Manufacturing Rev. **10**, 1 (2023)

https://doi.org/10.1051/mfreview/2022034

Manufacturing Review
Available online at:
https://mfr.edp-open.org

REVIEW | OPEN ACCESS

Nanofluids, micro-lubrications and machining process optimisations − a review

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Received: 19 May 2022 / Accepted: 19 November 2022

Abstract. The lubrication is a prime requirement of metal cutting industries to assure high quality performance. The conventional technique of coolant flow is less economical and eco-friendly. Recently, nano fluids found better cutting fluid in machining due to potential thermal and heat transfer properties. The role of micro-lubrication techniques and process optimization are equally important for improving process performance. The literature review presents the findings of different researchers in the field of nano fluids and micro-lubrication techniques. The experimental studies were focused on better process performance using micro-lubrication techniques, especially nanofluid MQL with optimized process parameters. The thermal conductivity of water based TiO_2 nano fluid shows improvement by 22% in base fluids. The case study discussed which is focused on preparation and characterization of nano fluid, experimental setup and optimization of process parameters by Jaya algorithm. Finally, application of nano fluid, and challenges during nano fluid preparation is identified. The scope of research work is recommended for further study to obtain an economical, eco-friendly manufacturing process.

Keywords: Cutting fluid / machining / modeling / micro-lubrication / optimization

1 Introduction

The recent industries are more concise for economical, eco-friendly and sustainable machining process to achieve quality production. The large amount of heat is generated during machining when tool and work piece contact and it varies from machining to machining type. Setti et al. [1] and Lee et al. [2] discussed the problem of heat generation in the grinding process due to contact of a wheel with workpiece surface for a fraction of seconds during material removal. The chips during grinding are in the form of debris which consumes a large amount of specific grinding energy. The prime requirement is to remove heat quickly from the machine cutting region to avoid further thermal damage to the workpiece and cutting tool. The efficient and better penetration of cutting fluid at the contact zone improves the performance of the machining process. At the same time, optimized process parameters are equally important for a quality product, reducing machining costs and maximizing production rates. Brinksmeier et al. [3] discussed the importance of cutting fluid and its composition for improving process efficiency. The usage of metal working fluid (MWF) varies from machining to machining type and plays a significant role in process improvement. But the excessive use of cutting fluid for machining gives a lot of problems. Li et al. [4] suggested the excess use of metal working fluid (MWF) for machining is uneconomical and creates health issues to workers. In a review paper by Aurich et al. [5], the sustainability of abrasive processes, mainly three dimensions, such as economy, environment and society is discussed. The reason for focusing on abrasive processes is due to a complex material removal mechanism, high specific energy and high use of cutting fluid. Najiha et al. [6] explained the importance and necessity of process sustainability from a manufacturing view. The sustainable techniques of manufacturing such as dry machining, minimum quantity lubrication (MQL) solid lubricant, cryogenic coolant and nano fluid MQL are explained. The paper also suggests that 15–20% of the overall machining cost is related to cooling and lubricating fluids. The total cost associated with the procurement, maintenance, and discarding such fluids may amount to approximately 17% per component in the automotive

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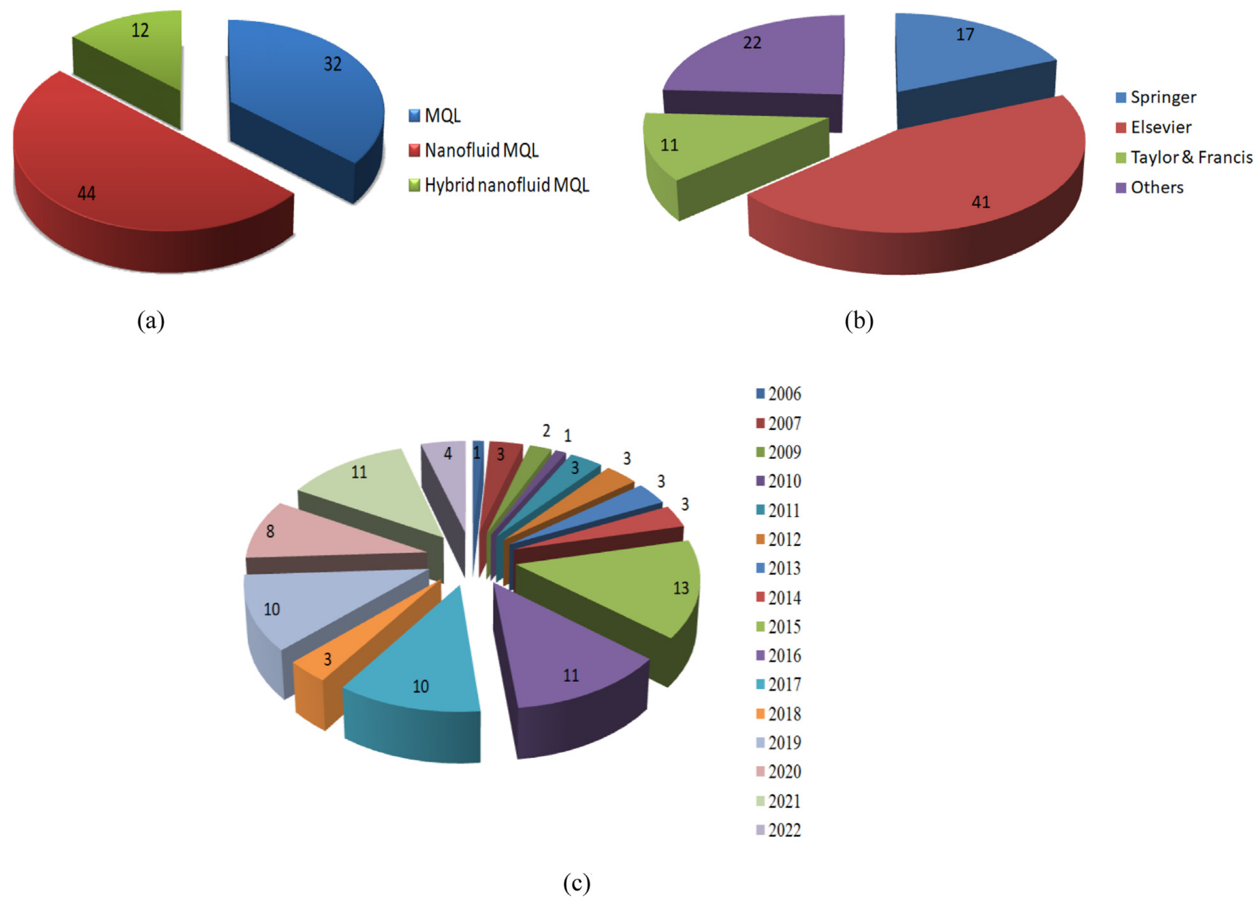


Fig. 1. Literature review on: (a) Micro-lubrication techniques; (b) Micro-lubrication techniques – publication wise; (c) Micro-lubrication techniques – year wise [7].

industry. The literature review related to micro lubrication techniques such as MQL, nano fluid MQL, and hybrid nano fluid MQL and process optimization for different machining processes are discussed in Sections 2 and 5 respectively. Recently, more attention is given on micro lubrication techniques for improving machining performance. The excess use of cutting fluid to obtain satisfactory machining results in conventional wet systems is overcome by using micro lubrication techniques. In the last few years, the efforts have been taken in this regards and recently the researchers are focusing on micro-lubrication techniques and process optimization. The micro- lubrication techniques also help to obtain economical and eco-friendly machining process. The optimization of process parameters is equally important to obtain quality production economically.

Figure 1 shows a literature review on micro lubrication techniques and optimization, publication wise and year wise for different machining processes. The work carried out by the researchers on micro lubrication techniques is discussed for various machining processes and materials. Some of the authors study the tribological performance of cutting fluid through different techniques. The techniques of optimization for optimizing the process parameters are also discussed for some of the machining processes. But it is found that very less work is carried out by researchers on performance of micro lubrication techniques, tribological study and optimization of machining process for materials. Also, very few works has been reported, such as the performance of hybrid nano fluid, MQL technique with optimization for machining of hard material. This paper focuses on recent micro-lubrication techniques and optimization of machining processes along with applications of nano fluid. The case study is also discussed for optimizing the turning process parameters using the Jaya algorithm. The future scope of nano-fluid with the MQL technique in machining is recommended for new researchers. From a literature review, it is noted that micro lubrication techniques give better machining performance. The limitation of a wet lubrication system is significantly reduced by micro-lubrication techniques. In micro lubrication techniques, especially mono and hybrid based nano-fluid MQL, nano fluid is used as the nano coolant due to excellent thermal properties and effective penetration at machining contact interface. The micro-lubrication techniques a prime alternative to conventional wet system that reduces production cost, environmental effect and problem of disposal. In machining industries, the operator selects the parameter values based on trial and error or experience. The manual selection of process parameter values varies from each experimental run and such practices affect significantly on process performance. Generally, the industry follows the traditional way of selecting the machining parameters based on industrial practices or data handbooks. The variables selected by such criteria are usually on the conservative side and cannot satisfy any economic criterion and customer requirements in a product. Thus, optimization of process parameters by proper optimization techniques is important to achieve quality production. Based on literature findings and gap, the study of tribological performance is important to understand the cooling and lubricating effect of cutting fluid at the machining contact interface. Therefore, there is a strong need for nano fluid technique in micro lubrication with optimized process parameters during different machining processes. Nowadays, the metal cutting industries require the proper selection of micro-lubrication techniques with optimized parameters to produce quality production and an eco-friendly manufacturing process. Therefore, micro-lubrication technique are the promising cooling-lubricating system and needs to be explored for different machining operations and materials.

