A Brief Review on Machining with Hybrid MQL Methods

Rahul Katna, M. Suhaib, Narayan Agrawal, and S. Maji

Abstract MQL has gained lot of attention in the past decade owing to its effectiveness over the conventional fluid delivery method. Conventional cutting fluid delivery methods have major drawback of being used in large quantity and dangerous effect on environment and workers health. MQL has emerged as a viable alternate to the conventional fluid delivery method. However, lately many more methods have been found to be more effective than the raw MQL method. Different strategies of delivering the cutting fluid directly into the cutting zone have been conceptualized and tested. These techniques are collectively coined as "Hybrid Techniques". This paper describes the various hybrid delivery methods in machining with their benefits and drawbacks.

Keywords Sustainable · Manufacturing · Minimum · Quantity · Lubrication · Green · Manufacturing

1 Introduction

Machining is very important process in the manufacturing industry. Huge amount of cutting fluids are used in machining for keeping the temperature rise under control and have a good quality product [1–4]. The various zones where heat is generated are shown in Fig. 1.

R. Katna (✉) · M. Suhaib
Department of Mechanical Engineering, Jamia Millia Islamia, New Delhi 110020 08544, India
e-mail: katnarahul@gmail.com

N. Agrawal · S. Maji
Delhi Institute of Tool Engineering, Okhla Phase 2, New Delhi 110020, India

R. M. Singari et al. (eds.), *Advances in Manufacturing and Industrial Engineering*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-8542-5_11

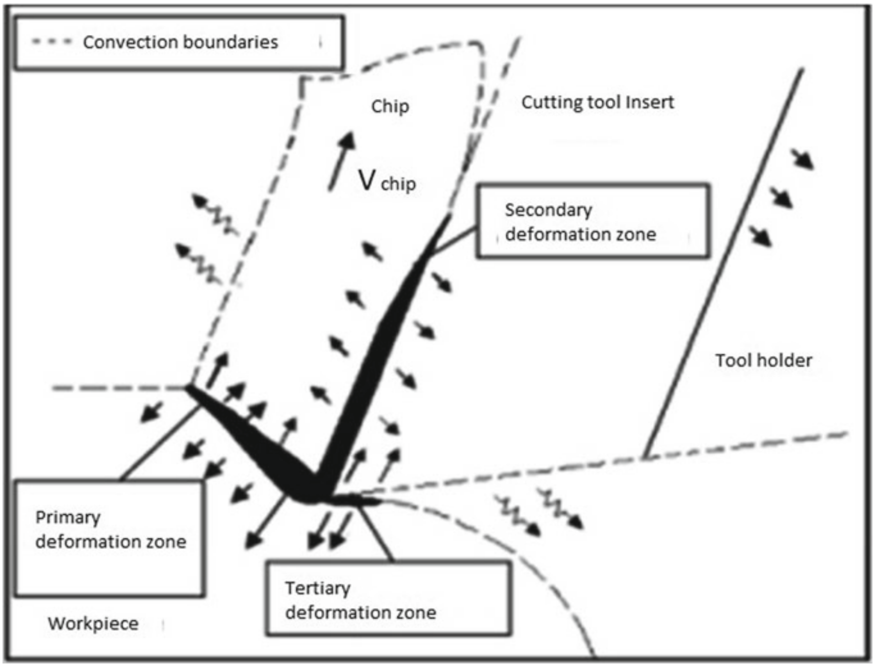

Fig. 1 Zones of heat generation in machining [4]

1.1 Conventional Cutting Fluids

However, the cutting fluids are used in large quantity and have negative effect on environment [5–7]. The high usage of cutting fluids affects the workers and also has negative impact on the environment [5, 8–10]. Dry machining is an alternative in which cutting fluids are not used and is an environment-friendly way of machining [11, 12]. However, there are many problems associated with dry cutting such as high temperature which can destroy the cutting tool and the workpiece surface [13–15]. Hence, the search is going on for a viable alternative that can be used for machining and which does not impact the environment and human [16–20]. Use of green cutting fluids has been in vogue for last many years and has proved to be better than conventional cutting fluids [21, 22]. One such alternative which has been found to be effective is MQL method. MQL stands for minimum quantity lubrication. It is a method of using straight cutting fluid, i.e. pure oil without water and atomizing it before delivering it to the machining zone during machining process. This method is effective than conventional flood delivery method in terms of providing better lubrication [23–28]. This is because the atomized oil droplets are of the order of microns and are effectively transported to the machining zone via the small cracks and also due to high delivery pressure of the carrier air. A typical MQL diagram is shown in Fig. 2. MQL method is also environment friendly as it uses very less

