

Performance Evaluation of Nano Cutting fluids in Different AISI Steels under MQL Surroundings-A Review

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ABSTRACT

Nanoparticle enhanced coolants (NPECs) are increasingly used in minimum quantity lubrication (MQL) machining as a green lubricant to replace conventional cutting fluids to meet the urgent need for carbon emissions and to achieve sustainable manufacturing. Minimum quantity lubrication (MQL) is considered a promising lubricating technique for machining processes that can reduce the environmental impact of conventional flooding lubrication systems and improve operator's safety. A comprehensive analysis of the archival literature on sustainable machining of different AISI steels. The current industrial requirement is on high-performance sustainable machining of advanced AISI Steels, Super alloys and Composites. To reduce the intensity of friction, wear, heat and cutting power throughout machining operations the conventional flood lubrication technique was practiced commonly on shop floor. Since cooling and lubrication action is mainly achieved through varieties of metal working fluids during flood cooling methodology utilizing large quantity of water that discharges contaminated effluents hence polluting the water, air and soil. Further, the excessive exposure and usage of fluids leads to unpleasant environment and uneconomical machining. Therefore the role of coolants is significant during the course of selection, application, handling and disposal activities. Also the wastage disposal of metal working fluids has become controversial due to undeviating environment protocols, strict government regulation and public awareness. Hence, the requirement to solve these problems is of utmost importance in present age of Industry 4.0 considering current scenario of water footprints, pollution levels and global warming impacts. So, to resolve these challenging situations, dry machining preferred by industries has uneconomical nature during processing of harder material. Consequently, the best solution to these issues probably has been achieved through minimum quantity lubrication assisted with biodegradable fluids. In present study, the various methodologies of cooling and lubrication employed during varieties of machining operations were critically analyzed and their potential towards sustainable machining was examined. This paper presents the evaluation of the performances of Nano cutting fluids under MQL conditions for machining different AISI Steel has been reviewed.

Keyword: - Nanoparticle enhanced Coolants, Minimum Quantity lubrication, Dry Machining, Nano fluid Minimum Quantity lubrication, AISI Steels, Nano cutting fluids.

1. INTRODUCTION

Increasing the heat dissipation area is an essential requirement during the cutting processes as it could offer effective results in terms of cutting tool life, energy consumption, and production rates. The conventional technique for increasing the heat dissipation for several industrial applications has focused on increasing the heat exchanging area; however, it associates with a problem of the thermal management system. Conventional cutting fluids have played a cardinal role in reducing the induced surface roughness, extended tool wear, and improving the overall machinability for difficult to cut materials. However, the immoderate use of mineral based cutting fluids is hazardous for soil and water, and it results in multifarious health and ecological complexities. The global consumption of mineral-based non-biodegradable cutting lubricants was 13,726 million tons in 2016 with annually 1% increment in consumption depicting the alarming situation. In addition, the continuous reduction of natural energy resources with the danger of loss proportion varies between 13 and 50% of natural lubricants in the terrestrial and aquatic ecosystem. Therefore, introducing new environmental lubrication and cooling techniques is extremely required especially in improving the machining performance of different AISI Steels and difficult to-cut materials. Many environmental lubrication technologies were presented such as minimum quantity lubrication (MQL),

cryogenic technology, as well as dry cutting. Eliminating the use of cutting fluids can be performed using dry cutting technology; however, dry cutting is associated with some problems such as short tool life and poor surface quality. Another environmental friendly technology is MQL where a fine mist is applied to the cutting zone using the optimal amount of cutting fluid with compressed air. Furthermore, the cryogenic technique is considered as another effective alternative for enhancing the machinability and dissipating the generated heat at the cutting zone as it affects the properties of the cutting tool and work piece using a super cold medium with liquefied gases at a temperature lower than 120 K (e.g., liquid nitrogen: LN₂). In addition, using nanofluids (NFs) in machining process could offer promising advantages to face the challenge of the heat dissipation when machining difficult-to-cut materials as Nano-cutting fluids can provide a highly observed thermal conductivity in comparison with the base fluids. Moreover, they have superior cooling characteristics due to their advanced capabilities to extract the generated heat. A nanofluid is defined as a new fluid result from the dispersion of non-metallic/metallic nano-additives with size less than 100 nm into the base fluid. Nano-additives are categorized into many types which are metallic, mixing metallic, non-metallic, carbon, and ceramic Nano-particles [1-2]. Various advantages of using NFs through different applications have been presented as follows.