2 Literature review on micro-lubrication techniques

The basic problem in conventional wet techniques is excess use of cutting fluid during cooling and lubrication of the cutting zone. The conventional technique of fluid flow is uneconomical and causes environmental pollution. The constituents of cutting fluid are harmful to the operator and cause different diseases. The limitations of conventional methods are stated in Section 1. It is on demand to reduce the excessive use of cutting fluid generally used for mass production systems. In the last few years, the effort has been taken in this regard and recently, the researchers are focusing on micro-lubrication techniques such as MQL, nano fluid MQL, and hybrid nano fluid MQL for process improvement. In micro-lubrication, a very small volume of cutting fluid is atomized by compressed air or gas to obtain micro-droplets and delivered to the machining zone at a very low flow rate. In MQL micro lubrication technique, the cutting fluid is oil or coolant which has poor lubricity. To increase the heat transfer efficiency of MQL and tribological performance of the cutting fluid, the nano fluid, the solid nanoparticle of size less than 100 nm is added to the base cutting fluid and is supply under MQL. The compressed air and nano fluid is atomized and sprayed to the area where the cutting takes place. Compressed air mainly plays a role in cooling, debris removal and nano fluid delivery, while the nano-fluid mainly lubricates the machining region. The heat transfer of the cutting zone increases due to higher thermal conductivity of nanofluid compared to base fluid. The nanofluid with micro lubrication technique is better option for improving the tribological performance of cutting fluid and to obtain significant process performance. Chakule et al. [8] reviewed the recent cooling and lubricating techniques to obtain green and sustainable manufacturing grinding process. The literature review on thermal properties of nanofluid and micro-lubrication techniques with process optimization is explained below and summarized in Tables 1–3.

2.1 Minimum quantity lubrication technique

In MQL technique of micro lubrication, the small quantity of cutting fluid in mist form is injected by compressed air into the contact region of cutting tool and work piece. The quick heat dissipation and chip removal from the contact interface is possible due to effective penetration of cutting fluid, thus improving the machining results. The cost reduction by 15% on equipment used for storage, recycling, pumping, filtration and cooling purposes is obtained. Post-cleaning of work piece is also not necessary. The significant improvement of machine life is obtained due to an unclean workplace.

Dhar et al. [29] investigated the machinability characteristics of the turning process for AISI-1040 steel rod material. The investigation was carried out to find the process performance in-terms of cutting temperature, chip reduction coefficient and dimensional deviation. The better results were reported using MQL compared to dry and wet machining conditions. da Silva et al. [30] evaluated the lubrication and machining conditions of ABNT 4340 steel using cylindrical plunge grinding. The performance of surface integrity in the form of roughness, residual stress, microstructure and micro hardness were found improved using optimized cutting conditions such as wheel speed (30 m/s), in-feed rate (1 mm/min), spark-out time (10 s), depth of cut (100 μm) and flow rate (40 ml/h). Similar lubricating performance of vegetable oil and synthetic oils cutting fluids has been reported by Sadeghi et al. [31] during machining Ti-6Al-4V material under MQL. The result shows best surface quality and lower grinding forces using synthetic oil cutting fluid. Tawakoli et al. [32] evaluated the effects of MQL grinding on performance of 100Cr6 workpiece. The better results in-terms of grinding forces and surface roughness were obtained during down cutting using MQL parameters such as oil flow rate, air pressure; spray distance from the contact zone and nozzle position angularly toward the wheel. Sharma et al. [33] reported, the improvement of machinability characteristics using MQL for different machining processes and materials. The author also concluded that MQL is an alternative to conventional machining processes in the future machining operations due to economical and eco-friendly nature of MQL technique of lubrication.

Chetan et al. [34] reported the contribution of cutting fluid is around 20% of the total manufacturing cost. The selected papers on MQL lubrication technique and process optimization discussed and summarized in Table 1.

Shokoohi and Shekarian [35] reported, almost 80% of all occupational health diseases of the machine operators are due to physical contact with cutting fluid. Huang et al. [36] evaluated the grind-hardening characteristics of AISI5140 steel. The result shows the lowest value of surface roughness (1.2 μm) using optimized parameter setting such as flow rate (240 ml/h), air pressure (6 bars), grinding depth (100 μm), wheel speed (45 m/s) and MQL spray distance (60 mm). Chakule et al. [18] have reported better grinding performance in-terms of coefficient of friction (0.3906), temperature at grinding zone (29.07 °C), surface roughness (0.1236 μm), and specific grinding energy (18.95 N/mm^2) using MQL during grinding AISI D3 steel.

Table 1. Literature review summary of MQL and optimization.

Reference Paper	Process	Material	Findings
Tosun and Pihtili [9]	Milling	7075 aluminum alloy	Optimized values based on grey relational analysis give better surface finish and maximum MRR. The feed rate is significant input parameter found for milling performance.
Liu et al. [10]	Turning	Titanium alloy	Coupling method of response surfaces under MQL improves manufacturability of titanium alloy in terms of cutting forces and surface roughness. Feed rate found the most significant parameter.
Gaitonde et al. [11]	Turning	Brass	Minimum surface roughness value varies from 0.23–0.5 μm is obtained using optimized MQL and cutting conditions obtained by Genetic Algorithm.
Ali et al. [12]	Turning	Compacted graphite iron (CGI)	Resultant cutting forces reduced by 2-5%, surface roughness by 25%, flank wear by 10%, crater width by 30% under MQL compared to dry condition.
Hadad [13]	Surface grinding	100Cr6 steel	Tangential force and surface roughness models were developed for improving process performance and to find the effects of MQL parameters such as oil flow rate, air pressure and nozzle distance.
Pavani et al. [14]	Turning	AISI 1040 steel	3%wt boric acid powder in coconut oil and soybean oil improves the machining performance in-terms of tool temperature, cutting forces and surface roughness under MQL.
Rabiei et al. [15]	Surface grinding	Soft steel: CK45&S305Hardsteel: HSS& 100Cr6.	Better values of cutting forces, coefficient of friction and surface finish reported for grinding hard steel. The surface roughness value of soft steel (0.42 μm) improved using optimized values of parameters obtained by Genetic Algorithm (GA).
Sarikaya and Giilli [88]	Turning	Haynes 25	The vegetable base cutting fluid, gives minimum values of flank wear, notch wear, and surface roughness based on optimized process parameter obtained by Grey Relational Analysis (GRA) technique.
Do and Hsu [16]	Hard Milling	AISI H13 steel (SKD 61)	Lowest value of surface roughness (0.145 μm) is obtained using optimized input process parameters: cutting speed (60 m/min), feed rate (0.01 mm/tooth), depth of cut (0.3) and workpiece hardness (45 HRC) obtained by Taguchi method.
Gupta et al. [17]	Turning	Titanium (Grade-II)	Lower values of tangential force (132.52), tool wear (0.31), surface roughness (0.53) and tool-chip contact length (0.793) are obtained using optimized process parameter determined by Particle Swarm Optimization (PSO) technique.
Chakule et al. [18]	Surface grinding	AISI D3 steel	Lowest surface roughness (0.124 μm), coefficient of friction (0.391) specific grinding energy (24.32 N/mm^2), and temperature (29.07 °C) is obtained under MQL.
Mia et al. [19]	Milling	AISI 4140 steel	Grey based Taguchi method gives lowest values of surface roughness (0.67 μm), and cutting force (6.5 N) using optimized input parameters.
Khan et al. [20]	Surface grinding	AISI D2 steel	Grey-Taguchi method reduces temperature up to (67.4%), cutting forces (79.26%), compared to dry grinding using optimized values of process parameters.

Table 1. (continued).

Reference Paper	Process	Material	Findings
Viswanathan et al. [21]	Turning	Magnesium alloy (AZ91D)	Optimum conditions of MQL system obtained from Taguchi based GRA shows improvement in flank wear by 16.66%, surface roughness by 52.94%, and cutting temperature by 11.36%.
Muaz and Choudhury [22]	Milling	AISI 4340	Optimized process parameters based on Taguchi-Gray relational analysis and multi-objective genetic algorithm gives better process performance using 10 wt.% boric acid in water based cutting fluid.
Tamang and Chandrasekaran [23]	Turning	Inconel-825	Lowest values of surface roughness (0.39 μm), tool wear (15.37 μm) and cutting temperature (56.47 °C) using optimized input process values by Genetic Algorithm is obtained.
Awale et al. [24]	Plunge grinding	AISI H13 tool steel	Average droplet size (51.03 μm) at nozzle angle (12°) is obtained using optimal mist parameters: air pressure (4 bar), flow rate (200 ml/h), and stand-off distance (50 mm) determined by grey relational analysis. The lowest grinding force, specific energy, grinding temperature, and surface roughness are also reported.
Abas et al. [25]	Turning	Aluminum alloy 6026-T9	MQL condition gives lowest surface roughness (1.14 μm) and maximum tool life and MRR (275 cm^3/s) using optimized process parameters obtained by Taguchi SN ratios.
Shastri et al. [26]	Turning	Titanium alloy (Grade II)	Multi- Cohort Intelligence (CI) optimization algorithm under MQL machining reduces cutting force by 8%, tool wear by 42%, tool-chip contact length by 38%, and surface roughness by 15% compared with PSO.
Gupta et al. [27]	Turning	2205 duplex steel	MQL nozzle position (flank + rake direction) produces the lowest surface roughness (1.55 μm). Moreover, dual-jet MQL gives lowest energy consumption (229 kJ) and tool wear (0.15 mm).
Van and Nguyen [28]	Roller-Burnishing	Hardened steel 5145	Decreased of cylindricity, circularity and surface roughness by 53.14%, 57.83%, and 72.97% respectively is obtained using optimal input values determined by artificial neural network.

