lubricants

Perspective

Role of Nanofluid Minimum Quantity Lubrication (NMQL) in Machining Application

Raj Shah [1], Khosro A. Shirvani [2,*], Alexandra Przyborowski [3], Nikhil Pai [4] and Mohsen Mosleh [5]

[1] Koehler Instrument Company, Holtsville, NY 11716, USA
[2] Department of Mechanical Engineering Technology, Farmingdale State College, Farmingdale, NY 11735, USA
[3] Department of Materials Science and Chemical Engineering, Stony Brook University, Stony Brook, NY 11794, USA
[4] Department of Mechanical Engineering, University of Texas, Austin, TX 78712, USA
[5] Department of Mechanical Engineering, Howard University, Washington, DC 20059, USA
* Correspondence: khosro.shirvani@farmingdale.edu; Tel.: +1-(202)-746-9766

Abstract: Gaining grounds as a potential heat transfer fluid due to its superior thermal and tribological properties, Nanofluid Minimum Quantity Lubrication (NMQL) has been classified as an environmentally friendly technique and has already been successfully applied in several machining processes. This paper presents a review of the role of NMQL for different machining processes. The mechanisms of the MQL technique are thoroughly explained for achieving optimal performance based on parameters like nozzle feed position, angle of elevation, distance from the nozzle tip to cutting zone, flow rate, and air pressure. NMQL is shown to enhance cooling performance and lubrication, as well as the tribological properties of the fluid and cutting performance. With government legislative and public opinion pushing manufacturing companies towards sustainable production techniques and practices, the implementation of MQL-nanofluid can slowly prevent the adverse effects that conventional cutting fluids contribute.

Keywords: nanofluid minimum quantity lubrication; machining; turning; milling; drilling; grinding; tribology; surface roughness; computational fluid dynamics

Citation: Shah, R.; Shirvani, K.A.; Przyborowski, A.; Pai, N.; Mosleh, M. Role of Nanofluid Minimum Quantity Lubrication (NMQL) in Machining Application. *Lubricants* **2022**, *10*, 266. https://doi.org/10.3390/lubricants10100266

Received: 9 June 2022
Accepted: 20 September 2022
Published: 18 October 2022

1. Introduction

Machining, the process in which raw or scrap material is cut into a desired final shape to create a utilitarian product, is considered one of the most efficient ways to cut down expenditure costs in the manufacturing process [1]. In all metal cutting machining operations, the goal is to raise productivity, reduce costs by machining at the highest practical speed consistent with long tool life, produce the fewest number of rejects, and minimize downtime with the production of surfaces of satisfactory accuracy and finish [2]. In conventional machining operations, the cutting tool comes into direct contact with the workpiece to remove material in the form of chips where the presence of relative velocity under high contact pressure between the flowing chips and rake surface of the tool leads to excessive rubbing and heat generation [3]. The delivery of prominent fluid to the cutting zone offers both cooling and lubrication effects as well as chip clearing that contribute to the efficiency of machining. While many machining operations can be carried out "dry", using the proper cutting fluid generally makes possible: higher cutting speeds, higher feed rates, greater depths of cut, lengthened tool life, decreased surface roughness, increased dimensional accuracy, and reduced power consumption [4].

Flood coolant systems have been most widely used for precise machining processes where the cutting fluid is allowed to come out of a nozzle in the form of a liquid jet to immerse the entire cutting zone. Flood cooling requires a large volume of cutting fluid to completely inundate the entire cutting zone which increases the overall cost of machining due to additional expenses for costly cutting fluid. Due to high volumes of fluid disposal, flood cooling is always associated with negative environmental impacts that lead to the ecological imbalance in disposal areas making it an inadequate delivery technique for cutting fluid [4]. Nanofluid Minimum Quantity Lubrication (NMQL) in machining processes has recently attracted the attention of researchers as a potential heat transfer fluid because of the superior thermal and tribological properties nanofluids present. MQL reduces the usage of coolant by spurting a mixture of compressed air and cutting fluid in an improved cooling method and nanoparticles incorporated into the lubricant increase the heat-carrying capacity, making MQL-nanofluid a potential alternative solution within the machining process [4,5]. The application of MQL-nanofluid in different machining processes, like turning, milling, drilling, and grinding have shown to be an appropriate method for offering better machining performance as well as reducing the environmental and machinist hazards that present themselves during operation [6,7]. Optimizing existing MQL processes with the addition of nanoadditives would facilitate widespread adoption of the sustainable method. With government legislative and public opinion pushing manufacturing companies towards sustainable production techniques and practices, the implantation of MQL-nanofluid can slowly replace the adverse effects that conventional cutting fluids have contributed.

This paper presents a review of the role of Nanofluid Minimum Quantity Lubrication (NMQL) for different machining processes, such as, turning, milling, drilling, and grinding. The mechanisms of the MQL technique are thoroughly explained for achieving optimal performance based on parameters like nozzle feed position, angle of elevation, distance from the nozzle tip to cutting zone, flow rate, and air pressure. Present work also discusses the employment of nanofluids in MQL within machining operations to show promising results to provide lubricity over a wide range of temperatures and for difficult-to-cut materials, such as hardened steel, aerospace alloys, carbon-fiber-reinforced plastic, etc. Further investigations are conducted on computational fluid dynamics (CFD) as an analysis of fluid flows using numerical solution methods that allow for the optimization and verification of design performance before costly prototypes and physical tests. Overall, the use of nanoadditives in MQL-based fluids has been shown to enhance the cooling performance and lubricating effects as well as tribological property of the fluid and is proven to be a viable alternative to flood lubrication.

2. Minimum Quantity Lubrication (MQL)

The effectiveness of traditional machining processes is highly dependent on the presence of cutting fluid to cool and lubricate the machining region. By having the right lubricating properties these fluids remove heat generated from frictional heating and shear heating during chip flow and material deformation, reduce coefficients of friction at tool–chip and tool–work interfaces, and facilitate the breaking of chips into small segments for evacuation and proper disposal [7]. Like any other manufacturing technique, machining produces many byproducts or waste including metal chips, spent cutting fluid, oil contaminated with water, oil mist, metal dust, and unnecessary energy usage [8]. Conventional petroleum-based mineral oils (MO) are the most common cutting fluids used today. While these conventional cutting fluids reduce the induced surface roughness, extend tool life, and improve the overall machinability for difficult-to-cut materials, mineral-based cutting fluids possess harmful waste byproducts that have major consequences for health, environment, productivity, and manufacturing cost [9–11]. In efforts to eradicate these adverse effects minimum quantity lubrication (MQL) is being explored greatly by researchers as a sustainable and efficient cutting fluid for machining operation.

Minimum quantity lubrication (MQL) has been classified as an environmentally friendly technique due to its drastically reduced environmental impact and has been successfully applied in many different machining processes. The major benefits of MQL are reduction of consumption of cutting fluid, cost efficiency, environmental friendliness, improved overall performances in cutting operation, and surface quality. The principle of MQL is that it applies a fine mist of a compressed air mixture containing a less amount of cutting fluid to the cutting zone through the spindle of the machine tool, where the lubricating effect is very high to decrease the friction coefficient [12]. The diameter of the nozzle in MQL application is about 1 mm and the pressure applied is around 600 kilopascals [12,13]. The flow rate of cutting fluid is in the range between 0.05 and 2 L/h [14] instead of 500 to 1000 L/h in the case of conventional lubrication systems [5,15]. The performance of MQL depends on parameters like nozzle feed position, angle of elevation, distance from the nozzle tip to cutting zone, flow rate, and air pressure [16]. The cutting fluids used in MQL should be biodegradable and remain stable for a longer period compared to conventional cooling systems because of the difference in the consumption of oil. MQL fluids must possess characteristics of high lubrication, high stability, and biodegradability due to their requirements of sustainability and low oil consumption [17].