High heat transfer surface between additives and fluids because of the high specific surface area of nanofluid and saving power consumed in the intensification of pure liquid since NFs can offer the desired heat transfer properties and Surface wettability and heat transfer properties can be controlled by changing the Nano-additives concentrations. Previous studies have focused on modeling, analysis, and heat transfer enhancement using Nano-fluids. Examples of several applications, which implemented the nanofluid technology to improve its thermal, rheological, and stability properties, are cooling of electronics, engine cooling, solar water heating, cooling of welding, engine transmission oil, nuclear systems cooling, and NFs in different cutting operations. Furthermore, previous studies employed MQL-nanofluid technology using nano-tubes and nano-particles, and both scenarios showed better results (e.g., tool wear, power consumption, surface roughness) in comparison with the classical MQL. The MQL-nanofluid approach achieves two main advantages: applying sustainable technique since MQL consumes less amount of oil and enhancing the process performance as the nano-additives improve heat and transfer characteristics. After a careful review of the open literature, it is found that no study offers a clear and comprehensive review of the effects as well as the mechanisms associated with MQL and Nano-fluids in machining processes. Thus, the main goal of this work focuses on reviewing and analyzing the work done using MQL, NFs as well as the integrated approach of MQL-nanofluid in different machining operations with a various cutting tool and work piece materials. This work does not only show what other researcher did in the filed, but also discusses the mechanisms (i.e., tribological and heat transfer) of MQL-nanofluid approach, and how physically these mechanisms affect the machining process performance. Regarding the current work, it is mainly focused on reviewing the mechanisms associated with the application of MQL and MQL-nanofluid during machining operations (i.e., drilling, milling, turning, and grinding). These mechanisms include physical aspects, tribological behavior, as well as heat transfer effects of such cooling/lubrication techniques on the over machining performance. The performance of the machining processes includes several quality characteristics such as tool wear, surface quality, and cutting forces.

In the recent decade, nanotechnology has emerged as a novel area of study and has integrated well with CFs, presenting new possibilities for the advancement of CFs, namely in the creation of CFs based on nanotechnology. These CFs have been enhanced by using nanoparticles (NPs) to improve the lubricating and cooling properties of the base CFs. The NPs exhibit unique surface interactions that are not present in bulk materials due to their significantly high surface area-to-volume ratio [5]. The outcome of Nano-based CFs has a significant influence on the reduction of cutting zone friction thus reducing heat and cutting tool wear. For example, the inclusion of metal oxide NPs can enhance the ability of the CFs to transfer heat, which is crucial for efficient dissipation of heat from the cutting/machining areas and is vital for high-speed machining processes. Grapheme and carbon nanotubes, which are carbon-based NPs, create a strong and mechanically resilient tribofilm on the surfaces of tools and work pieces as a result there is a notable decrease in friction and wear. Figure 1 illustrates the chronological progression of notable developments in the creation of CFs based on nanotechnology, spanning from 2000 to 2025. The graph illustrates significant stages, including the first phase of research and testing, the enhancement of NPs dispersion, the invention of hybrid NCFs, and the incorporation into advanced formulations. Every stage is characterized by gradual enhancements in the efficiency and reliability of NCFs. The graph also illustrates the gradual growth in research effort and innovation, showcasing the transformation of the field from simple experimentation to advanced, high-performance formulations that are now being widely used in industrial applications. This review aims to provide a thorough and evaluative analysis of the existing state-of-the-art NCFs used in machining. It is crucial to examine the advancements in NCFs for cutting processes, particularly in hybrid Nano-lubricating systems. This review presents a

detailed summary of research findings and offers insights into the mechanisms that improve machining performance of Different AISI steels and difficult to cut super alloys machining with NCFs. Additionally, it explores the potential applications of NCFs in various machining processes. NCFs can achieve superior machining performance and support environmentally sustainable manufacturing practices [5].