2.2 Thermal properties of nano fluid

The better process responses has been reported by different researchers using MQL but poor lubrication and cooling effects of soluble oil restricted to achieve the best results. Recently, the nano fluid has been widely used in machining due to potential properties of nano fluid. The nano fluid is prepared by mixing nano particles of size (10–100 nm) in base fluid. The base fluid can be water, oil or ethylene/propylene glycol. The better tribological properties of nano particles especially high surface-to-volume ratio, improve the heat capacity of base fluid. The stable nano fluid without any nano particle agglomeration is the prime requirement to obtain better results of nano fluid in application. The selected papers on nano fluid are discussed below.

Zhang et al. [37] investigated the effect of nano particle size, concentrations on thermal conductivity and thermal diffusivity. Different nano fluids such as Au, Al_2O_3, TiO_2, CuO and CNT mixed in water were used for experimentation. Saidur et al. [38] have reported the scope of nano fluid in various areas due to high thermal conductivity of nanofluids. Xie et al. [39] discussed the techniques of thermal conductivity measurement and important parameters for improving the thermal conductivity. Yu et al. [40] investigated thermal transfer ability of Al_2O_3 nano fluid for different volume concentrations and temperature range. The nano fluids were prepared in base fluid of proportion 45% ethylene glycol and 55% water. The result shows improvement in thermal conductivity using 3.0 vol.% concentration whereas heat transfer coefficient increases up to 106% using 2.0 vol.% concentrations. Mishra et al. [41] have focused the important parameters of nano particles and nano fluids that significantly affects on viscosity such as shape and size of nano particles, temperature, pH, surfactants, dispersion techniques, particle aggregation, and shear rate. The theoretical models of viscosity are also discussed in this paper. Mao et al. [42] investigated the suspension stability of Al_2O_3 nanofluid. The best stability of nano fluid found using nano fluid parameters such as mass fraction of dispersant (0.5%), pH value (7), and sonication time (1 h). The better process performance was reported using stable nano fluid under MQL. Sonawane et al. [43] evaluated the experimental and theoretical finding of thermal conductivity of TiO_2 nano fluids at different fractions. The result shows improvement of thermal conductivity of water based nano fluidby 22% using 6 vol.% concentrations. The Bruggeman model gives more closely results of thermal conductivity. Devendiran and Amirtham [44] have discussed the reviews of nano fluid preparation, and characterization techniques of nano fluid. The paper also focused on importance of thermal property and stability of nanofluid and the challenges during nanofluid preparation and application. Chiam et al. [45] have evaluated the thermal conductivity and dynamic viscosity of Al_2O_3 nano fluids when mixed in water (W) and ethylene glycol (EG) at different volume ratio. The different concentration range and temperature were considered while evaluating the thermal conductivity and viscosity of nano fluids. The result shows improvement of thermal conductivity and viscosity of Al_2O_3 nanofluid using 1.0 vol.% concentration when mixing ratio of water and ethylene glycol was 40:60. Chaudhari et al. [46] have evaluated the heat transfer performance of Al_2O_3 and CuO nano fluids mixed in water at different vol.% concentrations. The result shows improvement in thermal conductivity ratio of Al_2O_3 and CuO nano fluids by 19.74% and 36.21% respectively whereas absolute viscosity ratio is enhanced by 29.77% and 48.71% respectively using 1 vol.% concentration.

2.3 Nanofluid MQL technique

The better thermo-physical properties of nano fluid and MQL approach to supply cutting fluid effectively at machining contact interface is the best technique for enhancing process performance. Mao et al. [47] have evaluated the importance of spraying parameters for effective penetration of nanofluid under MQL during grinding AISI52100 steel. The process performance in-terms of grinding forces, temperature and surface roughness improves significantly due to proper setting of spraying parameters such as nozzle position angularly 15° from horizontal toward the grinding wheel, air pressure of 0.6 MPa, and spray distance of 20 mm. Manoj Kumar and Ghosh [48] have reported, the grinding performance of AISI 52100 steel in-terms of G ratio (38), tangential grinding force (22 N), normal force (65N) and surface finish (0.35 μm) using MWCNT nano fluid under SQL, coolant flow rate of 350 ml/h at 3 bar air pressure. Setti et al. [1] investigated the performance of nano fluids under MQL for surface grinding process during grinding Ti-6Al-4V material. The Al_2O_3 and CuO nano particles of different vol.% concentration such as 0.05, 0.1, 0.5 and 1% mixed in water were used during experimentation. The result shows significant reduction of coefficient of friction and cutting forces by Al_2O_3 nano fluid using 1 vol.% concentration, and flow rate of 200 ml/h. The better surface integrity, chip formation and wheel morphology found better by Al_2O_3 nanofluid with MQL. Wang et al. [49] have evaluated the lubricating performance of Al_2O_3 nano fluid on nickel alloy GH4169 under different machining conditions. The lowest value of sliding friction coefficient (0.348), specific sliding grinding energy (82.13 J/mm^3), and surface roughness (0.302 μm) obtained whereas G-ratio (35.94) and surface morphology of work piece surface improved significantly by Al_2O_3 nanofluids under MQL using optimized process parameters. The better lubricating performance of Al_2O_3 nanofluids obtained compared to MoS_2 and SiO_2 nanofluids. The machining performance at different lubricating conditions is shown in Figure 2. Wang et al. [50] have concluded the tribological properties and grinding performance of Ni-based alloy GH4169 using Al_2O_3nanofluids MQL. The nano particles of different volume % concentrations were mixed in palm oil. The result shows better tribological performance and grinding results in-terms of force ratio (0.28), specific grinding energy (65 J/mm^3), G-ratio (32), and surface roughness (0.301 μm) using 1.5 vol.% concentration. Paul et al. [51] have investigated the performance of Al_2O_3 and MWCNT nano fluids on Ti-6Al-4V plates under different grinding environments. The reduction of specific tangential force (0.77 N/mm), specific energy (60.49 J/mm^3), and surface roughness (0.62 μm) were obtained by MWCNT nanofluid under SQL using 1 wt.% concentration. Patole and Kulkarni [52] have reported, the lowest value of surface roughness (1.26 μm), cutting force (7.69 kgf) by MWCNT nano fluid under MQL using 0.2% concentration. Setti et al. [53] have discussed the effectiveness of water based Al_2O_3 nano fluid under MQL for machining Ti-6Al-4V material. The result shows the lowest values of tangential cutting force (41.92 N), coefficient of friction (0.26), and surface roughness (0.4 μm) obtained using 0.1 vol.% nano fluid concentration, and coolant flow rate of 150 ml/h at 8 bars air pressure. Seyedzavvar et al. [54] have evaluated, the lubricating and cooling properties of graphite nano fluids using MQL for grinding AISI 1045 steel. The research work shows better grinding results in-terms of cutting forces, subsurface temperature of work piece, surface roughness, and micro-hardness. The work piece surface morphology improved using graphite nano fluid under MQL compared to other machining environments.

Li et al. [55] have evaluated, the surface integrity of TC21 alloy using graphene nano fluid under MQL. The nano particle weight concentration of 0.1% was used to prepare the nano fluid in oil. The significant reduction of surface roughness by 53.81%, micro-hardness by 14.10%, specific milling force by 26% and milling temperature by 62% were reported using nano fluid MQL compared to dry machining. Das et al. [56] have explained, the technological performance characteristics of hardened AISI 4340 steel to evaluate the machinability of turning process using vegetable based nano fluids. The result shows better performance by CuO nano fluid using 0.1% concentration followed by Fe_2O_3 and Al_2O_3 nanofluids. Chakule et al. [57] reported reduction of grinding forces by 33.50% and surface roughness by 21.51% during grinding OHNS material using Al_2O_3 nanofluid at 0.30 vol.% concentration under MQL. Giinan et al. [58] have discussed the performance of Al_2O_3 nano fluid with MQL on Hastelloy C276 alloy in milling process. The result shows improvement of tool wear and tool life by 23% and 10% respectively by

