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Elevating Sustainability: The Role of Machining in Modern Eco-Friendly Manufacturing Processes

Baizura Zubir, Jaharah A. Ghani*, Saima Yaaqob, Nizaroyani Saibani, Afifah Zakiyyah Juri, Che Hassan Che Haron, Nurul Sakinah Abdul Basir, Nurul Fatini Ismail, Natasha Ereena Mohd Nasir, & Nur Izati Abustarim

Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment,Universiti Kebangsaan Malaysia, 43600 Bangi Selangor, Malaysia

Corresponding author: jaharahaghani@ukm.edu.my

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ABSTRACT

Sustainable manufacturing has become a critical concern across various industries, including aerospace, automotive, and services. It involves the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources. Additionally, sustainable manufacturing aims to enhance employee, community, and product safety.This paper focuses on the machining process as a key component of sustainable manufacturing. Machining is widely used in manufacturing industries to fabricate components, but it also significantly contributes to environmental pollution. Sustainable machining has been a topic of discussion for over a decade. In sustainable machining processes, every factor acts differently like, the tool life, productivity, and effective utilization of resources must be increased. In contrast, the machining cost, machine cutting power, and adverse effect of cooling and lubrication fluids will be decreased. Important aspects of sustainable machining include dry and near-dry machining, cryogenic machining, and minimum quantity lubricant (MQL) were presented in this article. The effectiveness of these processes is assessed based on cutting tool life and the quality of machined components. In addition, the advancements consideration such as novel process variations, process hybridization, the use of sustainable tools and green transfer mediums, and the optimization of process parameters. Recommendations include increasing efficiency and reducing waste by incorporating recyclable tools in the machine industry implementing either stand alone or hybrid sustainable lubrication machining techniques.

Keywords: Sustainable manufacturing; dry machining; MQL; cryogenic machining

INTRODUCTION

Sustainable manufacturing, also referred to as green manufacturing or eco-friendly manufacturing, is receiving more attention in the process manufacturing world. A growing number of companies are treating "sustainability" as an important objective in their strategy and operations to increase growth and global competitiveness. Companies move forward along the path to sustainable by improving performance and reducing their resource footprint. Sustainable manufacturing includes avoiding causing harm to the local environment, reducing pollution and emissions, cutting waste of raw materials and other resources, reducing consumption of energy, water, and other limited substances (Anonymous 2023).

Increasing safety for workers and nearby communities' are important contributors to sustainable manufacturing which need to be considered as illustrated in Figure 1 (Rosen & Kishawy 2012). Competitiveness, profitability and productivity, environmental stewardship and sustainability are important for advancing manufacturing operations and technologies especially for environmentally sound practices.

FIGURE 1. Key contributors to sustainable manufacturing
Source: (Rosen & Kishawy 2012)

Sustainable machining is defined as the creation of products by cutting material that uses the processes which are environmentally friendly, economically sound and safe for employees, consumers and communities as well as can conserve energy (Prasad et al. 2022). Figure 2 shows various techniques and approaches for sustainable machining operations (Singh et al. 2022). The techniques/approaches consist of minimum quantity lubrication (MQL), dry cutting methods, high-pressure coolant, biodegradable oils, cryogenic cooling.

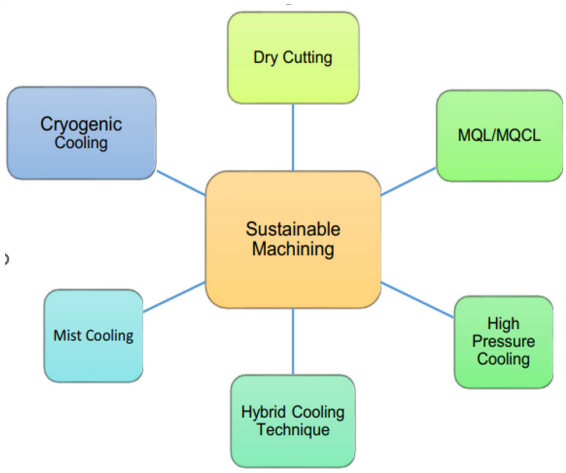

FIGURE 2. Sustainability machining techniques

At the product, process, and system levels, sustainable machining is concerned with lowering negative environmental effect, improving energy and resource efficiency, producing the least amount of waste, ensuring operational safety, and improving human health (Jawahir et al. 2020). Researchers have explored machining components without using cutting fluids, often known as dry machining, to avoid harmful cutting fluids during machining processes (Goindi & Sarkar 2017). Dry machining is thought to be the most long-lasting machining condition, as long as the machinability indices are not violated, which is an uncommon occurrence in reality. Dry machining has two primary goals of environmental and economic success (Krolczyk et al. 2019). On the other hand, the cryogenic liquid evaporates and becomes a part of the atmosphere during the cryogenic machining process, leaving no trace (Jadhav 2019). Because of this, cryogenic machining is a long-term solution for the industry. Cryogenic machining, as a result, can be a more ecologically responsible alternative to coolant. When machining engineering alloys, traditional lubricants are still widely used, however a number of recent articles have shown that using vegetable oil, nanofluids, and nanoplatelets in a MQL system provides improved machining results when compared to traditional lubrication technologies (Sen et al. 2021). The entire energy of turning a component was simulated and optimised in order to produce a cost-effective tool-life that meets the minimal energy footprint criteria. The research clearly highlights essential factors for reducing energy use and, as a result, lowering energy costs and lowering environmental impact (Rajemi et al. 2010). Hybridization of two or more such processes is very much capable of achieving the goal of sustainability (Prasad et al. 2022). According to Prasad et al. (2022) newly evolving technologies such as use of big data, genetic algorithm, artificial neural network, machine learning and artificial intelligence are the need for machining in the era of industry 4.0.

