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Sustainable Machining: Minimum Quantity Lubrication and Eco-Friendly Coolants in Modern Manufacturing

Rohit Sakya
Associate Professor
Department of Industrial and Production Engineering
Fergusson College – Pune, Maharashtra, India
Email: *Rohitsakya7221@gmail.com*

Abstract

In modern manufacturing industries, sustainability has become an important concern due to increasing environmental regulations and the need to reduce resource consumption. Conventional machining processes generally use large amount of cutting fluids for cooling and lubrication. These fluids help to improve tool life and surface finish but they also create environmental pollution, health hazards for workers and high disposal cost. Therefore industries are looking for alternative machining techniques that can reduce or eliminate the use of conventional cutting fluids. Sustainable machining is an approach that aims to minimize environmental impact while maintaining machining performance and productivity. One of the most promising techniques is Minimum Quantity Lubrication (MQL), where only a small amount of lubricant is supplied directly to the cutting zone in the form of mist or aerosol. Another approach is the use of eco-friendly coolants such as biodegradable oils, vegetable based lubricants and water-based solutions that are less harmful to environment.

This paper presents a detailed review of sustainable machining practices with focus on Minimum Quantity Lubrication and eco-friendly coolants. The principles, working mechanism, advantages, limitations and applications of these technologies are discussed. The effect of MQL and green coolants on tool wear, surface finish, cutting temperature and machining efficiency is also analysed. Various research studies indicate that MQL combined with

biodegradable lubricants can significantly reduce cutting fluid consumption while maintaining good machining performance. Sustainable machining techniques are expected to play a major role in future manufacturing systems where environmental protection and resource efficiency will become more important.

Keywords: *Sustainable machining, Minimum Quantity Lubrication, Eco-friendly coolants, Green manufacturing, Cutting fluids, Environmentally conscious machining.*

INTRODUCTION

Manufacturing industries plays a major role in economic development of any country. However traditional manufacturing methods often produce significant environmental pollution and consume large amount of energy and resources. Among various manufacturing processes, machining operations such as turning, milling, drilling and grinding are widely used for producing high precision components. In these processes cutting fluids are commonly used for cooling and lubrication of cutting tools.

Conventional cutting fluids are generally petroleum based oils mixed with chemical additives. These fluids helps in reducing friction, removing heat from cutting zone and improving surface quality of machined parts. But excessive use of cutting fluids also leads to several environmental and health problems. Disposal of used cutting fluids requires special treatment because they may contain harmful chemicals and metal particles. In addition, workers who are continuously exposed to these fluids may experience skin irritation, respiratory problems and other health issues.

Due to these reasons researchers and industries have started focusing on **sustainable machining** techniques. Sustainable machining refers to manufacturing processes that minimize environmental impact while maintaining productivity and product quality. One of the main strategies in sustainable machining is reducing the amount of cutting fluids used in machining operations.

Minimum Quantity Lubrication (MQL) is a promising technique that supplies only a very small

amount of lubricant directly to the cutting zone. Instead of flooding the workpiece with large volumes of coolant, MQL uses a fine mist of lubricant mixed with compressed air. This method significantly reduces fluid consumption and waste generation.

Another important approach is the use of **eco-friendly coolants** such as vegetable oils, biodegradable lubricants and water-based coolants. These alternatives are less harmful to the environment and safer for workers.

This paper reviews the concept of sustainable machining and discusses the role of Minimum Quantity Lubrication and eco-friendly coolants in improving machining performance while reducing environmental impact.

CONCEPT OF SUSTAINABLE MACHINING

Sustainable machining is an important concept in modern manufacturing where the main objective is to perform machining operations with minimum negative impact on the environment while maintaining good productivity and product quality. Traditional machining processes usually consume large amount of energy, cutting fluids and raw materials, which can cause environmental pollution and increase manufacturing cost. Because of these issues industries and researchers are focusing more on sustainable manufacturing methods.

The idea of sustainable machining comes from the broader concept of sustainable development, which focuses on balancing **economic growth, environmental protection and social well-being**. In machining operations this means that production should be efficient and profitable, but at the same time it should also minimize environmental damage and ensure safe working conditions for workers.