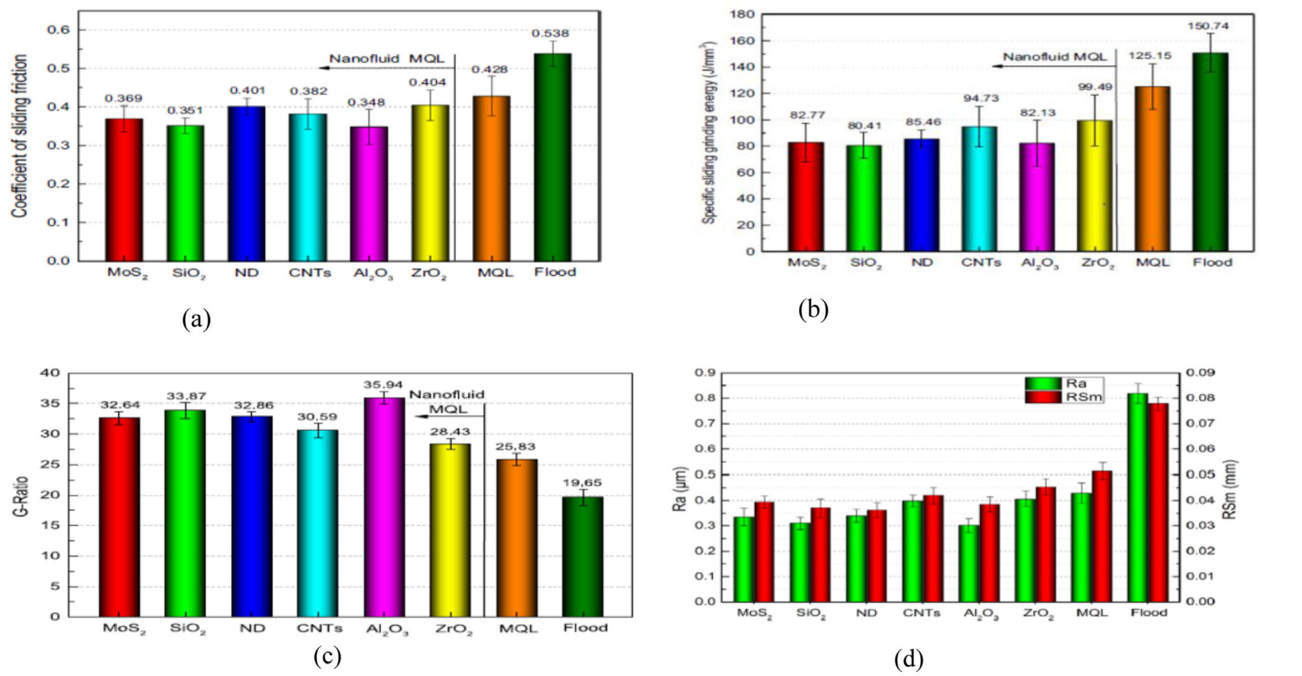


Fig. 2. Machining performance at different lubrication conditions: (a) Sliding friction coefficient; (b) Specific sliding grinding energy; (c) G-ratio; (d) Surface roughness [49].

Al_2O_3 nano fluid at 1 vol.% concentration using optimized machining parameters. Manoj Kumar and Ghosh [59] reported the cooling and lubricating effect of small quantity cooling lubrication (SQCL) technology on responses such as G ratio, grinding temperature, force ratio, and specific grinding energy during grinding AISI52100 steel using MWCNT nano fluid. Patole et al. [60] have presented a review of MQL-based application of cutting fluids such as mineral oils, vegetable oils and nano fluids used for different machining processes, such as, drilling, turning, milling and grinding. The findings of study show that MQL with nano fluid can substitute the flood lubrication for better surface finish. Sarikaya et al. [61] have presented, the review on machining and sustainability characteristics of MQL, nano fluids-MQL, Ranque-Hilsch vortex tube MQL (RHVT + MQL), cryogenic-MQL as alternative to flood cooling applications in the cutting of light-weight materials such as Al, Mg and Ti alloys. The review paper by Sen et al. [62] focused the capabilities of eco-friendly MQL technique for sustainable manufacturing. The selected papers on nano fluid MQL and optimization is discussed and summarized in Table 2.

2.4 Hybrid nano fluid MQL technique

The literature review of nano fluid MQL process stated the better process performance for a wide material except materials of extremely hard nature. The limitations of nano fluid MQL during machining difficult-to-cut materials are overcome by hybrid nano fluid MQL technique. In nano fluid MQL, the nano particles are used for preparing the nano to obtain better thermal performance. Zhang et al. [73] have explained the performance of oil-based MoS_2-CNT hybrid nanofluids for grinding Ni-based alloy (Inconel 718). In hybrid nano fluid of MoS_2-CNT, the mixing ratio of 2:1 and concentration of 6 wt.% was used for conducting the experiments. The lowest values of grinding forces (91.28 N), coefficient of friction (0.2757), and surface roughness (0.294 μm) obtained using optimal concentration of hybrid nanofluid under MQL. The better work piece morphology obtained using hybrid nano fluid under MQL compared to nano fluid MQL grinding process. The similar lubricating effect of MoS_2-CNTs hybrid nano fluids was evaluated for Ni-based alloy by Zhang et al. [74]. Zhang et al. [75] have investigated, the performance of Ni-based alloy using Al_2O_3/SiC hybrid nano fluid MQL. The reduction of grinding force ratio, specific grinding energy and surface roughness obtained by hybrid nano fluids when mixed in oil, using mixing proportion of 2:1. The nano fluid of different concentrations and nanoparticle type combination were used for evaluating the performance of grinding process. The result shows the lowest grinding force ratio (0.274) and surface roughness (0.328 μm) obtained using 8 wt.% concentration of nanofluid. Kumar et al. [76] have investigated the grinding performance of silicon nitride using mono and hybrid nanofluids at different concentrations and grinding environments. The reduction of grinding forces, specific grinding energy, grinding force ratio, surface roughness obtain using MoS_2-WS2 hybrid nanofluid, mixing ratio of 1:1. The better chip formation and surface integrity obtained using hybrid nano fluids. Jamil et al. [77] have evaluated, the effectiveness of cryogenic and hybrid nanofluids MQL cooling techniques for machining Ti-6Al-4V using CNC machine. The CO_2 (dry ice) and Al_2O_3-MWCNTnanofluids mixed in distilled water was used as the lubricant for cryogenic and hybrid nano fluids MQL cooling techniques.

Table 2. Summary of literature review of nanofluid MQL and optimization.

Reference Paper	Nano fluid	Nano particle size	Process	Material used	Findings
Mao et al. [47]	Al_2O_3 nanoparticles mixed in deionized water	60 nm	Surface grinding	AISI 52100 steel	Reduction of specific tangential grinding force (1.90 N/mm), coefficient of friction (0.3), surface roughness (0.2 µm) and grinding temperature (350 °C) obtained using 0.75 wt% concentration of nanofluid.
Setti et al. [1]	Al_2O_3 and CuO mixed in water	40 nm	Surface grinding	Ti-6Al-4V	Water based Al_2O_3 nanofluid improves grindability of material by reducing tangential grinding forces, coefficient of friction, grinding zone temperature.
Nam et al. [63]	Nanodiamond particles in paraffin and vegetable oils (concentration: 2, 4% vol.)	30 nm	Micro-drilling	Aluminum	The optimized process parameters obtained by genetic algorithm gives minimum drilling torques and thrust forces and maximized material removal rate (MRR).
Gupta et al. [17]	Aluminium oxide (Al_2O_3), molybdenum disulfide (MoS_2) and graphite mixed in vegetable oil (concentration: 3 wt.%)	40 nm	Turning	Titanium alloy	Optimized conditions such as cutting speed (215 m/min), feed rate (0.10 mm/rev), approach angle (83°) and graphite based nanofluid reduces the cutting forces, tool wear, surface roughness and cutting temperature. Particle Swarm Optimization (PSO) and Bacterial Foraging Optimization (BFO) found better technique of optimization.
Wang et al. [49]	MoS_2,SiO_2, Nanodiamond,CNT, Al_2O_3,and ZrO_2 nanoparticles mixed in palm oil (6% mass fraction)	CNT (average length 10–30 µm) & other nanofluid (50 nm)	Grinding	Nickel alloy GH4169	The reduction of sliding friction coefficient (0.348), specific sliding grinding energy (82.13 J/mm^3), and surface roughness (0.302 µm) obtained using Al_2O_3 nanofluid.
Patil and Patil [64]	Water based Al_2O_3 and CuOnanofluids	100 nm	Surface grinding	En8 flat plate	The best optimized process parameters such as CuO nanofluid (2% concentration), depth of cut (5 µm), coolant flow rate (5 ml/min), feed rate (2000 mm/min), and wheel speed (35 m/s) obtained by multi-objective grey relational analysis. It gives better G ratio and surface finish.
Wang et al. [50]	Al_2O_3 mixed in palm oil	50 nm	CNC surface grinder	Ni-based alloy GH4169	The better tribological performance such as force ratio (0.28), specific energy (65 J/mm^3), G-ratio (30), and surface roughness (0.301 µm) reported using nanofluid of 1.5 vol.% concentration.

Table 2. (continued).