The main drawback of MQL technology is the low cooling effect, which limits the applicability and cutting performance in materials with high strengths and hardness [18]. MQL possesses certain restrictions especially at very high cutting speeds where the lubricating fluid tends to evaporate as it strikes the already heated cutting tool at elevated temperatures. To improve MQL technology, nanofluids containing nanoparticles (Al_2O_3, MoS_2, SiO_2, CuO, diamond, etc.) with at least one of their principal dimensions smaller than 100 nm have been explored and researched extensively to increase cutting performance and productivity [19,20].

3. Nanofluids

Nanofluids are defined as a base fluid containing nanometer-sized particles, called nanoparticles, which are designed or engineered based on the desired properties. Nanofluids allow for the penetration of cutting interfaces and they increase the overall heat transfer capabilities as the nanosized solids generally have a much higher thermal conductivity compared to other liquids [17,21] as seen in Table 1. The thermal conductivity of vegetable oil, commonly combined with MQL, is only 0.18 W/mK compared to the thermal conductivity of carbon nanotubes used in MQL being 3000 W/mK, a stark difference to effectively transfer heat and readily take up heat from the environment. Research shows that properly designed nanofluids could surpass conventional cutting fluids in thermal conductivity, convective heat transfer coefficient, critical heat flux, viscosity, and wettability [21]. Furthermore, carbon nanotubes are slowly becoming increasingly accessible and affordable, making for an attractive additive. Currently, the cheapest nanotubes on the market cost around $100–200 per kilogram, but advances in electrochemistry present a pathway to synthesize nanotubes at lower cost [22]. Aluminum oxide is also an affordable additive, combining low cost with favorable mechanical properties [23].

Table 1. Thermal conductivity at room temperature of typical solids and liquids used in MQL with nanolubricants [21].

Material	Thermal Conductivity (W/mK)
Carbon nanotubes	3000
Aluminum oxide	40
Water	0.60
Vegetable oils	0.18

MQL performance can further be enhanced by applying nanofluids, which are diluted with nanoparticles that were developed to increase the heat transfer rate, this is known as nanofluid MQL (NFMQL) [24]. The most common types of nanoparticles consist of graphene particles, Al_2O_3 particles, multiwalled carbon nanotubes, and carbon nanoparticles. In particular, carbon group nanoenhancers have been shown to reduce mechanical and thermal loads in the cutting zone [25]. Compared to conventional fluids, nanofluids possess the following superior properties such as high heat transfer surface area that transfers heat between fluid particles, Brownian motion of particles and dispersion stability, and no particle clogging with predominant system miniaturization at the nanoscale [5,26].

A statistical technique called response surface methodology with Box–Behnken Design was used to design experimental runs to empirically present the superiority of implementing NFMQL in comparison to MQL within the levels of process parameters [27]. Three different levels of feed rate, depth of cut, and cutting fluid flow rate were employed under MQL and NFMQL cooling environments as the process parameters. A total of 96 experiments were performed having 16 for each lubrication environment and repeated three times to mitigate any uncertainty. The comparison between MQL and NFMQL lubrication conditions has shown a significant reduction of temperature under NFMQL at the tool–workpiece interface from 16.2 to 34.5 percent and improved surface roughness from 11.3 to 12 percent [27] as seen in Figure 1. The research study confirms that NFMQL has the potential to enhance the surface quality of materials during cutting which saves energy consumption and cost in machining. A separate study considered the use of ZnO nanoparticles in NFMQL, showing a reduction of cutting temperature of around 15.3 percent [28].

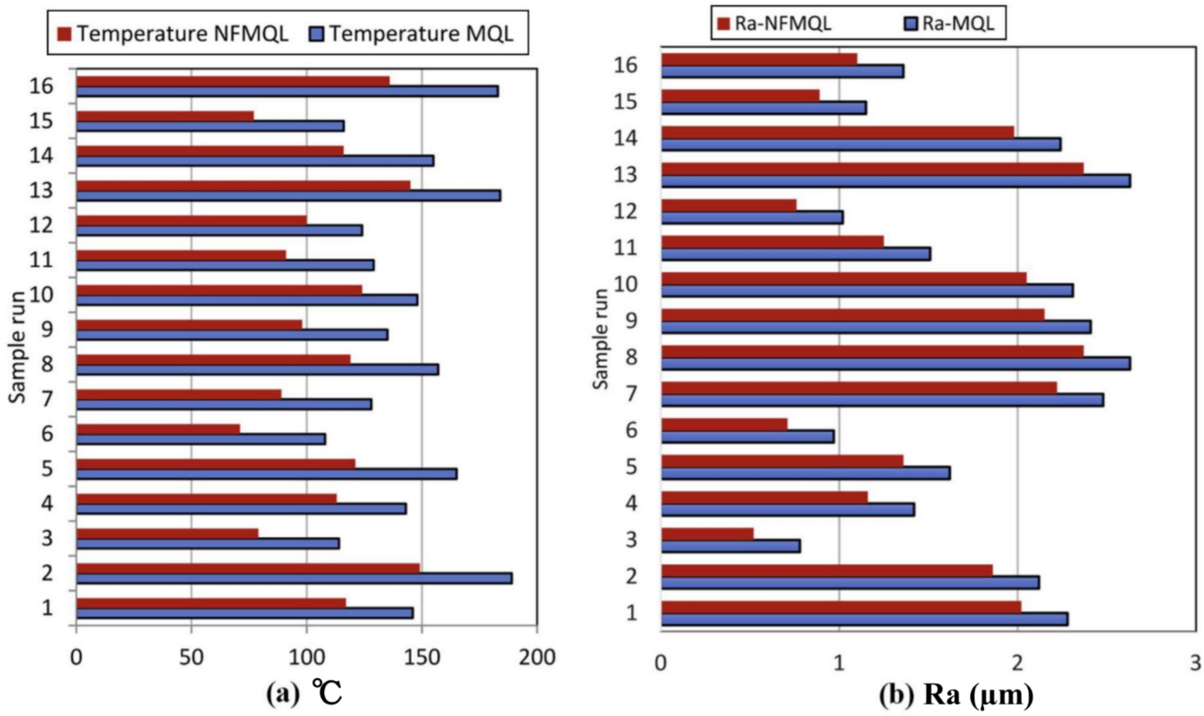

Figure 1. Comparison of measurements for MQL and NFMQL (**a**) Temperature and (**b**) Surface roughness [27].

4. Machining Application

Machining is considered the most versatile manufacturing process today, where a material's desired shape, size, and surface finish are achieved through the removal of excess materials in the form of small chips [29]. The device used to remove the excess material through direct mechanical contact is known as a cutting tool. When ferrous and other high-strength materials are machined, the temperature rises with the speed, and the tool strength decreases, leading to faster wear and tool failure [29,30]. Machining at high speeds is most desirable for higher productivity, but the tradeoff can result in faster tool wear due to high temperatures. The heat produced, needs to be cooled down constantly around the cutting zone so that the workpiece and cutting tool can be kept under controlled temperatures. During machining operation, the cutting fluid aids in three ways: cools the workpiece surface and the cutting tool, removes the chips from the cutting zone, and lubricates the tool–workpiece interface [4,6]. Nanofluids employed in MQL have been examined and tested for machining operations such as turning, milling, drilling, and grinding and have shown promising results to provide lubricity over a wide range of temperatures and for difficult-to-cut materials, such as hardened steel, aerospace alloys, carbon-fiber-reinforced plastic, etc. [31–33].

4.1. Turning

Turning is a form of machining, a material removal process, in which excess material is removed to create rotational parts typically axisymmetric. These rotational parts have many features, such as holes, grooves, threads, tapers, various diameter steps, and even contoured surfaces [34]. The turning process requires a turning machine or lathe, workpiece, fixture, and cutting tool. The workpiece is a piece of preshaped material that is secured to the fixture, which itself is attached to the turning machine and rotated at high speeds. Typically, a single point cutting tool that does not rotate but moves linearly along a helix tool path on the rotating workpiece is used for operation, although some operations make use of multipoint tools. The cutting tool feeds into the rotating workpiece and cuts away material in the form of small chips to create the desired shape [34]. The continuous contact between the workpiece and the cutting tool generates very high heat at the cutting zone which should be taken away by a suitable coolant. Various research shows that nanofluid MQL is best suited for cutting fluid in the turning process.