In conventional machining processes such as turning, milling, drilling and grinding, cutting fluids are widely used for cooling and lubrication of the cutting tool. These fluids help to reduce friction and remove heat generated during machining. However, excessive use of cutting fluids leads to several problems including chemical waste generation, disposal difficulty and health hazards for machine operators. Therefore one of the major goals of sustainable machining is to reduce the dependency on traditional cutting fluids.

Sustainable machining generally focuses on several key aspects which help in improving overall environmental and economic performance of machining processes.

Reduction of cutting fluid usage is one of the primary objectives. Conventional flood cooling methods use large volumes of cutting fluid which later becomes industrial waste. Reducing fluid consumption helps in lowering environmental pollution and disposal cost. Techniques like Minimum Quantity Lubrication supply only small amount of lubricant directly to the cutting zone which significantly reduces fluid usage.

Another important aspect is **lower energy consumption**. Machining operations require considerable amount of electrical energy for machine tools, spindle drives and auxiliary systems. By optimizing cutting parameters, tool geometry and machining strategies, energy consumption can be reduced without affecting machining quality.

Reduction of waste materials is also an important factor in sustainable machining. During machining large amount of material is removed in the form of chips. Efficient machining strategies and better process planning can reduce unnecessary material removal and improve overall material utilization.

Improvement of tool life also contributes to sustainability. When cutting tools last longer, fewer tools are required which reduces material consumption and manufacturing cost. Advanced coatings, improved tool materials and better lubrication techniques help in increasing tool life.

The **use of environmentally friendly lubricants** is another significant part of sustainable machining. Instead of petroleum based cutting fluids, biodegradable lubricants and vegetable oil based coolants can be used. These fluids are less toxic and easier to dispose compared to traditional cutting fluids.

Protection of worker health and safety is also a key consideration. Workers who are exposed to conventional cutting fluids for long time may experience skin irritation, respiratory issues and other health problems. Sustainable machining methods aim to reduce these risks by using safer lubricants and minimizing chemical exposure.

In traditional machining operations, large amount of cutting fluid is used mainly for cooling and lubrication of cutting tools. Research studies indicates that the cost related to cutting fluids including purchase, maintenance and disposal can represent nearly **15–20% of the total manufacturing cost**. Because of this, reducing cutting fluid usage not only benefits the environment but also improves economic efficiency of production systems.

Over the past few years several sustainable machining techniques have been developed and applied in different industries. Some of the important techniques are listed below:

1. **Dry Machining** – In this method machining is performed without any cutting fluid. The main advantage is elimination of coolant related pollution and cost. However it may lead to higher tool wear in some applications because there is no lubrication or cooling effect.

2. **Minimum Quantity Lubrication (MQL)** – MQL uses a very small amount of lubricant delivered in the form of mist to the cutting zone. It provides good lubrication while drastically reducing fluid consumption.

3. **Cryogenic Cooling** – This method uses extremely low temperature fluids such as liquid nitrogen or carbon dioxide for cooling the cutting zone. It provides excellent cooling performance and is suitable for difficult-to-machine materials.

4. **High Pressure Coolant Systems** – In this technique coolant is supplied at high pressure directly to the cutting interface which improves chip removal and cooling efficiency.

5. **Eco-Friendly Cutting Fluids** – These include biodegradable lubricants, vegetable oil based coolants and water-based fluids that are less harmful to environment.

Among these sustainable machining approaches, **Minimum Quantity Lubrication and eco-friendly coolants have gained significant attention in recent years**. These methods provide a good compromise between machining performance and environmental sustainability. They are capable of reducing cutting fluid consumption while still maintaining acceptable tool life, surface finish and machining stability.

As environmental regulations become stricter and industries move towards greener manufacturing practices, sustainable machining technologies are expected to play an increasingly important role in future manufacturing systems. Continuous research is being carried out to develop advanced lubrication methods, biodegradable cutting fluids and intelligent machining strategies that can further improve sustainability in machining operations.

