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CRITICAL REVIEW

Nanoparticle-based lubrication during machining: synthesis, application, and future scope—a critical review

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Abstract
This research paper explores the integration of nanotechnology into Minimum Quantity Lubrication (MQL) systems for enhancing machining processes. Nanotechnology offers a novel approach by incorporating nanoparticles into lubricants, thereby improving thermal management, reducing friction, and enhancing overall machining efficiency. The paper reviews recent advancements in nanofluid MQL across various machining operations such as milling, turning, grinding, and drilling, highlighting significant improvements in tool life, surface finish quality, and environmental sustainability. Key properties of nano-lubricants, including thermal conductivity, wettability, and tribological performance, are discussed in detail, emphasizing their critical role in mitigating tool wear and optimizing cutting conditions. It was also observed that nanofluid MQL method directly aids in improving the cooling and lubrication process during machining, which leads to increasing overall efficiency and process stability. In addition, the improved tribological properties reduce friction and wear between cutting instruments and workpieces during the nanofluid MQL process. Hence, nanofluid MQL systems become a viable alternative to traditional machining lubrication systems in a variety of applications. Furthermore, the future prospects of nanofluid MQL machining are explored, focusing on potential innovations and applications that could further revolutionize precision manufacturing. Ultimately, this paper underscores the transformative impact of nanofluid MQL on modern machining practices and its potential to drive sustainable technological advancements in the manufacturing industry.

Keywords Nanofluids · Minimum Quantity Lubrication (MQL) · Nanoparticles · Machining applications

1 Introduction

1.1 Background

The process of developing a product is referred to as "manufacturing." Metals are shaped into useful products/shapes by a variety of manufacturing processes. Using a cutting tool to remove extra material from a workpiece in order to mold it into the desired shape is known as metal machining. Machining methods have been there for a while and played a crucial part in the advancement of the engineering upheaval [1–3]. There has been a lot of interest in investigating machining processes under dry or near-dry conditions recently [4]. This is a consequence of the fact that the cutting fluids employed in

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machining operations generate an array of problems with people's health and production expenses [5]. Toxic cutting fluids cause skin irritation, respiratory difficulties, cancer, and other disorders [6]. Based on a study carried out by the German Social Accident Insurance, the costs of using and disposing of cutting fluids contribute to about 16% of the overall cost of production [7, 8]. Based on these conclusions, researchers have emphasized that manufacturing methods in the modern era should be in conformity with cleaner production standards and should be free or use a minimal quantity of cutting fluids [9–11]. However, despite the recent attempts to avoid the use of cutting fluids, they are still widely used in machining operations as they were the main factor to increase the cutting tool life and improve the surface characteristics [12–14]. Also, the cutting fluids execute a wide range of tasks throughout the metal cutting process, such as forming a coating of lubricating oil, removing the heat generated during the machining process, disposing of the chips generated, improving the cutting environment, and eventually raising the quality standard of the finished product [15, 16]. Hence, it is important to explore new cutting technologies and lubricating methods, in order to remove the challenges faced by conventional cutting methods to make them environmentally friendly without compromising the finished product quality and tool life [17–19].

1.2 Importance

In industries, a range of lubricants have been utilized to prolong machine life and minimize wear and friction. Metal working fluids (MWF) are lubricants used in the metal working sector, which account for approximately 5% of all industrial lubricants [20–22]. Use of cutting fluids in metal machining specifically results in an increase in tool life and improved surface quality as the cutting fluids act as a medium to perform lubrication, provide cooling action, and aid in chip evacuation and can boost efficiency by allowing faster cutting parameters [23, 24]. Hence, for a sustainable machining process, which at present gains rapid concern due to environmental problems and depletion of natural resources [25–28], a suitable alternative to MWFs needs to be found out so that the characteristics of conventional machining method cannot be abolished [29, 30]. Because most lubricants are made of mineral oil, which is extracted from petroleum, they are hazardous and non-biodegradable, causing a negative impact on the environment. Furthermore, machinists in the metalworking business have a significant likelihood of developing health problems from prolonged exposure to mineral oil-based MWFs, such as asthma, skin irritation, and bronchitis [31–33]. However, dry cutting technology, which was first used in the 1990s, completely eliminated the use of cutting fluid [34]. Several investigations regarding the possibilities of dry machining have been carried out in academia and industry [14, 35, 36], offering novel application possibilities within the field of environmental sustainability. The realization of cleaner production techniques has been significantly accelerated by this [37–39]. But in dry machining, the high temperature encountered during the machining process cannot be lowered due to the absence of a cooling medium [40, 41]. Also, dry machining results in a higher cutting force, thermal gradient, and residual stress, which adversely diminishes the workpiece surface finish, reduces surface integrity, and might result in a shorter tool life [42–44]. These problems limited the use of dry machining to the machining of soft materials only. As an alternative to dry machining, air-cooling methods have been used which is also an environmentally sustainable method. The air-cooling method provides a substantial improvement over dry machining; however, it introduced new issues, such as wrinkles and chipping [45–47]. In addition, the difficult-to-machine materials machined under the air-cooling process do not provide satisfactory results [48, 49], which ultimately concluded that air-cooling machining is not the optimal approach for sustainable machining method [50, 51]. Hence, it was concluded by the researchers that it was impossible to eliminate MWFs completely from the machining process. Therefore, an environmentally biodegradable lubricant (like vegetable oils) or quantity of lubricant used should be minimized (like Minimum Quantity Lubrication), or use of hybrid lubricants by adding nanoparticles in mineral oil-based lubricants to make them environmentally friendly and safe to use for the machinists in addition to without compromising the machining efficiency of the method are some of the approaches proposed for sustainable machining [31, 33, 52–54]

1.3 Objective

Vegetable oils are increasingly being utilized as an alternative to petroleum-based polymeric MWFs in machining operations because of a growing interest to implement environmentally friendly machining [55–57]. Vegetable oils are biodegradable, non-toxic, and renewable. Additionally, they have low volatility, a high ignition point, and good viscosity, all of which contribute to the formation of boundary lubrication, making them suitable to be employed in the metal machining industry as a sustainable lubricant [58–60]. Hence, a number of investigations had been performed in recent times to develop new bio-based cutting fluids or use existing vegetable oils as a possible substitute for mineral-based lubricants during machining operations. Some of the prominent examples are the use of rapeseed oil [61, 62], coconut oil [63, 64], canola oil [65, 66], sunflower oil [67, 68], jatropha oil [69, 70], mango seed oil [71, 72], and groundnut oil [73, 74] as a lubricant in machining operations. However, vegetable oils have one serious inherent drawback which limits their use as a lubricant in machining operations, and that is poor thermal and oxidation stability, reduced fluid flow, and solidification chances machining is poised to revolutionize precision machining, fostering innovation, efficiency, and sustainable growth in global manufacturing.

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Saood Ali: methodology, investigation, writing—original draft preparation.

Rendi Kurniawan: writing—reviewing and editing, investigation.

Rohit Kumar Singh Gautam: validation.

Thirumalai Kumaran Sundaresan: writing—reviewing and editing.

Khursheed Ahmad: writing—reviewing and editing.

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Declarations

Ethics approval An ethics statement is not applicable because this study is based exclusively on published literature.

Competing interests The authors declare no competing interests.

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