Behera et al. performed an experiment applying nanofluids under MQL methods during the turning process, where the outcomes were compared with those obtained by applying biodegradable emulsion and dry machining [35]. It was observed that the small contact angle, more spreadability, and tiny droplet size of applied alumina nanofluids provided reduced effects in tool wear, cutting forces, and chip curling parameters during the machining process. The tribo-film formation has also been observed with alumina nanofluids which have shown to protect the rake face, the cutting-edge angle that has large effects on cutting resistance, chip disposal, cutting temperature, and tool life [36]. Overall, the nanoball bearing effect of silver nanofluids resulted in a good surface finish and reduced abrasion wear. Figure 2 shows a schematic of the rake angle and its effect when using alumina nanofluids that have shown to protect rake face and cutting-edge angle. When rake angle is increased in the positive direction sharpness is improved and when rake angle is increased by 1° in the positive direction the cutting power is decreased by about 1%. Hegab et al. performed a study aimed at improving the cooling efficiency of MQL during the machining of titanium alloys with nanoadditives [37,38]. The main objective was to investigate the influence of dispersed multiwalled carbon nanotubes (MWCNT) into vegetable oil by implementing the MQL technique during the turning of Ti-6AL-4V. It was found that two percent MWCNT nanofluid reduced the power consumption by eleven percent. The same concentration of nanofluid also reduced the flank wear by 45% [38].

Abundant analysis of vegetable-oil-based nanofluids has not been explored and seen earlier, but Das et al. researched the best vegetable-oil-based nanofluids from a set of three nanoparticles enriched cutting fluids for machining [39]. The study also investigated the cutting performance and comparative assessment toward machinability improvement during hard turning of high-strength-low-alloy steel using four different compositions of nanofluids by MQL technique. In a comparison of three NFMQL cutting fluids (CuO, Al_2O_3, Fe_2O_3) the study showed: superior machined surface morphology, short-thin chips with lower curl radius, improved surface quality, least flank wear, and shorter tool–chip contact length along with smoother sliding marks. It has also shown that the surface finish of machined parted improves with the change in nanofluid from aluminum-oxide-based nanofluid to copper-oxide-based nanofluid because the viscosity of copper-oxide-based nanofluid is lower resulting in proper settlement of the nanofluid in the work–tool interface. The heat-carrying capacity of copper oxide is also more compared to the other two nanofluids, which results in fewer microstructural changes. The application of nanoparticles in MQL has shown promising results in improving the performance of the turning process concerning cutting tool life due to the superior cooling and lubrication properties [39].

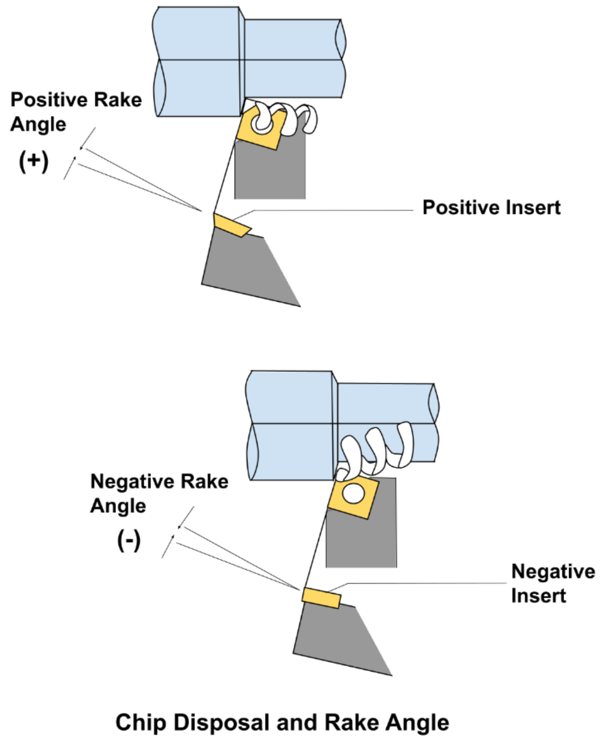

Figure 2. Chip Disposal and Rake Angle [36].

4.2. Milling

Milling is one of the most common manufacturing processes by which flat, curved, or irregular surfaces are machined by cutting away the unwanted material [40]. The cutter secured in the milling machine is a cutting tool with sharp teeth that rotates at high speeds with multiple cutting edges and is used to produce parts that are not axially symmetric. These parts have many features, such as holes, slots, pockets, and even three-dimensional surface contours. In a milling operation, the use of cutting fluid is not very common due to the ease in crack propagation in the tool which is caused by the fluctuation in temperature. However, milling of difficult-to-cut materials at high speed, a process that combines lighter milling passes with high spindle speeds and high feed rates to achieve a very high metal removal rate, results in very high temperatures to the cutting zone which require cutting fluids for efficiency [41]. This high temperature is attributed to poor machinability and adhesion, abrasion, and chemical reaction of tool–workpiece material. Thus, NFMQL has been identified as the best alternative in intermittent operations and should be adopted by manufacturers.

High-speed machining is a process that focuses on making very fast, but also very light, low-pressure cuts which increase the overall rate in material removal and decreases the cost of machining [42]. To machine at high speeds, there is much more stopping and starting which can increase the rate of wear in machine parts such as spindle bearings, ball screws resulting in higher maintenance costs. Using the proper nanofluid for minimum quantity lubrication can help avoid these high maintenance costs and further improve overall efficiency. The lubrication performance of different nanofluids in MQL has been experimentally evaluated in milling titanium alloy Ti-6AL-4V in terms of milling force, surface roughness, the morphology of workpiece surface, and viscosity of the nanofluids [43]. Titanium alloy exhibits low thermal conductivity and high chemical activity which causes poor machinability and categorizes it as a difficult-to-machine material. Out of all six types of nanofluids tested experimental results demonstrated that the Al_2O_3 nanoparticles obtained the minimal milling force ($F_x = 277.5$ N, $F_y = 88.3$ N), followed by the SiO_2 nanoparticle ($F_x = 283.6$ N, $F_y = 86.5$ N). Surface roughness was measured by using a contact pointer measuring instrument SC6C while the surface morphologies of the debris and workpiece were measured by electronic scanning electron microscope (SEM) DV2TLV. The surface roughness was measured under NMQL and MQL conditions by selecting five points on the workpiece surface, therefore, seven groups of roughness values were obtained. The spacing characteristic parameter RS_m and height characteristic parameter R_a were used as evaluation parameters in characterizing surface roughness. Pure cottonseed oil MQL obtained the highest value ($R_a = 1.772$ μm) and the lowest value was obtained with the addition of Al_2O_3 nanoparticles ($R_a = 0.594$ μm). The minimum RS_m was achieved by the Al_2O_3 nanofluid (0.093 mm), whereas the maximum RS_m was obtained by the CNT nonfluid (0.409 mm). The comprehensive values were calculated and found to be in the following order: Al_2O_3 < SiO_2 < MoS_2 < CNTs < graphite < SiC, meaning Al_2O_3 NMQL milling obtained the best surface quality [40]. Morphology is an important index in evaluating workpiece surface integrity and it can reflect the interaction between tool and workpiece and the removal mode of metal material. The workpiece surface morphology was the best for Al_2O_3 and SiO_2 and both spherical nanoparticles improved the lubrication effect of base oil. Table 2 shows the different observations made for each nanoparticle and its direct effects on tribological performance. The application of six nanoparticles in MQL demonstrated different characteristics but have helped in the overall formation of the lubrication film during processing which improves the tribological properties and wear reduction performance of nanofluids during milling.