Reference Paper	Nano fluid	Nano particle size	Process	Material used	Findings
Paul et al. [51]	MWCNT and Alumina in de-ionized water	40 nm	Surface grinding	Ti-6Al-4V plates	1 wt% MWCNT nanofluid gives the lowest grinding forces (1.04 N/mm), specific energy (62.4 J/mm^3) and surface roughness (0.62 µm) using optimized process parameters.
Setti et al. [53]	Al_2O_3 nanoparticle mixed in water (0.1 vol.%)	40 nm	Surface grinding	Ti-6Al-4V	Al_2O_3 nanofluid reduces coefficient of friction, surface roughness whereas wheel life improved.
Chakule et al. [65]	Al_2O_3 nanoparticle mixed in distilled water	30–50 nm	Horizontal surface grinding machine	EN31 soft and hard type	Better surface finish is obtained for hardened material. Optimized values of Jaya algorithm gives reduction of surface roughness (0.138 µm) value for soft steel.
Seyedzavvar et al. [54]	Graphite nanoparticles mixed in distilled water plus 20 vol.% canola oil	32 nm	Surface grinding	AISI 1045 steel	Graphite nanofluidof 0.35 vol.% concentration under MQL gives lower specific tangential force, force ratio and surface roughness.
Sirina and Kıvak [66]	hBN, graphite, MoS_2 mixed in vegetable oil (concentration: 0.25, 0.50, 0.75 and 1.0 vol.%)	80 nm	Milling	Inconel X-750 superalloy	Optimized value of hBN nanofluid gives superior performance in-terms of surface roughness, cutting force and tool wear using 0.50 vol.% nanofluid concentrations.
Sharmin et al. [67]	CNT-water based nanofluids (concentration: 0.2, 0.3, 0.4 and 0.5%)	Single walled, size less than 30 nm	Milling	42CrMo4 hardened steel	Stable nanofluid concentration of 0.3 vol.% gives reduction in temperature by 29%, surface roughness by 34%, cutting forces by 33% and reduction in tool wear by 39%.
Seyedzavvar et al. [68]	CuO added in vegetable oil	20 nm	Surface grinding	AISI 1045 steel	1% mass fraction of CuO nanoparticles in base fluid reduces wear rate by 71.2%, tangential grinding force by 20%, and surface roughness by 30% compared to lubricant without nanoadditive.
Ibrahim et al. [69]	Graphene nanoplatelets mixed in palm oil (0.1 wt.% to 0.4 wt.%)	Diameter (5–10 µm), Thickness (3–10 nm)	Grinding	Ti-6Al-4V alloy	GNPs (0.1 wt. %) decreased the cutting forces and save the energy by 91.78% compared to dry cutting. The surface quality improved using nanofluid.
Manoj Kumar and Ghosh [59]	MWCNT mixed in de-ionized water	–	Surface grinding	Hardened AISI 52100 steel	Reduction of specific energy, force ratio, and temperature is obtained. The maximum enhancement of thermal conductivity is obtained using 1 wt.% nanofluid concentration.

Table 2. (continued).

Reference Paper	Nano fluid	Nano particle size	Process	Material used	Findings
Prashantha Kumar et al. [70]	Al_2O_3, CuO mixed in emulsified base fluid (concentrations: 0.3, 0.5 and 0.7 vol.%)	30–50 nm	Turning	Duplex stainless steel (DSS-2205)	Better result of surface roughness and cutting force by Al_2O_3 nanofluid (0.7%) is obtained using optimized process parameters based on Desirability Function Analysis.
Tiwari et al. [71]	Al_2O_3, CuO, TiO_2 mixed in water (concentration: 0, 1,2,3,4,5 and 6%)	Average diameter 50-75 nm	Grinding Milling Drilling Turning	Analysis through MATLAB	Input parameters such as thermal conductivity, specific heat, viscosity and density whereas responses like surface roughness, tool wear, machining temperature were considered. Better result obtained by Al_2O_3nanofluid using 5-6 vol.% concentration.
Yiicel et al. [72]	MoS_2 mixed in mineral oil (0.6% vol. conc.)	80 nm	Turning	AA 2024 T3 aluminum alloy	Improvement of surface roughness and surface topography is obtained. Built-up edge formation is also significantly reduced.

The reduction of surface roughness and cutting forces by 8.72% and 11.8% respectively were reported using hybrid nano fluid MQL compared to cryogenic cooling whereas tool life increased by 23%. Gugulothu and Pasam [78] have explained the thermo physical properties of CNT/MoS_2 hybrid nanocutting fluids for machining AISI 1040 steel. The mixing proportion of 1:2 and concentrations such as 0.5%, 1%, 1.5%, 2%, 2.5% and 3% were used during experimentation. The result shows significant reduction of cutting forces, tool flank wear, cutting temperature, and surface roughness by hybrid nano fluids with MQL using 2 wt.% concentrations. Haghnazari and Abedini [79] have evaluated the effect of Al_2O_3 and CuO hybrid nano fluids using MQL for machining AISI 4340 alloy steel. The different mixing proportions of nano fluids were used for conducting the turning trials. The lowest value of cutting forces and surface roughness obtained using mixing proportion of CuO nano fluid (0.75) and Al_2O_3 nano fluid (0.25) and optimized process parameters. Tanmai Sai Geetha et al. [80] have evaluated the grinding performance of AISI4340 under different grinding environments. The least cutting temperature was reported by graphene and copper hybrid nano fluids under MQL using mixing proportion of 1:1 and concentration of 0.3wt%, but the least flank wear obtained by graphene nano fluid. Dubey and Sharma [81] have focused, on the use of hybrid nano fluids in different machining operations namely turning, grinding, and drilling. The review paper deals with the tribological properties of different hybrid nanofluid and the temperature control in the machining operations. The selected papers on hybrid nano fluid MQL technique for machining are discussed and summarized in Table 3.

3 Preparation and characterization of nanofluid

The nano fluid preparation and its characterization are important before use in application for better results. The nano particles of different metals or oxides; size less than 100 nm is mixed in base fluids such as water, ethylene glycol, oils in different proportion for nano fluid preparation.

3.1 Nanofluid preparation

The nanofluid preparation and characterization are important before use of nanofluid in application. The nanoparticles of different metals or oxides; size less than 100 nm is mixed in base fluids such as water, ethylene glycol, oils in different proportion for nanofluid preparation. The steps to prepare the nanofluid are firstly the amount of nanoparticles in 100 ml base fluid is determined based on vol.% concentration and density of nanoparticles. The second step is proper selection of surfactants and quantity requirement for nanofluid preparation to avoid agglomeration. Thirdly, homogeneous mixing and sonication is needed to obtain stable nanofluid. Lastly calibrated instruments are required to measure the thermal properties such as thermal conductivity, viscosity and stability of nanofluid. Prashantha Kumar et al. [70] prepared the nanofluids of aluminium oxide (Al_2O_3) and copper oxide (CuO) nanoparticles of average size 30–50 nm. The analytical grade of nanoparticles and purity of 99.50% was used to

Table 3. Summary of literature review of hybrid nanofluid MQL and optimization.

Reference Paper	Nanofluid	Nanoparticle size	Process type	Material used	Findings
Zhang et al. [73]	MoS_2-CNTs (concentration: 2, 4, 6,8,10, and 12 wt.%)	MoS_2:30 nm. CNT: 10–30 nm long and 30 nm diameter.	Surface grinding	Ni-based alloy	The lowest value of coefficient of friction (0.274) and surface roughness (0.328 μm) obtained by hybrid nanofluids using 8 wt.% concentrations.
Zhang et al. [75]	Al_2O_3-SiC (Mixed in synthetic lipids. Mass fraction of 6% and mixing ratio of 1:1, 1:2, and 2:1)	50 nm	Grinding	Ni based alloy	Lowest values of tangential force (20.03 N), grinding force ratio (0.28), specific grinding energy (60.68 J/mm^3), and surface roughness (0.323 μm) obtained using hybrid nanofluids, mixing proportion of 2:1.
Singh et al. [82]	Mixing alumina nanofluid with graphene nanoplatelets in water (volumetric ratio: 90:10 and concentrations: 0.25, 0.75 and 1.25 vol.%)	Al_2O_3:45 nm Graphene: Average thickness (11–15 nm) and particle size (5 μm).	Turning	AISI 304 steel	Hybrid nanofluid with MQL significantly reduces the surface roughness by 20.28%, cutting forces by 9.94%, thrust force by 17.38% and feed force by 7.25% compared to Al_2O_3 nanofluid.
Anil Kumar et al. [76]	MoS_2-WS_2, WS_2-hBN, MoS_2-hBN (Mixing ratio: 1:1 and concentration: 0.5 wt.%)	MoS_2:90 nm, h-BN: 70 nm	Diamond grinding	Silicon nitride (Si_3N_4)	Reduction of normal grinding force and specific grinding energy by 27% and 39% respectively whereas surface roughness and chipping layer depth of silicon nitride workpiece reduces by 41% and 86% using MoS_2-WS_2 hybrid nanofluids compared to water based fluid.
Jamil et al. [77]	Al_2O_3-CNT (Mixed in vegetable oil ratio of 90:10)	Al_2O_3: 30 nm, CNT (length of 10-30 nm and diameter of 30 nm)	Turning	Ti-6Al-4V	Hybrid nanofluids reduces the surface roughness, and cutting force by 8.72% and 11.8% respectively whereas the tool life increases by 23% compared to cryogenic cooling.
Sai Geetha et al. [80]	Graphene–copper (Mixing proportion: 1:1 in water soluble oil	Cu: average size 30-50 nm and Graphene: diameter: 2 μm)	Turning	AISI 4340 steel	Least flank wear, and decrease in temperature is obtained using hybrid nanofluids, mixing proportion of 1:1 compared to other machining conditions.
Gugulothu et al. [78]	CNT/MoS_2 (Mixing ratio: 1:2 and concentration: 0.5, 1, 1.5, 2, 2.5 and 3 wt.%)	CNT: 30 nm MoS_2: 30 nm	Turning	AISI 1040 steel	CNT/MoS_2 (2 wt.%) reduces coefficient of friction (0.038), cutting forces (162.7 N), temperature (140 °C), surface roughness (2 μm) and tool flank wear (0.05).
Haghnazari et al. [79]	Al_2O_3-CuO mixed in water (Concentration: 1, 0.75, 0.50, and 0.25 wt.%).	CuO:40 nm Al_2O_3: 20 nm	Turning	Alloy steel AISI4340 steel	Mixing proportion of CuO (0.75%) and Al_2O_3 (0.25%) gives the lowest value of resultant forces (364 N), and surface roughness (0.335 μm).