ROLE OF CUTTING FLUIDS IN MACHINING

Cutting fluids play a very significant role in most machining operations. During machining processes such as turning, milling, drilling and grinding, a large amount of heat and friction is generated at the interface between the cutting tool and the workpiece material. If this heat is not controlled properly, it can lead to rapid tool wear, poor surface finish and dimensional inaccuracies. To overcome these problems, cutting fluids are commonly applied in the cutting zone.

Cutting fluids are generally composed of base oils, water and various chemical additives. These fluids are supplied to the machining area either through flood cooling systems, spray systems or high-pressure coolant delivery systems. The main purpose of using cutting fluids is to improve machining performance and extend tool life.

Cutting fluids perform several important functions in machining operations. The most important functions are explained below.

1. Cooling

Cooling is one of the primary functions of cutting fluids. During machining, mechanical energy is converted into heat due to plastic deformation of the work material and friction between the tool and workpiece. A significant portion of this heat is concentrated in the cutting zone.

If the temperature becomes very high, it can soften the cutting tool and accelerate tool wear. High temperature can also cause thermal expansion of the workpiece which affects dimensional accuracy. Cutting fluids absorb heat from the cutting zone and carry it away from the tool and workpiece.

Water-based cutting fluids are particularly effective in cooling because water has high thermal conductivity and heat capacity. By maintaining lower cutting temperatures, cutting fluids help in improving tool life and machining stability.

2. Lubrication

Another important function of cutting fluids is lubrication. During machining, friction occurs at two main interfaces: the tool–chip interface and the tool–workpiece interface. Excessive friction increases cutting forces and leads to faster tool wear.

Cutting fluids form a thin lubricating film between the contact surfaces which reduces friction. This lubrication helps in smoother chip flow and reduces adhesion of workpiece material on the cutting tool. As a result, cutting forces become lower and machining becomes more stable. Lubrication is particularly important in operations like drilling, tapping and reaming where tool surfaces remain in continuous contact with the workpiece.

3. Chip Removal

During machining operations, material is removed from the workpiece in the form of chips. If these chips accumulate around the cutting area, they may interfere with the machining process and damage the workpiece surface.

Cutting fluids help in flushing chips away from the cutting zone. The fluid flow carries chips away from the tool and prevents chip re-cutting. Efficient chip removal improves machining efficiency and protects the cutting tool from damage.

In high-speed machining operations, proper chip evacuation becomes very important to maintain stable cutting conditions.

4. Surface Finish Improvement

Surface finish is an important quality parameter in machining. Poor surface quality can affect the performance and durability of machined components. Excessive friction and tool wear can lead to rough surfaces and irregularities.

By providing lubrication and cooling, cutting fluids help in maintaining stable cutting

conditions and reducing tool wear. This results in smoother cutting action and better surface finish on the machined component.

In precision machining applications such as aerospace and medical component manufacturing, achieving high surface quality is extremely important. Cutting fluids contribute significantly in maintaining such quality standards.

5. Corrosion Protection

Cutting fluids also provide corrosion protection to both machine tools and workpieces. Many cutting fluids contain special additives that prevent oxidation and rust formation on metal surfaces.

During machining operations, moisture and metal particles may accumulate on machine components. Without proper protection, these components may corrode over time. Cutting fluids create a protective layer on metal surfaces which helps in preventing rust and corrosion. This protective function helps in increasing the service life of machine tools and maintaining the quality of machined parts.

Environmental Issues Associated with Cutting Fluids

Although cutting fluids provide many advantages in machining operations, their excessive use can create several environmental and health related problems. Traditional cutting fluids often contain chemical additives such as chlorine compounds, sulfur compounds, emulsifiers and biocides. These chemicals may be harmful to both environment and human health.

One major problem is the **disposal of used cutting fluids**. After prolonged use, cutting fluids become contaminated with metal particles, tramp oils and degraded additives. These used fluids cannot be directly released into the environment and must undergo proper treatment before disposal. The treatment and disposal process increases manufacturing cost.