Table 2. Tribological performance observations for the milling of Ti-6AL-4V using six different nanofluids [43].

Work-Piece	Tool	Nanofluid (Diameter = 70 nm)	Tribological Performance Observation (Milling Force, Surface Roughness, etc.)
Ti-6AL-4V (40 mm × 30 mm × 30 mm)	Dema ML1060B	Al_2O_3	• The addition of this nanoparticle showed the most significant effect in improving the tribological properties of base oil and obtained the lowest milling force • Most significant friction and wear reduction effect • Obtained best surface quality
		MoS_2	• Lubrication performance was poor due to small viscosity which resulted in thin oil films
		SiO_2	• Higher viscosity like Al_2O_3, which increases adhesive strength, Brownian motion, and viscous force among the nanofluid molecules
		CNTs	• Maximum RS_m was obtained (0.409 mm), the mean of profile irregularity distance in the sampling length L
		SiC	• The viscosity of nanofluid was next to that of SiO_2, but the workpiece surface quality was unsatisfactory which indicated that lubrication performance is concerned not only with viscosity but also the shape of nanoparticles
		graphite	• Similar viscosity as SiO_2 and SiC, poor performance

In one of the many detailed analyses and implementation of nanolubrication in machining, Sarhan et al. mixed SiO_2 nanosolid particles with mineral oil having 0.2% weight concentration through a sonification method where particles can be efficiently mixed [44]. This study showed a reduction in the friction coefficient in the tool–chip interface, which reduces the cutting force and working power considerably compared with conventional lubrication systems. In another study, optimum SiO_2 nanolubrication parameters were used in the milling of AI6061-T6, a common alloy that possesses superior mechanical properties such as hardness and weldability [45]. These parameters include nanolubricant concentration, air carrier pressure, and nozzle angle. The Taguchi optimization method was used where then the average TPM values of measured cutting forces, cutting temperature, and surface roughness were calculated. The result shows an improvement of 25.02, 29.34, and 25.28 percent in cutting force, cutting temperature, and surface roughness [45], respectively compared to the values obtained from experiments shown in Table 3. The outstanding performance of MQL oil mixed with nanoparticle additive over pure oil led to the conclusion that to improve the machining process NFMQL should be used.

Table 3. The measured values of cutting force, cutting temperature, and surface roughness [45].

	Control Factors and Levels (i)			**The Measured Values**											
Test Levels	**Nanoparticle Suspended Concentration (*A*)**	**Air Pressure (*B*)**	**Nozzle Orientation (*C*)**	**Cutting Force (N)**				**Cutting Temperature (°C)**				**Surface Roughness (µm)**			
				Reading			**Average**	**Reading**			**Average**	**Reading**			**Average**
				1	**2**	**3**		**1**	**2**	**3**		**1**	**2**	**3**	
1	$i = 1$	1	1	132.11	135.23	135.14	134.16	56.80	57.50	57.30	57.20	3.21	3.11	3.10	3.14
2	$i = 1$	2	2	199.56	195.44	198.73	197.91	70.90	71.80	70.90	71.20	0.78	0.82	0.66	0.75
3	$i = 1$	3	3	127.82	133.64	130.88	130.78	55.70	56.90	55.70	56.10	1.39	1.38	1.48	1.42
4	$i = 1$	4	4	183.9	182.63	186.76	184.43	48.80	49.50	48.10	48.80	1.47	1.51	1.60	1.53
5	$i = 2$	1	2	56.98	51.14	53.31	53.81	43.10	43.80	43.60	43.50	0.79	0.77	0.65	0.74
6	$i = 2$	2	1	145.31	149.77	155.85	150.31	53.60	54.20	52.70	53.50	1.59	1.55	1.71	1.62
7	$i = 2$	3	4	165.48	157.69	162.8	161.99	73.90	72.90	72.50	73.10	0.87	0.84	0.93	0.88
8	$i = 2$	4	3	153.56	155.87	163.46	157.63	70.60	71.10	67.40	69.70	1.30	1.30	1.42	1.34
9	$i = 3$	1	3	172.75	173.33	169.35	171.81	68.40	67.20	67.80	67.80	1.09	1.13	0.99	1.07
10	$i = 3$	2	4	109.45	113.32	100.33	107.70	61.80	61.30	61.40	61.50	0.95	0.99	0.85	0.93
11	$i = 3$	3	1	120.56	122.87	122.33	121.92	51.80	52.40	49.70	51.30	0.83	0.72	0.84	0.80
12	$i = 3$	4	2	186.73	190.21	187.18	188.04	64.70	63.80	66.50	65.00	1.54	1.59	1.61	1.58
13	$i = 4$	1	4	112.85	111.73	109.71	111.43	56.60	57.80	60.90	58.10	0.79	0.77	0.69	0.75
14	$i = 4$	2	3	146.76	144.45	145.77	145.66	57.30	56.10	57.30	56.90	0.69	0.70	0.64	0.68
15	$i = 4$	3	2	188.22	185.38	186.68	186.76	67.20	65.30	64.00	65.50	0.32	0.32	0.37	0.34
16	$i = 4$	4	1	175.07	179.37	177.49	177.31	67.90	68.20	68.50	68.20	0.74	0.76	0.73	0.74

4.3. Drilling

Drilling, one of the most important machining processes, produces cylindrical holes in metallic and nonmetallic materials that are often intended to aid in assembly through the usage of a drill. One estimate suggests that 40–60% of the total material removed in the aircraft frame industry comes from the drilling operation [46]. Another estimate is that 75% of all metal cutting material removed is drilled [47]. The creation of holes is accomplished most typically by using a twist drill where the chips must exit through the flutes to the outside of the tool. The cutting font is embedded within the workpiece, making cooling difficult [48]. The type of cutting fluid used has a significant impact on the drilling performance.

The performance of cutting fluid having soluble oil-based TiO_2 nanoparticles was investigated in terms of heat transfer by Salimi-Yasar et al. [49]. Three modes of dry drilling, drilling with pure cutting fluid, and soluble oil-based TiO_2 were employed. The average heat transfer ratio showed an upward trend with increasing of Reynolds number, increasing from 5.7% at Re 300 to 9.5% at Re of 900 at the constant weight concentration of 0.03%.

The results showed a decline in temperature distribution in the drilling procedure in the presence of nanofluid compared to the dry drilling and drilling with cutting fluid. This experiment concluded that soluble oil-based TiO_2 nanofluid could be a great alternative for drilling procedures. Chatha et al. performed drilling experimentation on aluminum 6063 by applying NFMQL [50]. It was concluded that thrust forces and drilling torques reduced while the number of frilled holes significantly increases because of NFMQL application, compared to conventional coolant lubricant conditions. Advantages in using NFMQL may have been due to the characteristic rolling effect of nanoparticles that resulted in a low frictional force at tool–workpiece and tool–chip interfaces.

The application of NFMQL in emerging machining processes, such as high-speed drilling and orbital drilling, has shown promising results for difficult-to-cut materials, such as hardened steel, aerospace alloys, carbon-fiber-reinforced plastic (CFRP), etc. High-speed drilling can be referred to as spindle speeds high enough to permit penetration rates of three to ten times the conventional rate, and orbital drilling represents a promising alternative drilling process that can reduce tool inventory, reduce axial force, and repair misaligned and damaged holes [33,51]. One research study performed by Mosleh et al. conducted both orbital drilling and tribological testing using a four-ball tester to examine the effectiveness of solid lubrication in MQL [33]. A modified brand model four-ball tester with a maximum rotational speed and a normal load of 10,000 rpm and 10,000 N, respectively, was used. The ball configuration and geometry are shown in Figure 3, where the lower balls are fixed, and the upper ball rotates with a rotational speed so that the relative linear speed at the contact points was 1.0 m/s. In both the orbital drilling and four-ball testing results show improvements in characteristics, such as less transfer film on the drilling tool, a smoother frictional torque, and lower surface temperature from nanofluids containing MoS_2 nanoparticles [52]. The incorporation of NFMQL in these drilling processes resulted in less wear on lower titanium balls in four-ball testing and provided fluid lubrication, cooling, and solid lubrication for process improvement with less cleanup. When using NMQL methods in high-speed drilling or orbital drilling, the process is significantly more efficient and optimal, with soluble oil-based TiO_2 nanofluids showing great promise.