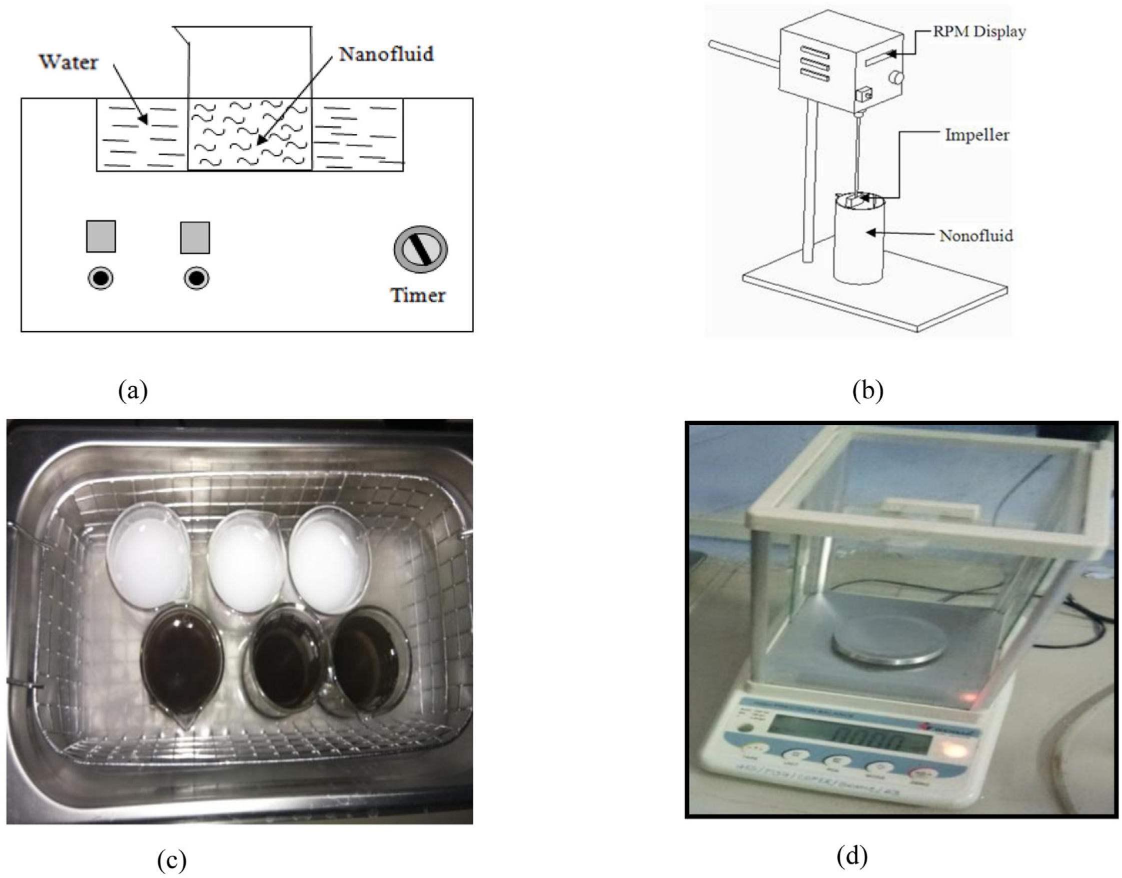


Fig. 3. Preparation of nanofluids: (a) Ultrasonic cleaner; (b) Magnetic stirrer; (c) Nanofluids; (d) Weighing machine [70].

prepare the nanofluids of 0.3, 0.5 and 0.7 vol.% concentrations in distilled water. The definite quantity of nanoparticles was measured by electronic balance for nanofluid preparation, determined based on true density of nanoparticle and volume fraction of nanoparticle in 100 ml distilled water. The anionic dispersant sodium dodecyl benzene sulphonate (SDBS), weight of 10% of total nanoparticle requirement was mixed for avoiding agglomeration of nanoparticles during nanofluid preparation. The paper reported process such as sonication of nanofluid for 2 h using ultrasonic cleaner and afterwards mixing by 1 h using magnetic stirrer at 1000 rpm for preparing the stable nanofluids. The preparation of nanofluids is shown in Figure 3.

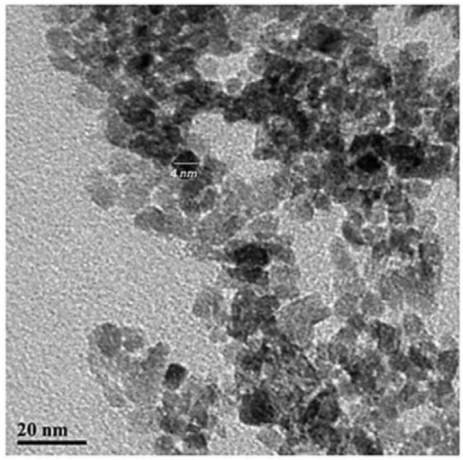
3.2 Characterization of nanofluid

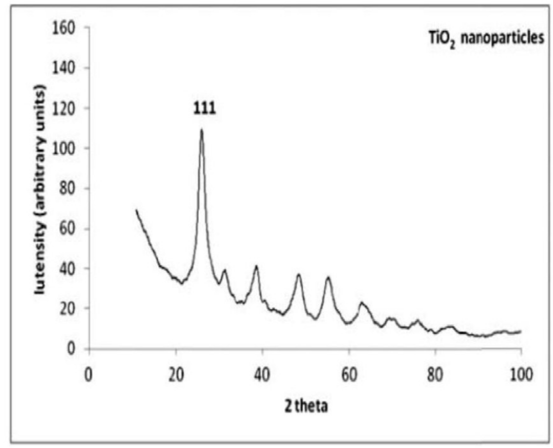
Sonawane et al. [43] focused the importance of characterization of TiO_2 nanoparticles during nanofluid preparation. In this paper, different characterization techniques of nanoparticles such as transmission electron microscopy (TEM), energy-dispersive X-ray spectroscopy (EDX), X-ray diffraction (XRD) are discussed. The characteristics techniques of nanofluid for measurement of thermal conductivity, viscosity and stability are also discussed. The Field Emission Scanning Electron Microscope (FESEM) is used to confirm the nanoparticles characteristic such as shape, average particle size and particle nature whether isolated or agglomerated. The energy-dispersive X-ray spectroscopy (EDX) measured the composition and percentage of each element. The X-ray diffraction (XRD) measurement recorded from 10 to 90 (2 theta) with a scanning step of 0.017 to investigate the crystal structure and related information. The KD2 Pro thermal properties analyzer apparatus is used to measure the thermal conductivity of nanofluids and Brookfield viscometer for viscosity measurement. The paper stated value of zeta potential which is higher than +30 mV or lower than −30 mV to obtain stable nanofluid. The characterization of nanoparticles and nanofluid are shown in Figure 4.

The effect of TiO_2 nanofluids of different volume fraction on effective thermal conductivity is evaluated for different base fluids such as water, ethylene glycol and paraffin oil. The effect of sonication time on thermal conductivity is also presented. The paper reported better results of effective thermal conductivity enhancement for TiO_2 nanofluid especially when mixed in paraffin oil and increased of sonicaion time. The effective thermal conductivity as a function of volume fraction of nanoparticles is shown in Figure 5.

4 Experimental setup

The literature review discussed in Section 2, reported the best machining results using nanofluid (mono and hybrid types) with MQL. Liu et al. [83] developed experimental





(a) (b)

(c) (d)

Fig. 4. Characterization of nanoparticles and nanofluid: (a) TEM micrograph (b) XRD image (c) KD2 Pro thermal properties analyzer (d) Nanoplus for zeta potential [43].

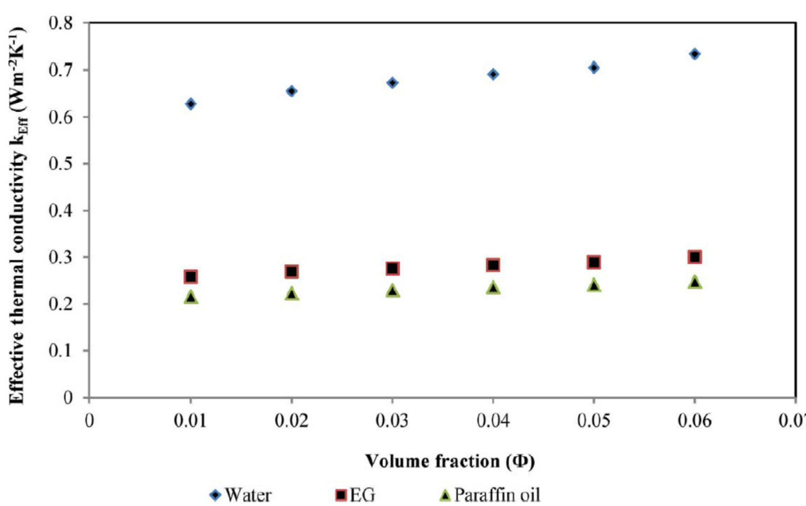


Fig. 5. Effective thermal conductivity as a function of volume fraction of nanoparticles [43].

