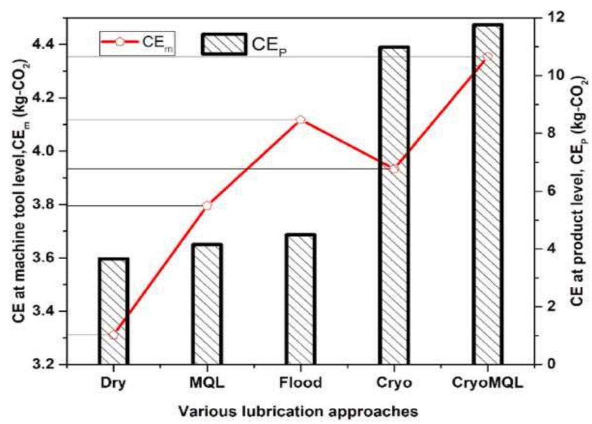

Fig. 9 Analysis of carbon emission at various levels of the machining process [41]

Table 3: sustainability effects associated with various machining techniques

Technique	Environmental Effects	Economic Effects	Social Effects
Dry Machining	Reduced chemical and coolant waste, minimizing environmental pollution.	Lower operational costs due to the elimination of coolant purchase and disposal.	Improved worker health and safety by eliminating exposure to cutting fluids.
Flood Cooling	Potential environmental impact due to the higher consumption and disposal of coolants.	Increased tool life reduces tool replacement frequency, lowering tooling costs.	Operator exposure to coolants may impact health and safety, necessitating precautions.
Cutting Tool Modifications	Extended tool life reduces the frequency of tool replacements, minimizing waste.	Initial investment in coatings or texturing may increase upfront costs.	Improved worker satisfaction and safety through enhanced machining performance.
Minimum Quantity Lubrication (MQL)	Reduced lubricant usage decreases environmental impact and waste generation.	Lower lubricant costs contribute to economic savings.	Improved worker safety by minimizing exposure to cutting fluids.
Cryogenic Cooling	Enhanced tool life reduces tooling waste and resource consumption.	Potential economic strain due to high equipment and operational costs.	Worker safety concerns due to handling cryogenic fluids may impact social well-being.
Hybrid Machining	Optimization of energy efficiency and machining performance can lead to sustainable operations.	Balanced consideratio n of conflicting objectives may lead to optimized costs.	Skilled labor may be required for effective implementation , impacting workforce dynamics.

5. Conclusions and future directions
    a) Dry machining is an eco-friendly solution, but it faces challenges with hard metals. Coolant is still preferred for such situations.
    b) Flood cooling remains essential, with a focus on improving coolant compositions and delivery methods. Biodegradable oils and automation are also beneficial.
    c) Minimum Quantity Lubrication (MQL) is a sustainable choice with ongoing enhancements like nanofluids and mist-assisted lubri-cooling.
    d) Cryogenic machining, using extremely low temperatures, offers benefits like improved tool life and surface finish.
    e) Hybrid machining, combining MQL and cutting tool modifications, improves cutting forces, surface finish, and tool life.

Future research should focus on advanced tool coatings, smart MQL, and optimization for better sustainability.

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