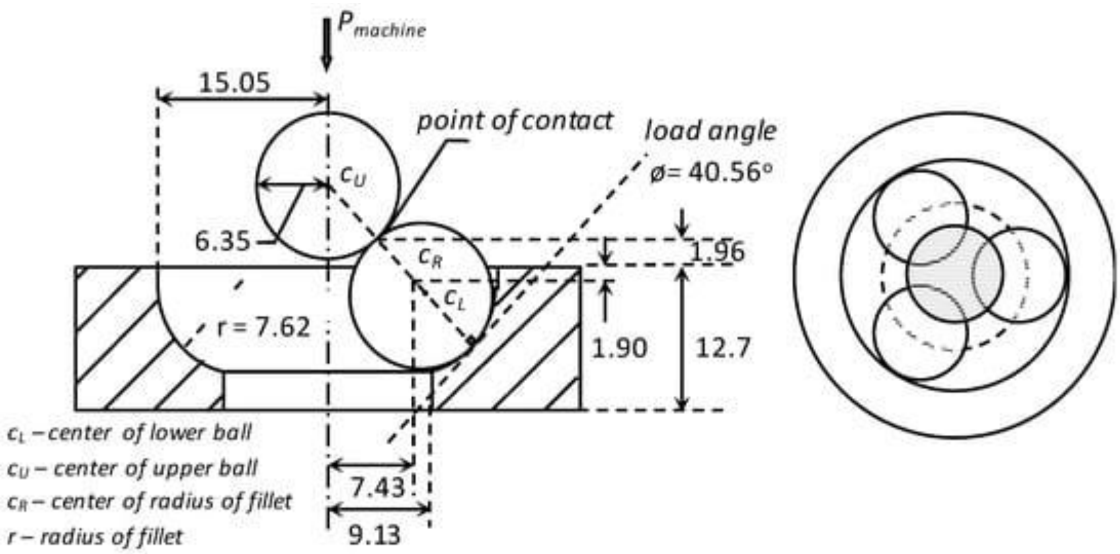

Figure 3. Four-ball test setup and the ball configuration and geometry are given in units of mm [33].

4.4. Grinding

Grinding is widely used as the finishing machining process for components that require high accuracies, close dimensional tolerances, and smooth surface finishes. The precision obtained through grinding can be up to ten times better than with either turning or milling. It involves the use of disc-shaped grinding wheels, some of which include grindstones, angle grinders, die grinders, and specialized grinding machines. Regardless of the grinding wheel, all grinding processes use abrasive particles to "grind" away material from a workpiece's surface [52]. A large volume of grinding fluid is used to flood the grinding zone which inherits the high cost of disposal or recycling which becomes a major environmental concern. Minimizing the quantity of cutting fluid used is desirable in grinding.

The use of nanofluids in MQL grinding has shown benefits of reducing grinding forces, improving surface roughness, and preventing workpiece burning in the following research [53]. Shen et al. investigated the wheel wear and tribological characteristics in wet, dry, and minimum quantity lubrication grinding of cast iron. Water-based Al_2O_3 and diamond nanofluids were applied in the MQL grinding process and all results were compared with those of pure water. Experimental results showed that G-ratio, defined as the volume of material removed per unit volume of grinding wheel wear, could be improved with high-concentration nanofluids which can significantly reduce the grinding temperature compared to dry grinding. Another research study explored the use of nanofluids under MQL to improve grinding characteristics of Ti-6AI-4V alloy [54]. Taguchi's experimental design technique has been used and a second-order model has been established to predict grinding forces and surface roughness. Different concentrations of water-based Al_2O_3 nanofluids were applied in the grinding operation which showed results that the grinding forces reduced significantly when the nonfluid was used even at low concentrations and would improve at higher concentrations. Cui et al. studied the use of cryogenic gas to enhance the heat transfer capacity of nanolubricant in titanium alloy grinding, with results showing enhanced cooling performance [55]. Overall, it is determined that, compared to standard MQL, the addition of nanoadditives, such as diamond nanofluids or aluminum oxide nanoparticles, results in favorable tribomechanical properties when grinding.

5. Future Work

Minimum quantity lubrication technique has been widely investigated in recent years as a good alternative to flood coolant in machining and nanofluids have attached the attention of many researchers due to their high thermal conductivity and ability to remove heat which MQL lacks. Further investigations are still required to understand and optimize the effects of nanoadditives size and concentration on the machining performance to achieve a balance between the induced nanoadditives wear and overall frictional behavior [56]. As nanotechnology is still a new and upcoming field the cost of nanoparticles and manufacturing cost of nanofluid both are very high making it a pricey endeavor that manufacturers are trying to avoid. Efforts in minimizing the cost of nanofluids must be taken to make NFMQL an affordable and efficient option in machining.

5.1. Computational Fluid Dynamics to Study Nanofluid MQL

Computational Fluid Dynamics (CFD) is the analysis of fluid flows using numerical solution methods that allows for the optimization and verification of design performance before costly prototypes and physical tests [57]. Many CFD models are developed to model the temperature profile, oil droplet behavior in the cutting zone, the heat transfer characteristics of the resultant nanocutting fluid, interactions between the cutting tool and workpiece, and resulting residual stress using NFMQL in machining processes [58,59]. One study developed a 2-D axisymmetric CFD to simulate the thermal effects of resultant nanomist and obtained the thermal characteristics of the nanofluid [60]. The obtained results were used in the finite element model to simulate the machining process with nanofluid which showed that the cutting temperature and residual stress performed better when using NFMQL. The experiment presented the first attempt to simulate the machining process using MQL-nanofluid; however, more improvements are still required to enhance the integrated model's accuracy. The authors suggest that a CFD model can be further improved by developing a 3-D CFD model of NFMQL to consider the honing and roundness effects of the cutting edge and to provide accurate simulations of the nanoadditives plowing effects.

A literature survey reveals that there are very few simulation models available for MQL in milling and overall machining applications. CFD simulation is necessary because it helps in determining the effect of nozzle position on the penetration of MQL spray and helps study the effect of a change in air pressure and mass flow rate on the wetting area which all contributes to the performance of MQL [61]. In the high-speed milling process of wrought aluminum alloys, it is usual to observe the presence and growth of built-up edge. Built-up edge (BUE) results in a poor surface finish and cutting-edge frittering when the BUE has torn away [62]. Two techniques are used to avoid this problem: an emulsion of oil in water, and spray of oil microdrops in air. First, the efficiency of MQL is assessed when compared to the inefficiency of emulsion techniques, which can be assessed through CFD simulations and experimental evidence. One research study simulated the conventional flood cooling process and MQL and found that MQL is very efficient in lubrication because of the high jet velocity which penetrated through the backflow of milling [63]. Another research study developed a numerical model to replicate the mist formation in MQL grinding using a fluent-based CFD flow solver [64]. The MQL parameters considered were air pressure and the mass flow rate, the same used in milling applications. Simulation of the atomization under turbulent conditions was done in a discrete phase model (DPM) because oil mass flow rates are very low and oil acts as a discrete medium in air. Jet velocity and droplet diameters were also obtained under different input conditions to find the optimum value of air pressure and mass flow rate of oil to achieve the desired results in MQL grinding of superalloy. The experiment showed that the medium size (around 16.3 µm) of droplets plays a significant role in improved performance by the way of reduction in cutting force and surface roughness.