SUSTAINABLE MACHINING METHODS

DRY AND NEAR-DRY ELECTRICAL DISCHARGE MACHINING

Dry EDM is a method that includes passing a high-velocity gaseous dielectric fluid (such as oxygen, nitrogen, hydrogen, or compressed air) via a tube-shaped electrode in the machining zone, which is the space between the tool electrode and the workpiece to be machined. The dielectric medium in near-dry EDM, on the other hand, is a liquid–air/gas mixture or mist (at extremely high pressure). The near-dry EDM technique is a possible alternative for traditional EDM because of its environmental friendliness, high productivity, and improved surface quality (Gupta & Gupta 2019).

Tanimura et al. (1989) found a new process variation that improved the performance of the EDM process. As a dielectric media, this method type uses a gaseous and liquid mixture. The near-dry EDM procedure is the name for this innovative approach. Stable machining is aided by the dielectric mix (liquid and gas). In addition, near-dry EDM had a greater MRR and strong surface integrity (Ra 0.08 μm) while having a lower environmental impact. When comparing wet EDM to near-dry EDM, it was discovered that wet EDM created much more gas. This emission has toxicological significance, since it is the source of a variety of health hazards for humans and the environment (Dhakar et al. 2019). Near-dry machining process was used to overcome the environmental issues by means of providing negligible health hazards (Chaudhari et al. 2022). Authors found that a better surface quality with reduced surface defects was obtained in near-dry WEDM in machining of nitinol SMA.

Without the use of a hydrocarbon oil dielectric medium, the near-dry EDM may be researched. Water usage might be decreased to a minimum, resulting in zero gas emissions from near-dry EDM. Mixing gases with a high viscosity dielectric medium has the potential to increase process performance.

CRYOGENIC MACHINING

Cryogenic machining is indeed opportunities arise method of producing high-quality items. The efficiency of cryogenics in assisting in the manufacture of much better in performance items was presented (Zindani & Kumar 2020). Jadhav (2019) stated that coolant is crucial in lubrication because it reduces heat dissipation and friction between the tool and workpiece. The cryogenic liquid evaporates and becomes part of the structure during the cryogenic machining process, leaving no leftovers. Because cryogenic liquid evaporates into the atmosphere when it has outlived its usefulness, cryogenic machining is environmentally beneficial. As a result, cryogenic machining is a viable option as it helps mitigate the deleterious impact of increasing cutting parameters.

LN2 and CO2 are commonly employed as coolants in this process, which produces nearly little waste. LN2 cooling is provided at very low temperatures, whereas CO2 cooling is provided by fast expansion of carbon dioxide gas. Cryo-cooling is extensively utilised in the aerospace and automotive sectors to machine composite and elastomer materials, as well as nickel, titanium, steel, and Mg alloys that are difficult to cut. Its industrial availability is growing due to its cost-effective and environmentally friendly cooling approach, as well as its ability to meet the needs of highly machined surfaces (Bayraktar 2020).

Hegab et al. (2020) presents that the Grey Relational Analysis (GRA) results revealed that within the four examined situations, the majority of the cryogenic coolant tests performed better which shows higher GRA index than flood coolant testing, particularly for roughing and productivity instances. The experimental findings provided by Khanna & Agrawal (2020) state that using a cryogenic coolant for machining Ti-6Al-4V titanium alloy has a substantial effect on surface roughness and power consumption. Cryogenic cooling conditions provide better surface roughness and result in a good performance and improve product life at higher cutting parameters.

To support the sustainability practice Mohd Nasir et al. (2023) utilized the tool wear monitoring systems by developing a database for machining S45C for automotive parts.

MINIMUM QUALITY LUBRICATION (MQL) MACHINING

Minimum quantity lubrication (MQL) is a sustainable lubrication approach in which a small amount of fluid is delivered to the cutting zone for effective lubrication between the tool-work interface in order to manage heat generated and achieve the optimum machinability. Synthetic esters, fatty acids, and vegetable oils are used to create the lubricants used in the MQL process. MQL makes near-dry machining possible (Gupta 2019). In context of sustainable manufacturing, the MQL system is a cost-effective method that can save up to 15% in comparison to flooding. Furthermore, when it is applied with biodegradable and highly stable cutting fluids like vegetable-based oils and synthetic esters, it makes minimum quantity lubricant (MQL) a more environmentally and health-friendly option (Hamran et al. 2020). Furthermore Hamran et al. (2020) categories the MQL advancements as shown in Figure 3.