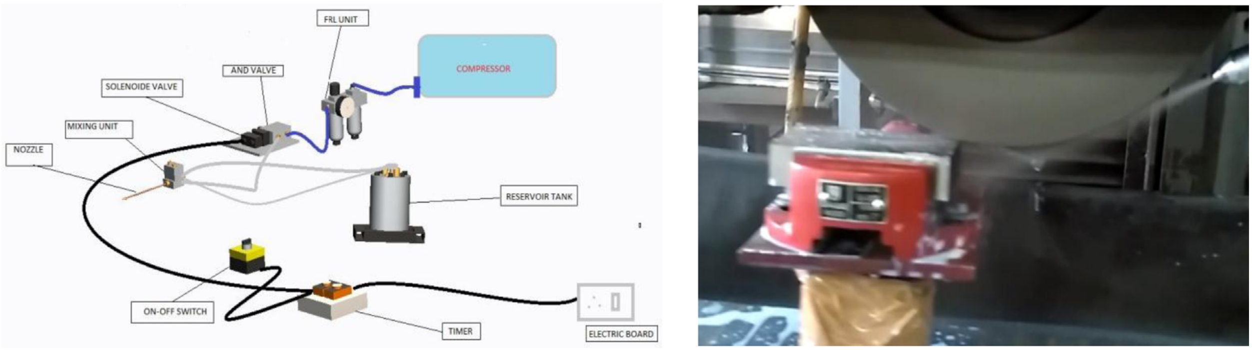


Fig. 6. Block diagram of MQL and Experimental setup [83].

setup for horizontal surface grinding machine for conducting the experiments using nanofluid under MQL. The block diagram of MQL and experimental set up is shown in Figure 6. The listed parts of MQL setup are compressor, FRL unit, AND valve, coolant tank, solenoid valve, mixing unit, timer, ON/OFF switch and nozzle. With the help of MQL setup, the atomization of cutting fluid occurs into mist due to compressed air pressure and mist cutting fluid then supply to machining contact interface. The levels of nanofluid MQL machining process parameters are important to select accurately for obtaining better responses such as grinding forces, temperature, surface roughness and MRR while investigating the performance of machining process. The paper reported experimentation on Ti-6Al-4V material under dry, flood, MQL and nanofluid MQL machining environments. The volume fraction of 2% Al_2O_3 nanofluid in distilled water, as the nanocoolant used for conducting the nanofluid MQL experiments. The experimental design plan is important for conducting the experiments accordingly. The paper also focused the important parameters such as nozzle position, wheel dressing, and process parameters to penetrate the cutting fluid effectively at contact interface and to obtain better process performance. The different attachments such as strain gauge dynamometer for cutting force measurement, thermocouple for temperature measurement, and surface profiler for surface roughness measurement fitted to horizontal grinding machine to measure the responses. The paper reported significant results of responses in-terms of cutting forces, surface roughness, and material removal rate under nanofluid MQL grinding environment. The analysis of workpiece surface and grinding debris is also reported by using scanning electron microscope (SEM).

5 Modeling and optimization of process parameters

Based on literature, better machining results have been reported on micro lubrication techniques. At the same time, the design of experimentation and process optimization are equally important to improve the process performance. The global setting of parameters gives quality production economically. It helps to avoid the operator problem of setting parameter values for each experimental run based on judgment and experience. Many researchers have been focusing on the area of process optimization since the last decades. The literature on optimization of micro-lubrication techniques process parameters are discussed and summarized in Tables 1–3.

Siva Prasad et al. [84] have presented the review on experimental design plan for plasma arc welding process. The paper also focused on response surface method, Taguchi's method and factorial method in Welding. Krishnaiah and Shahabudeen [85], Montgomery [86] and Mathews [87] have discussed the importance of design of experiments, analysis, modeling and optimization for improvement of process performance. Sayuti et al. [88] have performed the optimization of nano fluid MQL turning process using Taguchi and fuzzy logic approach. The result shows minimum tool wear (19.50 μm) and surface roughness (0.44 μm) using optimized parameters namely nano particle concentration of 0.5 wt.%, air pressure of 1 bar and nozzle angle position of 30°. Rabiei et al. [15] have explained the modeling and optimization of soft steel namely CK45 and S305 under MQL grinding. The modeling of response was carried out by response surface methodology whereas the optimal values determined by genetic algorithm (GA). The result shows the lowest value of surface roughness (0.42 μm) using optimized setting of parameters. Hadad [13] has discussed the modeling and analysis of responses under MQL for grinding hardened 100Cr6 steel. Sarikaya and Giillii [89] have investigated the optimized process parameters for turning cobalt base super alloy Haynes 25 using Taguchi based GRA technique. The result shows improvement of grey relational grade (GRG) by 39.4% using optimized values.

Recently researchers are focusing more on nontraditional techniques for process optimization due to simplicity and best results. The nontraditional techniques categories under evolutionary or meta-heuristic inspired by nature or animal behavior and are based on iterations. The literature review based on optimization of conventional and modern machining process by evolutionary techniques is discussed below.

Nam et al. [63] have discussed the performance of nano fluid MQL micro-drilling process considering paraffin oil and vegetable oil as the base fluid. The quadratic models of responses were developed and their validity checked by ANOVA and coefficient of determination value. The optimized values obtained by genetic algorithm for paraffin oil gives the better performance in-terms of torque (0.0087 N-m), thrust force (0.53 N), and MRR

($2.08\,mm^3/min$). Gupta et al. [90] have discussed the optimization of turning process parameters under MQL using desirability function approach and particle swarm optimization (PSO). The weight was assigned to the responses based on their importance in application to develop the Combine Objective (CO) function. The result shows better value of responses such as tangential force (132.52 N), tool wear (0.31 mm), surface roughness (0.53 μm), and tool-chip contact length (0.793 mm) using optimized input process parameters obtained by PSO. Rao and Rai [91] have evaluated the optimization of casting process namely squeeze, continuous and die casting using Jaya algorithm and quasi-oppositional based learning (QO) Jaya algorithm. The better machining results reported using optimized values of process parameters obtained by Jaya and QO-Jaya algorithms compared to GA, SA, PSO and TLBO algorithms. Similarly Mia et al. [19] have investigated the optimized process parameters using Taguchi based Grey relational analysis (GRA) for milling hardened AISI 4140 steel. The result shows the lowest value of cutting force (6.5 N) and surface roughness (0.67 μm) using optimized process parameters. Patole and Kulkarni [52] have investigated the performance of nanofluid MQL process during turning of AISI 4340. The full factorial method used for designing the experimental matrix. The cutting performance investigated based on GRG and result shows improvement of GRG value by 4.32%. The minimum surface roughness and cutting force values obtained using fluid flow of 140 ml/h at 5 bar air pressure. Rao et al. [92] have reported the performance of wire-electric discharge machining (WEDM), laser cutting process, electro-chemical machining (ECM) and focused ion beam (FIB), micro-milling machining using multi-objective (MO) Jaya algorithm. The regression model used in MO Jaya algorithm is same as considered in previous paper of author. The better machining performance using MO-Jaya algorithm reported by MO Jaya algorithm compared to other optimization techniques. Similar work is performed by Rao and Rai [93] for submerged arc welding (SAW) process using QO Jaya algorithm. The results of QO Jaya algorithm was compared with the results of other algorithms such as GA, PSO, Imperialist Competitive Algorithm (ICA) and TLBO. The result shows better process performance using QO-Jaya algorithm as convergence speed of responses is high. Chakule and Chaudhari [94] have, investigated the hardness effect on surface roughness for nanofluid MQL grinding process. The experimentation was performed on EN 31 steel; hard and soft nature. The optimized process parameters obtained by Jaya algorithm were used for grinding the soft steel. The better results of surface roughness (0.138 μm) for soft steel obtained using less function evaluations. Chaudhari et al. [95] have reported the improvement of surface roughness by 14% during grinding EN31 soft steel under nano fluid MQL technique. The lowest surface roughness (0.158 μm) obtained using optimized values of input process parameters determined by Jaya algorithm. Chakule et al. [8] have investigated the optimization of nanofluid MQL process parameters for grinding hardened OHNS plate. The result shows reduction of surface roughness and cutting forces by 33.5% and 21.51% respectively compared to wet grinding using optimized process parameters obtained by Jaya algorithm. Similar process performance in-terms of cutting forces, surface roughness, and material removal rate reported by Chakule et al. [96] during grinding EN31 values obtained by hardened steel using optimized Jaya algorithm. Patole et al. [60] have developed the model which is helpful while understanding the behavior of the cutting process. The performance of the developed model is studied with the experimental data of MQL turning of alloy steel AISI 4340 material. The values obtained from the model and experimental for cutting forces are very nearer to each other.

5.1 Optimization of machining process

Optimization of turning process parameters is important for industries to obtain better surface quality and machining performance. Kumar Abhishek et al. [97] have discussed the optimization of process parameters using different optimization techniques. The experiments were planned as per the Taguchi L9 orthogonal array on Carbon fibre reinforced polymer (CFRP) (epoxy) composite bars with high-speed steel (HSS) tool. The optimization of turning process was evaluated considering the responses such as material removal rate, surface roughness, and resultant cutting force. In this paper, multi responses are converted into equivalent single response called multi-performance characteristics index (MPCI) using Fuzzy inference system (FIS). Afterwards the same value was used for optimization purpose as the fitness function. The paper reported different optimization techniques such as Jaya, Teaching Learning Based Optimization (TLBO), Genetic Algorithm (GA) and Imperialist Competitive Algorithm (ICA) for optimizing the process parameters. The experimental study discussed shows better process performance during turning of CFRP composites using optimization techniques especially Jaya algorithm. The special features of Jaya algorithm such as parameter-less optimization algorithm, less computational efforts and time and efficiency is highlighted. The Convergence plot for optimizing MPCI through the Jaya algorithm is shown in Figure 7.