5.2. Multiphase Flow Distribution in MQL Machining

MQL is a two-phase flow, where the characterization of flow is more complex as compared to a single-phase flow. Several methods are available for the analysis of two-phase flow, which can be broadly classified into invasive methods and noninvasive methods. Invasive methods usually measure the flow directly, such as using probes, but they can change the flow field and causes disturbances in measurements. Noninvasive techniques, on the other hand, do not interfere with the flow which results in more accurate flow results, but this advantage comes at the expense of computational effort required by the correlation algorithms. A new method was proposed in a research study aimed to qualitatively compare the oil distribution across the channel using high-speed imaging and intensity analysis of the image [65]. The study compared the identified oil distribution and single-phase CFD simulation to observe the correlation between the airflow and mist flow distribution. Figure 4 shows the experimental setup of the study which consists of a dual-channel MQL system that transfers the pressurized air and lubricant in separate concentric channels and atomizes the lubricant near the tool entry for more uniform mist at the exit. An MQL fluid, UNIST Coolube 2210, was used as the lubricant, which has intermediate surface tension and viscosity among commonly used products. In this study, flow images were captured at two different angles, 0° and 30°, for a better understanding of the oil distribution in three dimensions.

In a multiphase flow where one of the media is transparent and the other is either translucent or opaque, optical imaging would only capture the nontransparent phase. In the case of liquid droplets in a gas flow as in MQL, the use of a strong light source to increase the contrast and decrease any possible attenuation mitigates the challenge of identifying the droplet phase. A single-phase CFD was conducted for the airflow since most of the two-phase flow in MQL was air. The CFD was solved using the FLUENT module on ANSYS for obtaining the velocity profile. The major findings are that the distribution of oil droplets in MQL mist flow is highly related to the velocity profile which can be confirmed when comparing the measured flow structure and CFD simulated velocity field. This means that a single-phase CFD can be used to estimate the multiphase flow distribution without a time-consuming simulation such as Volume of Fluid (VOF) or SPH-CFD coupled analysis. To advance the current study, future work included experimentation for different channel cross-sectional shapes and areas, incorporating the effect of surface roughness on the oil distribution, flow distribution during the cutting conditions.

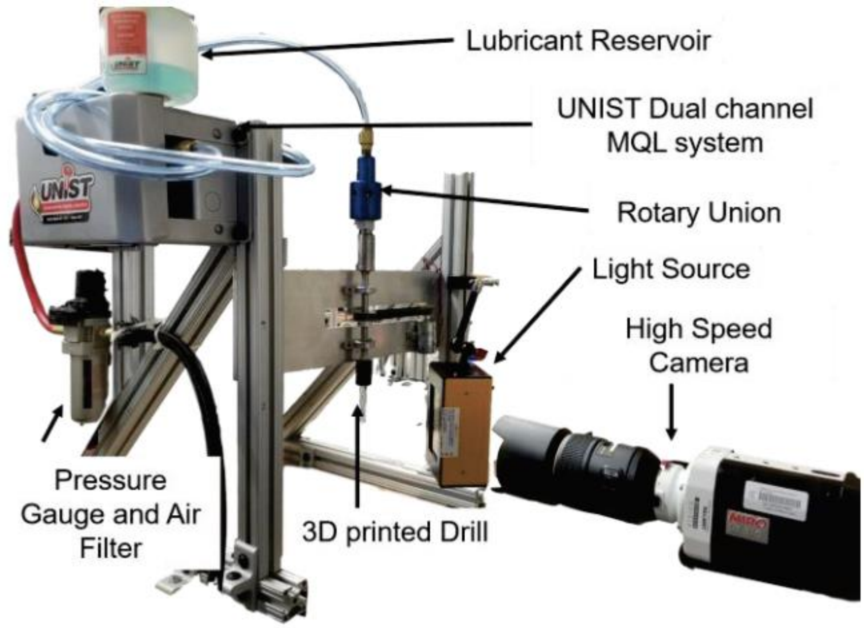

Figure 4. Experimental setup for simulating MQL flow in internal channel drill bits [65].

6. Conclusions

To reduce the environmental loads caused by the full usage of cutting fluids in machining operations, nanofluid minimum quantity lubrication has recently been widely explored and researched as an alternative coolant. In metal cutting industries, all used up cutting fluids that are applied for cooling and lubricating the contact zone contribute the largest amount of disposal, around 30%, which can end up as the contaminant in rivers leading to water pollution [60]. Therefore, it is necessary to work towards ecological solutions that can reduce the usage of coolants while still enhancing the performance of machining operations [66]. The addition of carbon nanotubes or aluminum-oxide- and copper-oxide-based nanoparticles greatly enhanced the thermophysical properties of MQL [67,68]. Application of nanofluids in MQL during different machining processes, such as, turning, milling, drilling, and grinding has shown promising results in decreasing the cutting force, cutting temperature, surface roughness, and overall tool wear. The cutting fluid in the form of oil mist is directly sprayed to the cutting zone, minimizing the amount of fluid used and effectively lubricating the cutting zone to decrease the friction coefficient, which is responsible for cutting forces, cutting temperature, and tool wear.

When working with difficult-to-cut materials, using nanoadditives in MQL-based fluids has been shown to:

- enhance the cooling performance and lubricating effects
- enhance tribological property of the fluid
- increase the cutting performance

The application of nanoenhanced biolubricant in MQL has been proven to be an effective and cleaner machining technology [69]. The superior cooling characteristics of nanofluids in MQL for machining technology have shown to be a suitable alternative for machining processes for sustainable production of materials.

Author Contributions: Conceptualization, R.S., M.M. and K.A.S.; methodology, R.S. and K.A.S.; software, A.P. and N.P.; writing, R.S., A.P. and N.P.; writing—original draft preparation, A.P. and N.P.; writing—review and editing, K.A.S. and N.P., project administration, R.S. and K.A.S.; funding acquisition, M.M. All authors have read and agreed to the published version of the manuscript.