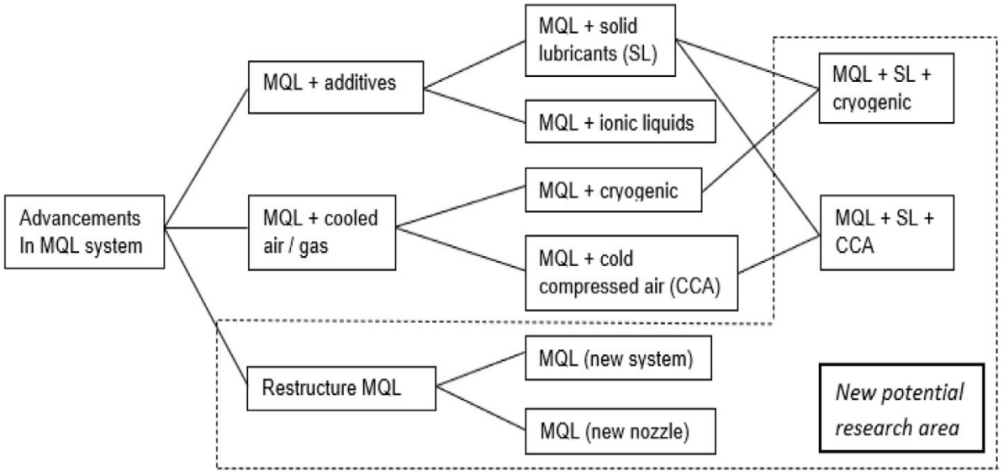

FIGURE 3. Categories of MQL advancements
Source: Hamran et al. (2020)

MQL can be successfully used in conditions where the dry machining parameter range is at its limit. This method, which uses vegetable oil and biodegradable fluids, should be a suitable alternative to mineral oil based on petroleum (Singh et al. 2019). MQL technology eliminates the use of conventional coolant and substitutes them with a small amount of lubricant-air mixture in the metal cutting operation. The lubricant or oil used for MQL is generally vegetable oil or nanofluid, which protects the environment and minimizes the lubrication cost of machining. MQL based nanofluid lubrication has clearly demonstrated significant decrease in consumption of cutting fluid as well as the cutting energy or cutting power while improving surface quality. This technique has been established as an environmentally friendly green manufacturing (Rajmohan et al. 2020).

According to Sen et al. 2021, diffusion of nanoparticles and nanoplatelets in the MQL base fluid is a beneficial technology for reducing friction during the machining process. Because of concern for the environment, nanoparticles and nanoplatelets are considered an innovative, cost-effective option for food lubrication due to their outstanding qualities and low cost. MQL technology has a lot of promise to improve different areas of traditional machining, such as turning, grinding, milling, and drilling, according to a lot of previous research.

HYBRID LUBRICATION TECHNIQUE IN MACHINING

A hybrid lubrication is relatively a new technique, numerous studies also proposed its application in improving the machinability of hard-to-cut material especially at high cutting parameters (Liu et al. 2021; Schoop et al. 2017; Seid Ahmed & Ryon, 2022; Tu et al. 2021; Zhang et al. 2021). Hybrid cryogenic minimum quantity lubrication technology is a combination of two sustainable machining strategies: cryogenic and minimum quantity lubrication (Cryo+MQL). Cryogenic media in hybrid technique can be combined with MQL in three fundamental ways:

1. Liquid nitrogen plus minimum quantity lubrication (LN2+ MQL) (Gupta et al. 2020; Iqbal, et al. 2019);
2. Carbon dioxide plus minimum quantity lubrication (CO2+ MQL) or Liquid carbon dioxide plus minimum quantity lubrication (LCO2+ MQL) (Gajrani, 2020; Pereira et al. 2015) and
3. Cryogenic air plus minimum quantity lubrication (CA+MQL) (He et al. 2023; Saberi et al. 2016).
   d.

Hybrid technology reveals that the machinability performance are improved of difficult-to-cut materials as compared to conventional flooded machining, sustainable dry machining as well as stand-alone cryogenic and MQL techniques.

CONCLUSIONS AND RECOMMENDATIONS

In conclusion, the advancements take the shape of novel process variations, process hybridization, the use of sustainable tools and green transfer mediums, and the optimization of process parameters. It is advised that these novel approaches be used effectively in order to increase

the sustainability elements of nonconventional and conventional machining. Overall, it has greatly aided in decoupling environmentally unfriendly factors from nonconventional machining activities, resulting in significant reductions in hazardous waste and emissions, improvements in product quality and operational health and safety, increases in process productivity, and cost and eco-efficiency. The recent years, the electrical utilities are undergoing rapid restructuring process worldwide. In order to have a better sustainable machining method, it is recommended increasing in efficiency and reducing waste by using some recyclable tools in the machining industry, implementing either stand alone or hybrid sustainable lubrication machining techniques.

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DECLARATION OF COMPETING INTEREST

None

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