6 Applications of nanofluids

The nanofluids have wider applications due to their unique characteristics. The better performance of nanofluids in application is obtained due to large specific surface area, higher thermal conductivity and high dispersion stability. Due to unique features of nanofluids are widely used in various fields such as automotive engine cooling system, solar energy system, heat pipe, refrigeration, medical etc. In addition to the above applications, nanofluid has recently been used in cryosurgery. Nanofluids are also widely used in the petroleum industry. Nanofluid improves the stability of the emulsion and improves the efficiency of oil recovery. Devendiran and Amirtham [44] and Li et al. [98] discussed the application of nanofluids in different areas such as industrial, commercial, residential and transportation sectors. The better thermo physical properties of nanofluids (mono and hybrid) under MQL find wide scope in various areas such as refrigerators, automobile, coolant in machining, solar, cooling and heating in buildings, heat exchanger,

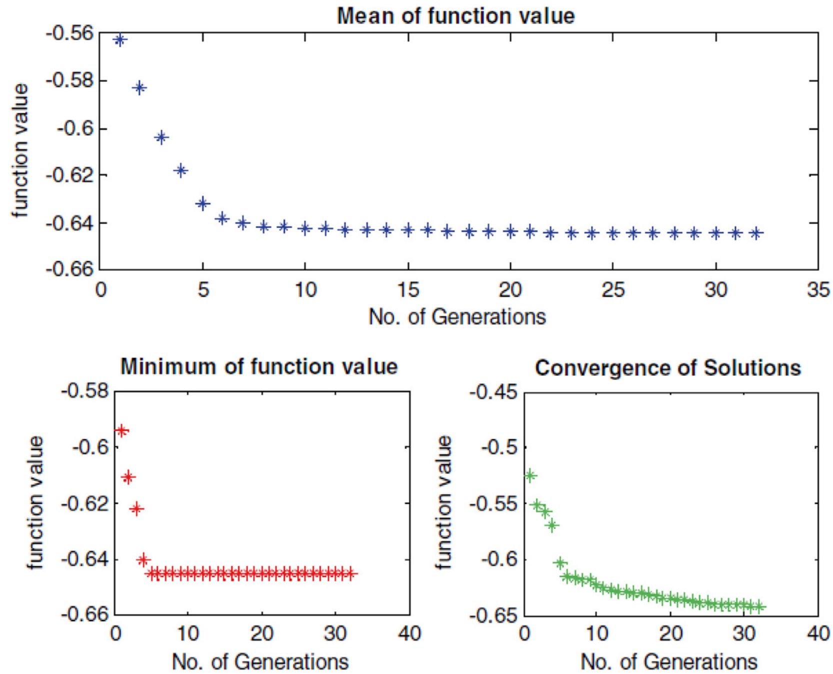


Fig. 7. Convergence plot for optimizing MPCI through the Jaya algorithm [97].

space, defense, ships, medical applications, application in nuclear reactor, optical application, electronics cooling, and process industries. Some of the applications of nanofluids are discussed below.

6.1 Friction reduction

The advanced lubricants, nanofluids reduces the friction and wear thus improves the productivity through energy saving and reliability of engineered systems. The nanoparticles have excellent load carrying capacity, good extreme pressure and friction reducing properties. The nanofluid MQL grinding reduces grinding forces, and surface roughness value and improves workpiece surface morphology and tool life due to formation of dense and hard slurry layer on the wheel surface.

6.2 Nanofluids in automobile

Engine oils, automatic transmission fluids, coolants, lubricants, and other synthetic high-temperature heat transfer fluids found in conventional truck thermal systems-radiators, engines, heating, ventilation and air-conditioning (HVAC) have inherently poor heat transfer properties. These could benefit from the high thermal conductivity offered by nanofluids that resulted from addition of nanoparticles.

6.3 Nanofluids in biomedical

Some special kinds of nanoparticles have antibacterial or drug-delivery properties. Organic antibacterial materials are often less stable particularly at high temperature and pressures. Thus inorganic materials such as metal and metal oxides have attracted lots of attention over the past decade due to ability to withstand harsh process conditions. The antibacterial activity increases with increasing nanoparticle concentrations and increases with decreasing particle size.

6.4 Nano cryosurgery

Cryosurgery is a procedure that uses freezing to destroy undesired tissues. This therapy is becoming popular because of its important clinical advantages although it still cannot be regarded as a routine method of cancer treatment; cryosurgery is quickly becoming an alternative to traditional therapies. According to theoretical interpretation and existing experimental measurements, intentional loading of nanoparticles with high thermal conductivity into target tissues can reduce the final temperature, increasing the maximum freezing rate and enlarge the ice volume obtained in the absence of nanoparticles. Additionally, introduction of nanofluid enhanced freezing could also make conventional cryosurgery more flexible in many aspects such as artificially interfering in the size, shape, image and direction of ice ball formation. The concept of nano cryosurgery may offer new opportunities for future tumor treatment.

6.5 Nanofluids in solar

Solar energy plays a vital role in energy application due to shortage of electricity productions. In recent years, the use of solar energy has a remarkable edge. The solar collectors absorb the incoming solar radiation, convert it into heat, and transfer the heat to a fluid usually air, water or oil flowing through the collector. The energy collected is carried from the working fluid, either directly to the hot water or space conditioning equipment or to a thermal energy storage tank, from which it can be drawn for use at night or on cloudy days. Nanofluids based direct solar collectors are solar thermal collectors where nano particles in a liquid medium can scatter and absorb solar radiation. They have recently received interest to efficiently distribute solar energy.

7 Significance and challenges of nano fluids

The literature review of different researchers reported good thermal properties of nano fluids and better process performance using micro-lubrication techniques. But the challenges are still there about stability of nano fluid in application. Saidur et al. [38] identified the challenges and suggested more focus on issues such as stability, thermal conductivity, viscosity, cost, specific heat, pumping power, and production in mass quantity of nano fluids. The nano fluids should have long term stability, moderate density and viscosity, optimized nano particle concentration value, high thermal conductivity and specific heat, and be available at low cost. Therefore, more attention is needed on selection of proper nano particles, base fluids, surfactants, and their proportionate composition, parameters related to homogeneous mixing, accuracy of measuring instruments. The characterization of nano particles and nano fluids are important before use. Similarly, the challenges are found during nano fluid application such as requirement of large quantity of nano particles, high production cost and stability issue of nano fluid. Stability of nano fluid is the key issue amongst the challenges before commercialization.

8 Conclusions

From literature review, it is seen that different researchers have proposed different micro lubrication techniques and cutting fluid for machining performance. The following findings are drawn as below:

- After extensive studies, it is observed that micro lubrication techniques give better machining performance using small quantities of cutting fluid. It is also reported that micro-lubrication techniques are sustainable, economical and eco-friendly. The micro-lubrication techniques are an alternative to conventional wet systems.
- The performance of machining processes using mono and hybrid nano fluids under MQL found better. The machining performance in-terms of cutting forces, cutting zone temperature, work piece surface morphology and tool life is reported due to better thermo-physical properties of nano fluids and effective penetration at contact zone. It is also observed that hybrid based nano fluid MQL technique gives better machining results especially for hard and difficult machining materials.
- The case study reported the enhancement of thermal conductivity by 22% using water based TiO_2 nanofluids compared to other base fluids such as ethylene glycol and paraffin oil. The stability and characterization of nano fluid was confirmed before being used.
- The modeling and optimization of process parameters are equally important to obtain better machining results. Recently, the optimization approach to micro- lubrication techniques based on machining processes is being applied successfully for achieving quality production economically.
- Based on case study, the reduction of surface roughness and cutting force is reported during turning carbon fibre-reinforced polymer (CFRP) composites. At the same time, the MRR is improved significantly using optimized values of process parameter obtained by Jaya algorithm. The special features of Jaya algorithm such as parameter-less algorithm, less computational efforts and time and efficiency is highlighted.

Thus, the approach of micro lubrication technique of cutting fluid and process optimization is equally important to obtain an eco-friendly machining process and the best process results. The suggested approach of optimization to micro lubrication techniques is today's necessity for an eco-friendly manufacturing process and to obtain quality production economically.

9 Recommendations for future work

This review paper presented the brief review on micro-lubrication techniques, namely MQL, nano fluid MQL and hybrid nano fluid MQL and optimization of micro-lubrication technique process parameters. The better machining results using mono and hybrid nano fluid MQL is discussed. Based on the above literature, the following recommendations for future work are suggested:

- Very few researchers have discussed the nano-lubricant film formation between the wheel-work piece interfaces under tribological studies for better understanding the effectiveness of cooling/lubrication of cutting fluid.
- The optimized concentration of nano particle is important for nano fluid preparation.
- The hybrid nano fluid with MQL can be used for different materials, especially hard and materials of difficult to cut nature.
- Optimization of process parameters using different optimization techniques, namely Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Simulated Annealing (SA), Teaching-Learning Based Optimization (TLBO) and Jaya algorithm are possible for different machining processes and materials.

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Cite this article as: Rahul R. Chakule, Sharad S. Chaudhari, Kailas V. Chandratre, Pralhad B. Patole, Poonam S. Talmale, Nanofluids, micro-lubrications and machining process optimisations – a review, Manufacturing Rev. **10**, 1 (2023)