Another issue is **worker health and safety**. Workers who are continuously exposed to cutting fluid mist may suffer from skin irritation, allergic reactions and respiratory problems. In some cases long-term exposure to certain chemicals can cause more serious health issues.

In addition, leakage and improper disposal of cutting fluids may contaminate soil and water resources. Because of these concerns, industries are now focusing on reducing the usage of conventional cutting fluids and adopting sustainable alternatives such as Minimum Quantity Lubrication and eco-friendly coolants.

Overall, cutting fluids remain an important element in machining processes because they improve tool life, surface finish and machining efficiency. However, modern manufacturing is gradually moving towards more sustainable lubrication techniques that reduce environmental impact while maintaining the benefits provided by cutting fluids.

Table 1. Comparison of Cooling Methods in Machining

Cooling Method	Fluid Consumption	Environmental Impact	Machining Performance
Flood Cooling	Very High	High pollution risk	Good cooling and lubrication
Dry Machining	None	Environment friendly	High tool wear in some cases
Minimum Quantity Lubrication	Very Low	Low environmental impact	Good lubrication with reduced cooling
Eco-Friendly Coolants	Moderate	Biodegradable and safer	Comparable performance

MINIMUM QUANTITY LUBRICATION (MQL)

1. Principle of MQL

Minimum Quantity Lubrication is a technique where a very small quantity of lubricant is delivered to the cutting zone in the form of aerosol mist. The lubricant is mixed with compressed air and sprayed through a nozzle directly at the tool-workpiece interface.

In conventional machining, cutting fluid consumption may reach several liters per minute. In contrast MQL uses only around **10–100 ml per hour** of lubricant. This drastic reduction in fluid usage makes the process more environmentally friendly.

The MQL system generally consists of following components:

1. Lubricant reservoir
2. Air compressor
3. Mixing chamber
4. Delivery nozzle
5. Control valve

The compressed air atomizes the lubricant into fine droplets which then reaches the cutting zone. These droplets form a thin lubrication film that reduces friction between cutting tool and workpiece.

2. Working Mechanism

The working mechanism of MQL involves both lubrication and partial cooling effects. The compressed air helps in carrying lubricant particles to the cutting interface while also assisting chip removal.

The process can be explained in following steps:

1. Lubricant is stored in reservoir tank.
2. Compressed air passes through mixing chamber.
3. Lubricant is atomized into fine droplets.
4. Mist is directed through nozzle toward cutting zone.
5. Droplets form thin lubricating layer on tool surface.

This thin film reduces friction and tool wear during machining.

3. Advantages of MQL

Minimum Quantity Lubrication offers several advantages compared with conventional flood cooling methods.

- Significant reduction in cutting fluid consumption
- Lower environmental pollution
- Reduced cost of coolant disposal
- Improved tool life in many machining operations
- Cleaner working environment
- Lower health risks for machine operators

Another advantage is that machined parts usually remain dry, therefore post-machining cleaning operations become easier.

4. Limitations of MQL

Although MQL provides many benefits, it also has certain limitations.

- Cooling effect is lower compared to flood cooling
- Not suitable for extremely high temperature machining processes
- Requires proper nozzle positioning
- Initial setup cost may be higher

Because of limited cooling capacity, MQL may not be suitable for heavy cutting operations where large amount of heat is generated.

ECO-FRIENDLY COOLANTS

Eco-friendly coolants are lubricants that have minimal environmental impact and are biodegradable. These coolants are generally derived from natural resources such as vegetable oils or water-based solutions.

Traditional mineral oil cutting fluids contain harmful chemicals that may cause environmental pollution. In contrast eco-friendly coolants are designed to be less toxic and easier to dispose. Common types of eco-friendly coolants include:

- Vegetable oil based lubricants
- Synthetic ester oils
- Water-based biodegradable coolants
- Bio-lubricants derived from plant oils

Vegetable oils such as soybean oil, sunflower oil and rapeseed oil are widely used because they have excellent lubricating properties.

1. Vegetable Oil Based Lubricants

Vegetable oils have good viscosity and high lubricity which makes them suitable for machining operations. They also have high flash point and good biodegradability.