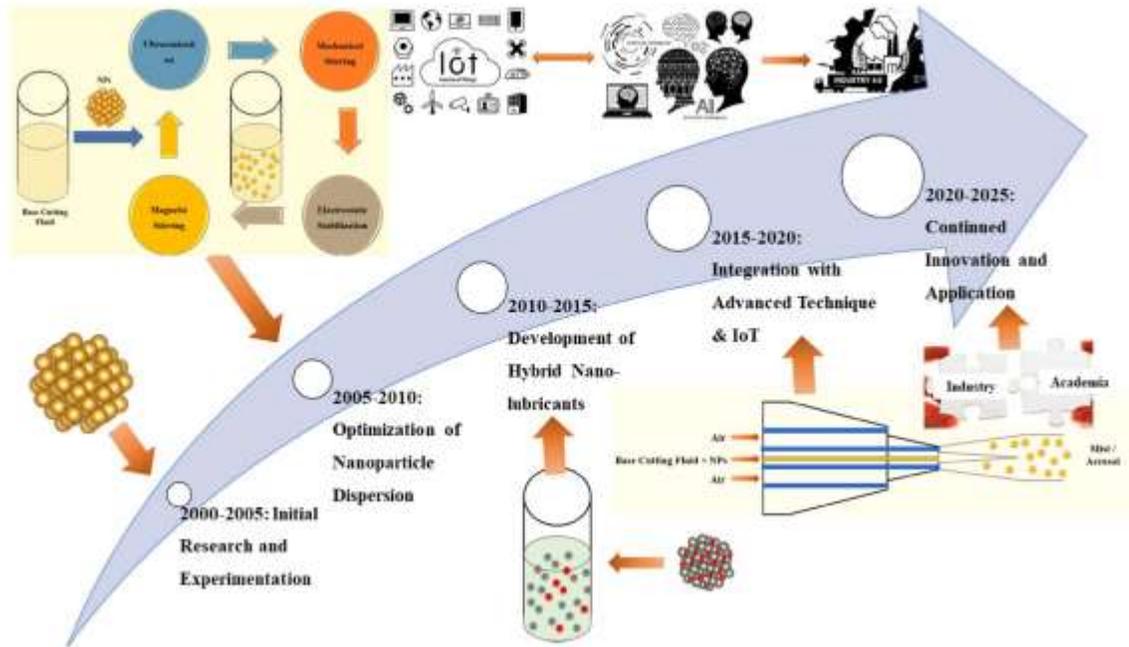


FIGURE 1: Advancements in the formulation of Nano-based Lubricants Over time

2. FUNDAMENTALS OF NANO CUTTING FLUIDS:

Nanotechnology has revolutionized the lubrication practices in manufacturing especially in machining by introducing NCFs that offer superior performance compared to conventional lubrication techniques. Modern CFs utilizes NPs, which are extremely small particles ranging in size from 1 to 100 nm. These NPs can improve the performance of lubricants by reducing friction, minimizing wear, and facilitating heat dispersion. The NCFs contain NPs that are evenly distributed in the base fluid, which can be either mineral-based or vegetable based. The appropriate choice of NPs depends on the desired characteristics of the machining process and the specific working conditions. The most utilized NPs include metallic particles such as copper, silver, and aluminium metal oxide particles such as titanium dioxide and zinc oxide, and carbon-based materials such as graphene and carbon nanotubes [2]. The metal and metal oxide-based NPs are utilized due to their hardness, high thermal conductivity, and resistance to chemical degradation. For example, the inclusion of silver (Ag) and copper (Cu) NPs in CFs enhances the conductivity. On the other hand, metal oxides like titanium dioxide (TiO₂) and zinc oxide (ZnO) exhibit exceptional wear resistance and anti-corrosion properties. These NPs function as additives that strengthen the existing lubrication coating and minimize friction in the cutting zone. The NCFs, especially those with NP additives like SiO₂ and TiO₂ in vegetable-based oils, offer enhanced lubrication by reducing friction and wear, aligning with sustainable and ecofriendly tribology practices. This makes them a promising alternative to traditional mineral-based lubricants in green manufacturing applications [2]. The carbon based NPs possess excellent mechanical properties and exhibit remarkable lubricating characteristics. Graphene is a single-layer arrangement of carbon atoms known for its strong heat conductivity and anti-wear properties. It acts as an effective solid lubricant due to its low friction coefficient and large surface area. Carbon nanotubes are cylindrical carbon structures with excellent load-bearing capacity, allowing them to effectively support lubricant coatings even under high pressure and temperature conditions. Figure 2 presents a summary of the categories of NPs used in CFs based on nanotechnology and depicts the many structural configurations of these NPs, including spherical, cubic, tubular, and multilayer shapes, which have an impact on their performance attributes in lubricating applications [2].