Funding: The support for this publication by the Minority Science and Engineering Improvement Program (MSEIP) of the Department of Education (ED) under Grant Number P120A190018 is gratefully acknowledged.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Lee, Y.; Resiga, A.; Yi, S.; Wern, C. The Optimization of Machining Parameters for Milling Operations by Using the Nelder–Mead Simplex Method. *J. Manuf. Mater. Process.* **2020**, *4*, 66. [CrossRef]
2. Cutting Fluids for Machining. Available online: https://www.thomasnet.com/articles/process-equipment/cutting-fluids-for-machining/ (accessed on 28 February 2022).
3. Difference between Flood Cooling and Minimum Quantity Lubrication (MQL). Available online: https://www.difference.minaprem.com/machining/difference-between-flood-cooling-and-minimum-quantity-lubrication-mql/ (accessed on 28 February 2022).
4. Rifat, M.; Rahman, M.; Das, D. A review on application of nanofluid MQL in machining. *AIP Conf. Proc.* **2017**, *1919*, 020015. [CrossRef]
5. Said, Z.; Gupta, M.; Hegab, H.; Arora, N.; Khan, A.; Jamil, M.; Bellos, E. A comprehensive review on minimum quantity lubrication (MQL) in machining processes using nano-cutting fluids. *Int. J. Adv. Manuf. Technol.* **2019**, *105*, 2057–2086. [CrossRef]
6. Sharma, A.; Tiwari, A.; Dixit, A. Progress of Nanofluid Application in Machining: A Review. *Mater. Manuf. Process.* **2015**, *30*, 813–828. [CrossRef]
7. Woon, K. High Performance Machining of Metal Matrix Composites. *Encycl. Mater. Compos.* **2021**, *1*, 512–524. [CrossRef]
8. Haider, J.; Hashmi, M. Health and Environmental Impacts in Metal Machining Processes. *Compr. Mater. Process.* **2014**, *8*, 7–33. [CrossRef]
9. Khan, M.; Mia, M.; Dhar, N. High-pressure coolant on flank and rake surfaces of tool in turning of Ti-6Al-4V: Investigations on forces, temperature, and chips. *Int. J. Adv. Manuf. Technol.* **2016**, *90*, 1977–1991. [CrossRef]
10. Ezugwu, E.; Bonney, J.; Da Silva, R.; Çakir, O. Surface integrity of finished turned Ti–6Al–4V alloy with PCD tools using conventional and high pressure coolant supplies. *Int. J. Mach. Tools Manuf.* **2007**, *47*, 884–891. [CrossRef]
11. Gajrani, K.; Sankar, M. Sustainable Cutting Fluids: Thermal, Rheological, Biodegradation, Anti-Corrosion, Storage Stability Studies and its Machining Performance. *Encycl. Renew. Sustain. Mater.* **2020**, *1*, 839–852. [CrossRef]
12. Debnath, S.; Reddy, M.; Yi, Q. Environmental friendly cutting fluids and cooling techniques in machining: A review. *J. Clean. Prod.* **2014**, *83*, 33–47. [CrossRef]
13. Kalpakjian, S.; Schmid, S.R. Cutting-Tool Materials and Cutting Fluids. In *Manufacturing Engineering and Technology*, 6th ed.; Pearson Education: London, UK, 2009; pp. 590–614.
14. Dudzinski, D.; Devillez, A.; Moufki, A.; Larrouquère, D.; Zerrouki, V.; Vigneau, J. A review of developments towards dry and high speed machining of Inconel 718 alloy. *Int. J. Mach. Tools Manuf.* **2004**, *44*, 439–456. [CrossRef]
15. Jayal, A.; Balaji, A.; Sesek, R.; Gaul, A.; Lillquist, D. Machining Performance and Health Effects of Cutting Fluid Application in Drilling of A390.0 Cast Aluminum Alloy. *J. Manuf. Process.* **2007**, *9*, 137–146. [CrossRef]
16. Yan, L.; Yuan, S.; Liu, Q. Influence of minimum quantity lubrication parameters on tool wear and surface roughness in milling of forged steel. *Chin. J. Mech. Eng.* **2012**, *25*, 419–429. [CrossRef]
17. Boswell, B.; Islam, M.; Davies, I.; Ginting, Y.; Ong, A. A review identifying the effectiveness of minimum quantity lubrication (MQL) during conventional machining. *Int. J. Adv. Manuf. Technol.* **2017**, *92*, 321–340. [CrossRef]
18. The Long, T.; Minh Duc, T. The Characteristics and Application of Nanofluids in MQL and MQCL for Sustainable Cutting Processes. In *Advances in Microfluidic Technologies for Energy and Environmental Applications*; IntechOpen: London, UK, 2020.
19. Minh, D.; The, L.; Bao, N. Performance of Al_2O_3 nanofluids in minimum quantity lubrication in hard milling of 60 Si_2Mn steel using cemented carbide tools. *Adv. Mech. Eng.* **2017**, *9*, 1687814017710618. [CrossRef]
20. Long, T.T.; Duc, T.M. Micro/Nanofluids in Sustainable Machining. In *Microfluidics and Nanofluidics*; Kandelousi, M.S., Ed.; IntechOpen: London, UK, 2018.
21. Krajnik, P.; Franci, P.; Amir, R. Nanofluids: Properties, Applications and Sustainability Aspects in Materials Processing Technologies. In *Advances in Sustainable Manufacturing*; Springer: Berlin, Germany, 2011; pp. 107–113.
22. Vanderbilt University. Cheap, Small Carbon Nanotubes. 2018. Available online: https://www.sciencedaily.com/releases/2018/05/180523160148.htm (accessed on 1 June 2022).
23. Shanmugam, K.; Sahadevan, R. Bioceramics—An introductory overview. In *Fundamental Biomaterials: Ceramics*; Woodhead Publishing: Thorston, UK, 2018; pp. 1–46. [CrossRef]

24. Sahoo, S.P.; Datta, S. Dry, MQL, and Nanofluid MQL Machining of Ti–6Al–4V Using Uncoated WC–Co Insert: Application of *Jatropha Oil* as Base Cutting Fluid and *Graphene Nanoplatelets* as Additives. *Arab. J. Sci. Eng.* **2020**, *45*, 9599–9618. [CrossRef]
25. Cui, X.; Li, C.; Ding, W.; Chen, Y.; Mao, C.; Xu, X.; Liu, B.; Wang, D.; Li, H.N.; Zhang, Y.; et al. Minimum quantity lubrication machining of aeronautical materials using carbon group nanolubricant: From mechanisms to application. *Chin. J. Aeronaut.* **2021**, *35*, 85–112. [CrossRef]
26. Zainali, A.; Tofighi, N.; Shadloo, M.; Yildiz, M. Numerical investigation of Newtonian and non-Newtonian multiphase flows using ISPH method. *Comput. Methods Appl. Mech. Eng.* **2013**, *254*, 99–113. [CrossRef]
27. Khan, A.; Jamil, M.; Ul Haq, A.; Hussain, S.; Meng, L.; He, N. Sustainable machining. Modeling and optimization of temperature and surface roughness in the milling of AISI D2 steel. *Ind. Lubr. Tribol.* **2018**, *71*, 267–277. [CrossRef]
28. Ibrahim, A.M.M.; Omer, M.A.E.; Das, S.R.; Li, W.; Alsoufi, M.S.; Elsheikh, A. Evaluating the effect of minimum quantity lubrication during hard turning of AISI D3 steel using vegetable oil enriched with nano-additives. *Alex. Eng. J.* **2022**, *61*, 10925–10938. [CrossRef]
29. Sharma, A.; Tiwari, A.; Dixit, A. Effects of Minimum Quantity Lubrication (MQL) in machining processes using conventional and nanofluid based cutting fluids: A comprehensive review. *J. Clean. Prod.* **2016**, *127*, 1–18. [CrossRef]
30. Bruni, C.; Forcellese, A.; Gabrielli, F.; Simoncini, M. Effect of the lubrication-cooling technique, insert technology and machine bed material on the workpart surface finish and tool wear in finish turning of AISI 420B. *Int. J. Mach. Tools Manuf.* **2006**, *46*, 1547–1554. [CrossRef]
31. Le Coz, G.; Marinescu, M.; Devillez, A.; Dudzinski, D.; Velnom, L. Measuring temperature of rotating cutting tools: Application to MQL drilling and dry milling of aerospace alloys. *Appl. Therm. Eng.* **2012**, *36*, 434–441. [CrossRef]
32. Brinksmeier, E.; Janssen, R. Drilling of multi-layer composite materials consisting of carbon fiber reinforced plastics (CFRP), titanium and aluminum alloys. *CIRP Ann-Manuf. Technol.* **2002**, *51*, 87–90. [CrossRef]
33. Mosleh, M.; Shirvani, K.; Smith, S.; Belk, J.H.; Lipczynski, G. A Study of Minimum Quantity Lubrication (MQL) by Nanofluids in Orbital Drilling and Tribological Testing. *J. Manuf. Mater. Process.* **2019**, *3*, 5. [CrossRef]
34. Turning Process, Defects, Equipment. Available online: http://www.custompartnet.com/wu/turning?newwindow=true (accessed on 1 March 2022).
35. Behera, B.C.; Ghosh, S.; Rao, P.V. Application of nanofluids during minimum quantity lubrication: A case study in turning process. *Tribol. Int.* **2016**, *101*, 234–246.
36. Mitsubishi Materials Corporation Function of Tool Features for Face Turning. Available online: http://www.mitsubishicarbide.net/contents/mmus/enus/html/product/technical_information/information/t_sukui.html (accessed on 1 March 2022).
37. Patole, P.; Kulkarni, V.; Bhatwadekar, S. MQL Machining with nano fluid: A review. *Manuf. Rev.* **2021**, *8*, 13. [CrossRef]
38. Hegab, H.; Umer, U.; Deiab, I.; Kishawy, H. Performance evaluation of Ti–6Al–4V machining using nano-cutting fluids under minimum quantity lubrication. *Int. J. Adv. Manuf. Technol.* **2018**, *95*, 4229–4241. [CrossRef]
39. Das, A.; Patel, S.; Das, S. Performance comparison of vegetable oil based nanofluids towards machinability improvement in hard turning of HSLA steel using minimum quantity lubrication. *Mech. Ind.* **2019**, *20*, 506. [CrossRef]
40. Milling Machine Definition, Process & Types-Engineering Articles. Available online: https://www.engineeringarticles.org/milling-machine-definition-process-types/ (accessed on 1 March 2022).
41. What Is High-Speed Machining-Grainger Know How. Available online: https://www.grainger.com/know-how/industry/metalworking/kh-what-is-high-speed-machining#:~{}:text=A%20process%20that%20combines%20lighter,life%20and%20increase%20shop%20productivity (accessed on 1 March 2022).
42. Frances, B. High Speed Machining: Disadvantages. Available online: https://www.bandbprecision.co.uk/high-speed-machining-disadvantages (accessed on 1 March 2022).
43. Bai, X.; Li, C.; Dong, L.; Yin, Q. Experimental evaluation of the lubrication performances of different nanofluids for minimum quantity lubrication (MQL) in milling Ti-6Al-4V. *Int. J. Adv. Manuf. Technol.* **2018**, *101*, 2621–2632. [CrossRef]
44. Sarhan, A.; Sayuti, M.; Hamdi, M. Reduction of power and lubricant oil consumption in milling process using a new SiO_2 nanolubrication system. *Int. J. Adv. Manuf. Technol.* **2012**, *63*, 505–512. [CrossRef]
45. Sayuti, M.; Sarhan, A.; Hamdi, M. An investigation of optimum SiO_2 nanolubrication parameters in end milling of aerospace Al6061-T6 alloy. *Int. J. Adv. Manuf. Technol.* **2012**, *67*, 833–849. [CrossRef]
46. Eltaggaz, A.; Deiab, I. Comparison of between direct and peck drilling for large aspect ratio in Ti-6Al-4V alloy. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 2797–2805. [CrossRef]
47. Baksi, S. Drilling Machine: Definition, Parts, Types, and Operations (With PDF). Available online: https://learnmechanical.com/drilling-machine/ (accessed on 1 March 2022).
48. Drilling Introduction, Drill Press Work Area. Available online: https://www.efunda.com/processes/machining/drill.cfm (accessed on 1 March 2022).
49. Salimi-Yasar, H.; Zeinali Heris, S.; Shanbedi, M. Influence of soluble oil-based TiO_2 nanofluid on heat transfer performance of cutting fluid. *Tribol. Int.* **2017**, *112*, 147–154. [CrossRef]
50. Chatha, S.; Pal, A.; Singh, T. Performance evaluation of aluminium 6063 drilling under the influence of nanofluid minimum quantity lubrication. *J. Clean. Prod.* **2016**, *137*, 537–545. [CrossRef]
51. Zelinski, P. The Fast Track to High Speed Drilling. Available online: https://www.mmsonline.com/articles/the-fast-track-to-high-speed-drilling (accessed on 1 March 2022).