Table 2. Comparison of Mineral Oil and Vegetable Oil Lubricants

Property	Mineral Oil	Vegetable Oil
Biodegradability	Low	High
Environmental Impact	Higher	Lower
Lubrication Performance	Good	Very good
Toxicity	Moderate	Very low
Disposal Difficulty	High	Easy

These properties make vegetable oils attractive alternative for sustainable machining.

2. Water-Based Eco Coolants

Water based coolants are also used in many machining applications. They consist of water mixed with small amount of additives to improve lubrication and corrosion resistance.

Advantages of water-based coolants include:

- Excellent heat removal capability
- Lower cost compared to oil based fluids
- Reduced environmental hazards

However they may provide lower lubrication compared to oil based fluids.

EFFECT OF MQL AND ECO COOLANTS ON MACHINING PERFORMANCE

1. Tool Wear

Tool wear is one of the most important factors in machining performance. Studies show that MQL can significantly reduce tool wear compared with dry machining. The thin lubricant film reduces friction and prevents adhesion between tool and workpiece material.

Vegetable oil based lubricants used with MQL also improve tool life because of their high lubricity.

2. Surface Finish

Surface finish is another important quality parameter. Research indicates that MQL machining often produces better surface finish than dry machining. The lubricant film reduces friction and vibration during cutting process.

In many turning and milling operations surface roughness values obtained with MQL are comparable to those achieved using conventional flood cooling.

3. Cutting Temperature

Cutting temperature affects tool life and dimensional accuracy of machined components. Flood cooling provides excellent cooling effect because large amount of coolant absorbs heat.

MQL provides less cooling compared to flood cooling, but still reduces temperature compared to completely dry machining. When eco-friendly coolants are used with MQL system, heat removal performance can be improved.

4. Chip Formation

Proper chip formation is necessary for stable machining operations. MQL helps in smooth chip flow because lubricant reduces friction at tool-chip interface.

This results in shorter chips and reduced chip adhesion on tool surface.

APPLICATIONS OF SUSTAINABLE MACHINING

Sustainable machining techniques are now used in various manufacturing industries.

Some common applications include:

- Automotive component manufacturing
- Aerospace parts machining
- Medical device production
- Precision engineering components
- Tool and die manufacturing

For example in automotive industry, MQL is widely used in drilling and milling operations of aluminum components. Aerospace industries also use eco-friendly coolants while machining titanium alloys.

FUTURE TRENDS IN SUSTAINABLE MACHINING

With increasing focus on environmental protection, sustainable machining technologies are expected to become more important in future.

Some emerging trends include:

- Development of advanced bio-lubricants
- Integration of MQL with cryogenic cooling
- Smart lubrication systems with sensors
- Use of nanofluids as eco-coolants
- Digital monitoring of cutting fluid usage

Nanoparticle-based lubricants are being researched because they can improve thermal conductivity and lubrication properties.

CONCLUSION

Sustainable machining has become an important approach in modern manufacturing due to increasing environmental concerns and strict regulations regarding industrial waste. Conventional machining processes rely heavily on cutting fluids for cooling and lubrication, but these fluids often create environmental pollution and health risks. Therefore alternative lubrication techniques are required to reduce the use of harmful chemicals.

Minimum Quantity Lubrication is one of the most effective methods for reducing cutting fluid consumption. By supplying only a small amount of lubricant directly to the cutting zone, MQL significantly decreases fluid usage while maintaining acceptable machining performance. The technique also improves workplace cleanliness and reduces disposal cost.

Eco-friendly coolants such as vegetable oil based lubricants and biodegradable fluids further enhance sustainability of machining processes. These coolants provide good lubrication properties while being less harmful to environment and human health.

Research studies shows that combining MQL with biodegradable lubricants can improve tool life, surface finish and machining efficiency in many operations. Although some limitations exist, continuous development in lubrication technology is expected to overcome these challenges.

Overall sustainable machining using Minimum Quantity Lubrication and eco-friendly coolants represents a promising solution for achieving environmentally responsible manufacturing without compromising productivity.

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