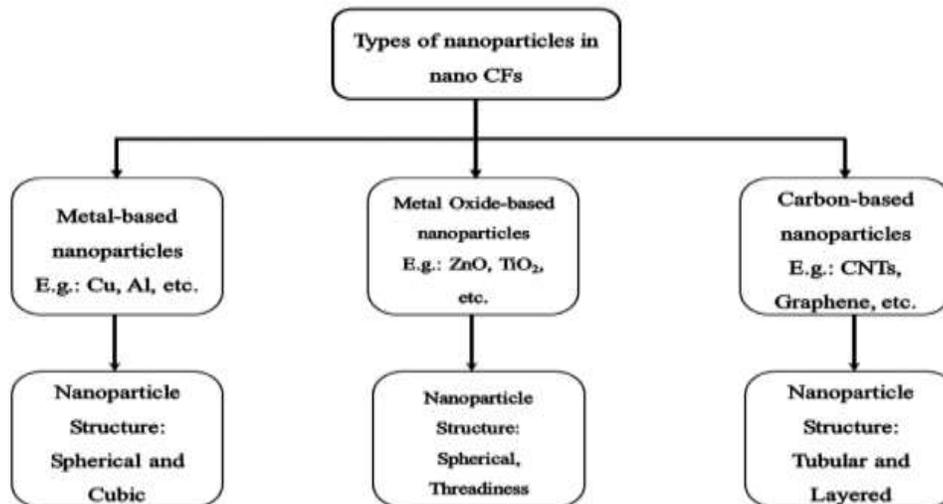


FIGURE- 2: Nanoparticles in NCFs and their Structure

3. LITERATURE REVIEW:

The influence of technological parameters in hard machining processes using MQL has been investigated in many studies. Most studies show that the MQL method gives better results in terms of surface quality and tool life than flood conditions [6]. The presence of these NPs can significantly reduce friction and wear at the machining interface, leading to lower operating temperatures and extended tool life. Additionally, research indicates that optimizing parameters such as charging voltage and mist distribution can further amplify the benefits of Nano particle assisted MQL technology, making it a viable alternative to traditional cooling methods in high-performance applications [5]. The detailed review related to the specified area is discussed below.

Monica Devendiran et al. [1] They undergone their research by performing Response surface design and taguchi approach. Cutting speed, feed rate, depth of cut, and fluid pressure were there process parameters. Their objective was to investigate surface finish, cutting force and tool wear mechanism were influenced by coolants under different pressure in turning of Monel by coated carbide tool. Also they compare the performance (CuO and Graphane) with respect to tool wear, cutting force, surface roughness, cutting zone temperature chip morphology and surface modification during turning of Monel. They found that under extreme wear conditions, GO-based nano fluids improved machining performance, as measured by increased cooling and lubrication regime, cutting temperature of 122 °C, and surface roughness of 0.0462 μm and flank wear of 0.2 mm.

Milon Selvam Dennison et al. [2] They done their research by reviewing the previous research on The implementation of NCFs in prominent machining operations such as turning, drilling, milling, and grinding has resulted in improved surface quality of machined parts and increased lifespan of cutting tools. This is achieved by reducing cutting forces, enhancing heat transfer, and minimizing friction at the cutting zone. Using NCFs in Minimum Quantity Lubrication enhances the machining process, promotes environmental friendliness, ensures sustainability, and effectively tackles the environmental concerns associated with conventional CFs. review provides a thorough analysis of researches on the use of NCFs in machining processes. It discusses the limitations of NCFs and explores potential opportunities for sustainable and enhanced machining operations in the future.

Ngo Minh Tuan et al. [3] they done their research on the machining performance of 90CrSi hardened steel in MQL and MQCL conditions, sing Al_2O_3 and MoS_2 Nano cutting fluids. Experiment of design was carried out also ANOVA were carried out to study the influence of input parameters including fluid type, lubrication method, nanoparticle type, nanoparticle concentration, cutting speed and feed rate on surface roughness. They found that the machinability of CNMG120404 TM T9125 carbide tools was improved and the highest machinable hardness was increased from 35 HRC to 60 ÷ 62 HRC by using the nanofluid MQL and MQCL methods. They also observed that MQCL gives better performance than MQL, and the Al_2O_3 nanofluid exhibits the better result in terms of surface roughness values than the MoS_2 nanofluid. Feed rate displays the strongest influence on surface roughness, while fluid type, nanoparticle concentration and cutting speed show low impacts.