52. Milling vs. Grinding: What's the Difference? Available online: https://monroeengineering.com/blog/milling-vs-grinding-whats-the-difference/ (accessed on 1 March 2022).
53. Shen, B.; Shih, A.; Tung, S. Application of Nanofluids in Minimum Quantity Lubrication Grinding. *Tribol. Trans.* **2008**, *51*, 730–737. [CrossRef]
54. Bhargavi, A.; Prashantha, S.T. Application of Nano Cutting Fluid under Minimum Quantity Lubrication (MQL) Technique to Improve Grinding of Ti–6Al–4V Alloy. *Int. J. Eng. Res. Technol. (IJERT) Icesmart* **2015**, *3*. [CrossRef]
55. Cui, X.; Li, C.; Zhang, Y.; Said, Z.; Debnath, S.; Sharma, S.; Ali, H.M.; Yang, M.; Gao, T.; Li, R. Grindability of titanium alloy using cryogenic nanolubricant minimum quantity lubrication. *J. Manuf. Process.* **2022**, *80*, 273–286. [CrossRef]
56. Hegab, H.; Darras, B.; Kishawy, H. Sustainability Assessment of Machining with Nano-Cutting Fluids. *Procedia Manuf.* **2018**, *26*, 245–254. [CrossRef]
57. Hanson, A. The Benefits of Using Computational Fluid Dynamics as a Tool for Innovation. Available online: https://www.pddinnovation.com/computational-fluid-dynamics/ (accessed on 1 March 2022).
58. El-Bouri, W.K. Investigation of Minimum Quantity Lubrication Coolant Strategy for the Machining of Austempered Ductile Iron (ADI). *Mater. Sci.* **2018**.
59. Byrne, G.; Dornfeld, D.; Denkena, B. Advancing Cutting Technology. *CIRP Ann.* **2003**, *52*, 483–507. [CrossRef]
60. Hegab, H.; Kishawy, H.; Umer, U.; Mohany, A. A model for machining with nano-additives based minimum quantity lubrication. *Int. J. Adv. Manuf. Technol.* **2019**, *102*, 2013–2028. [CrossRef]
61. Rohit, J.; Surendra Kumar, K.; Sura Reddy, N.; Kuppan, P.; Balan, A. Computational Fluid Dynamics Analysis of MQL Spray Parameters and Its Influence on MQL Milling of SS304. In *Simulations for Design and Manufacturing*; Lecture Notes on Multidisciplinary Industrial Engineering; Springer: Singapore, 2018; pp. 45–78.
62. Milling Troubleshooting. Available online: https://www.sandvik.coromant.com/en-us/knowledge/milling/pages/troubleshooting.aspx (accessed on 1 March 2022).
63. López de Lacalle, L.; Angulo, C.; Lamikiz, A.; Sánchez, J. Experimental and numerical investigation of the effect of spray cutting fluids in high speed milling. *J. Mater. Process. Technol.* **2006**, *172*, 11–15. [CrossRef]
64. Balan, A.; Kullarwar, T.; Vijayaraghavan, L.; Krishnamurthy, R. Computational fluid dynamics analysis of MQL spray parameters and its influence on superalloy grinding. *Mach. Sci. Technol.* **2017**, *21*, 603–616. [CrossRef]
65. Raval, J.; Hung, W.; Tai, B. Multiphase Flow Distribution in MQL Drilling Using Optical Intensity Distribution Based Approach. In Proceedings of the 14th International Manufacturing Science and Engineering Conference, Erie, PA, USA, 10–14 June 2019.
66. Eltaggaz, A.; Said, Z.; Deiab, I. An integrated numerical study for using minimum quantity lubrication (MQL) when machining austempered ductile iron (ADI). *Int. J. Interact. Des. Manuf.* **2020**, *14*, 747–758. [CrossRef]
67. Ammar, H.E.; Elaziz, M.A.; Das, S.R.; Muthuramalingam, T.; Lu, S. A new optimized predictive model based on political optimizer for eco-friendly MQL-turning of AISI 4340 alloy with nano-lubricants. *J. Manuf. Process.* **2021**, *67*, 562–578. [CrossRef]
68. Abrão, B.S.; Pereira, M.F.; da Silva, L.R.R.; Machado, Á.R.; Gelamo, R.V.; de Freitas, F.M.C.; Mia, M.; da Silva, R.B. Improvements of the MQL Cooling-Lubrication Condition by the Addition of Multilayer Graphene Platelets in Peripheral Grinding of SAE 52100 Steel. *Lubricants* **2021**, *9*, 79. [CrossRef]
69. Zhang, Y.; Li, H.N.; Li, C.; Huang, C.; Ali, H.M.; Xu, X.; Mao, C.; Ding, W.; Cui, X.; Yang, M.; et al. Nano-enhanced biolubricant in sustainable manufacturing: From processability to mechanisms. *Friction* **2022**, *10*, 803–841. [CrossRef]