Kerem Yavuz Camlı et al. [4] Researchers experimented ER7 steel for optimal cutting parameters by coated carbide inserts. The impact of the cutting speed and feed rate on surface roughness (Ra), energy consumption and

cutting temperature were investigated and used to determine the optimal cutting parameters. They also conducted the test on ER7 using g MQL and nano-MQL cooling technologies to determine their impact on the aforementioned machining outputs. According to preliminary tests, and within the tested range of the cutting parameters, using a cutting speed of 300 m/min and a feed rate of 0.15 mm/rev resulted in minimal surface roughness. As a result, using these optimal cutting parameters with MQL and Nano-MQL (NMQL) cooling technologies, the surface roughness was further reduced by 24% and 34%, respectively, in comparison to dry conditions. Additionally, tool wear was reduced by 34.1% and 37.6%, respectively. The overall results from this study demonstrated the feasibility of using MQL coolants as a sustainable machining alternative for steel parts for rail wheel applications. In addition, their research highlighted the enhanced performance of MQL cooling technology with the addition of Nano additives.

Mohana Rao G. et al. [5] In this research researchers carried out milling process on EN-36 Steel in Dry and MQL conditions, by nanofluid lubricants nanofluids were prepared by adding 6% volume and 8% volume of Al_2O_3 Nano particles to the vegetable fluid independently. These nanofluids were utilized during milling process of EN-36 Steel and measured the parameters in dry machining and with MQL nanofluid lubricants. Experiments were conducted by utilizing the Taguchi approach and the outcomes were dissected utilizing analysis of variance (ANOVA). Experimental and predicted values were compared and analyzed. The analysis of the results revealed that the roughness, temperature, cutting force and tool wear in 8% volume of nanofluid with MQL were 0.1 μm , 44.16 $^{\circ}C$, 280.46 N and 0.0031 mm respectively are significantly better than the dry machining and 6% volume of nanofluid with MQL performances. Finally, they conclude that the machining with 8% volume of nanofluid with MQL have improved the machining performance when compared with the dry milling process.

Kishan Zadafiya et al. [6] The research shows the overview of the impact regarding usage of nanofluid as a cutting fluid in different machining processes. This paper encapsulates an overview of the impact regarding usage of nanofluid as a cutting fluid in different machining processes. The environmental and health issues that emerged with the use of nanofluid was also reviewed. They observed that the implementation of a nano lubrication system can significantly improve the heat transfer characteristic of base fluid which ultimately leads to the functionally tremendous product. However, there are major unknowns related to the health and environmental impact of nanoparticles.

S. Vignesh and U Mohammed Iqbal et al. [7] The researchers prepared the Nano fluid TiO_2 , ZnO and Fe_2O_3 metallic nano particles with neat cold-pressed coconut oil in a fixed volumetric proportion (10:90). Prepared Nano fluid were tested for their rheological behavior and latter introduced into milling of AA7075. They observed that the nanofluids gave good performance when compared to conventional methods. Furthermore, the results obtained from the experiments confirm that the trio-hybridized lubricant has reduced the cutting force, tool wear and surface roughness in an improved way when related to monotype nano fluids. The response surface methodology is performed to evaluate the interaction of process parameters in minimum quantity lubrication environment with nano fluids. The results show that the cutting forces, surface roughness, tool wear was minimized while machining with hybrid cutting fluids and well within the desirability.

S. Zainal Ariffin et al. [8] Researchers objectives were focuses on evaluating the performance of Nano cutting fluid mixing titanium dioxide (TiO_2) in CNC Turning using AL319 Aluminium Alloy with MQL technique. The cutting performance is assessed in terms of surface roughness, cutting temperature, and tool wear was investigated. Machining parameters used for spindle speeds of 1000 to 1800 rpm and feed speeds of 0.10 to 0.20 mm / rev were used on CNC turning machines. MQL pressure is constant at 0.5 Mpa, and for parameters of TiO_2 Nano liquid with concentrations of three volumes (0.5, 1.0, and 1.5%) was then compared with conventional CNC cutting liquid. Response surface method (RSM) via Face Centered Design (FCD) was used in designing the experimental use of the variance analysis (ANOVA) to determine which parameters are statistically important. The stability of TiO_2 Nano cutting fluid was checked via visual sedimentation. They observed that the lowest cutting temperature of 28 $^{\circ}C$ and surface roughness of 0.863 μm Ra when TiO_2 Nano cutting fluid with 1.5% volume concentration was employed. The experimental research reveals that the performance of TiO_2 Nanofluid in terms of surface roughness, cutting temperature, and tool wear were found to be better compared to dry machining, wet, and MQL machining using conventional cutting fluid. Nanofluids can be considered as the future of heat transfer fluids in various heat transfer applications. They are expected to give better thermal performance than conventional fluids due to the presence of suspended nanoparticles.

Anshuman Das et al. [9] They focused on various machinability aspects using different cutting fluids. The effect of cutting fluids on various machining forces, tool flank wear and chip thickness were carried out using the minimal quantity lubrication technique (MQL). This method predicts minimal health risks and economical aspect compared to other techniques. Experiment was conducted and observed that depth of cut and speed was the principal cutting

parameter affecting the cutting force and feed force and speed as the principal cutting parameter for the radial force for compressed air and water soluble coolant. Instead, depth of cut, feed and speed were the principal cutting parameters influencing cutting force, feed force and radial force, respectively using nanofluid. In the flank wear analysis, nanofluid performed the best followed by water soluble coolant and compressed air. Finally the mathematical models were developed for the machining forces with 95% confidence level using Minitab 16 was used for statistical data analysis. ANOVA analysis, Anderson-Darling test and normal probability plot was used to inspect the effectiveness, adequacy, authenticity and statistical significance of the developed model.

Pralhad B. Patole et al. [10] Research presented a review of the important research papers published regarding the MQL-based application of mineral oils, vegetable oils and Nano fluid-based cutting fluids for different machining processes, such as, drilling, turning, milling and grinding, etc. Most of the experimental studies have shown that application of MQL produces surface better than the flood and dry machining. They observed that MQL with Nano fluid can substitute the flood lubrication for better surface finish.

3.1 SUMMARY OF LITERATURE REVIEW:

Based on the available literature review following observations can be drawn:

- The major disadvantage in flood/ wet coolant is that coolant never allowed penetrating properly into the actual-tool contact area. The sustainable machining practices focus on optimizing coolant use to balance environmental and economic considerations while enhancing overall machining efficiency.
- MQL (Minimum quantity lubrication) is a technique in which a small quantity of oil is applied with high pressure air. Many researchers have reported the achievement of effective lubrication in the cutting process from MQL by using small quantities of coolants. Minimum Quantity Lubrication (MQL) is an innovative technology in machining. It provides an ideal quantity of lubricant (often less than 50 mL per hour) in a fine spray straight to the cutting zone, serving as an alternative to traditional flood cooling Methods.
- Nanotechnology has revolutionized the lubrication practices in manufacturing especially in machining by introducing NCFs that offer superior performance compared to conventional lubrication techniques. Modern NCFs utilize NPs, which are extremely small particles ranging in size from 1 to 100 nm. These NPs can improve the performance of lubricants by reducing friction, minimizing wear, and facilitating heat dispersion.
- The NCFs contain NPs that are evenly distributed in the base fluid, which can be either mineral-based or vegetable based. The appropriate choice of NPs depends on the desired characteristics of the machining process and the specific working conditions. The most utilized NPs include metallic particles such as copper, silver, and aluminium metal oxide particles such as titanium dioxide and zinc oxide, and carbon-based materials such as graphene and carbon nanotubes.
- From the review it has been found that the Nano particle enhanced cutting fluid has superior heat transmission capability and improved tool life and surface quality of the machined surface.
- From the review it has been also found that Nano particle enhanced cutting fluids in comparison to traditional wet machining, cutting temperature, surface roughness, cutting force and tool wear decreases by 25% to 70%.

4. CONCLUSIONS

The conclusions are summarized below;

- The Nano-Cutting Fluids (NCFs) present a cutting-edge lubrication method that enhances machining performance while addressing environmental and social concerns compared to traditional lubrication methods.
- The NCFs incorporate nanoparticles (NPs) such as metals, metal oxides, and carbon-based materials, leveraging their unique properties to optimize lubrication, minimize friction, reduce wear, improvement in surface quality of machined surface and manage thermal conditions across diverse machining processes.
- Nano particle enhanced cutting fluid offer superior performance compared to conventional lubricants in terms of lubrication and cooling efficiency.
- The use of NCFs increases machining productivity and provides manufacturers with a competitive advantage by enhancing efficiency and cost-effectiveness.
- The Minimum Quantity Lubrication (MQL) systems, when combined with NCFs, significantly lower lubricant consumption, which in turn reduces operational costs and the environmental impact.
- Nano particle enhanced coolants with MQL technique equally favourable to all machining Processes (Turning, Milling, Drilling, and Grinding).

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