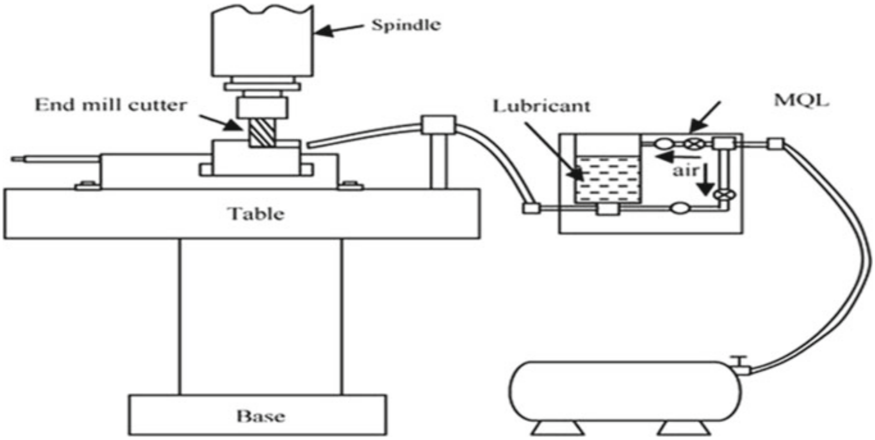

Fig. 2 MQL set-up [32]

amount if cutting fluid [29–31].

2 MQL or Minimum Quantity Lubrication

MQL has resulted in better surface finish and reduced tool wear in many experiments [33, p. 6]. However, many researchers oppose this result and have questioned the validity of the MQL in machining. Many researchers have also stated that MQL is effective in only some machining operations [34–37]. Researchers have raised serious concerns over the temperature reducing ability of MQL as it is used in very small quantity—of the order of 50–200 mL/h. It has also been reported that at very high cutting speeds, the MQL method loses its effectiveness as the oil gets vapourized before reaching the cutting zone and renders the process useless [38, 39].

Owing to the shortcomings in the conventional MQL methods, researchers have now focused on improving the effectiveness of the methods. Some research groups focus on improving the properties of the lubricant by various methods such as mixing nanoparticles and ionic liquids in the base oil. Addition of such additives greatly enhances the physiochemical properties of the oils, and machining with such lubricants has resulted in reduced friction and tool wear.

Other researchers focus on improving the delivery methods for increasing the effectiveness of the MQL method. Such methods use cooled compressed air via vortex tube, cryogenic MQL and electrostatic MQL. This paper gives an introduction to each of the methods and the current trend in their usage. In this paper, only the latest articles published in this year have been considered to give a brief overview on the applicability and the effectiveness of hybrid methods.

2.1 Minimum Quantity Lubrication in Machining

Minimum quantity lubrication is a method of cutting fluid delivery in which a very small quantity of lubricant is injected into the machining zone, mostly through the rake face of the tool. This is done by using pressurized air which atomizes the liquid lubricant and carries it with it to the machining zone. There are many benefits of MQL method over the conventional flood delivery method. It reduces the length of sticking zone of the chip on the rake face. It also reduces the friction between the chip and the tool by providing a film and thus decreases the frictional heat. High pressure also helps in chip curl and effective breaking of chips. In soft materials, use of MQL reduces the sticking tendency and thereby improves the tool life. There are two types of MQL delivery systems which are classified on the basis of mixing of compressed air with the lubricant. Figure 3 shows the different methods of mixing—external and internal. In internal mixing, the lubricant and air are mixed well before the nozzle exit, whereas in the external type of delivery, mixing is achieved just before exiting from the nozzle. The external method is far better than the internal mixing one as it ensures a homogenous flow of lubricant with the mixture. In internal mixing, the lubricant can stick to the walls of the carrying tube and can result in lumping, and the delivery is not homogenous. The pressure and the nozzle angle with respect to the cutting tool and the nozzle distance play an important role in achieving maximum efficiency from the MQL method.

3 Advancements in MQL Delivery Methods

Different ways have been researched on improving the effectiveness of MQL methods such as cryogenic MQL, cooled air MQL and electrostatic MQL. All these methods have been tested and have proved to enhance the effectiveness of the conventional MQL method. The commonly encountered problem is the air cushion or the vapour film generation which prevents the entry of the lubricant in the cutting zone.

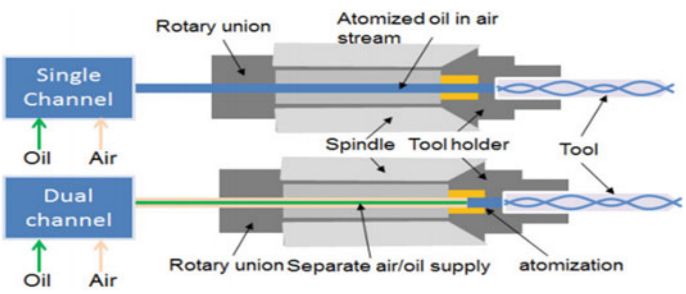

Fig. 3 Types of MQL mixing [40]

3.1 Cooled Air MQL

Cooled air MQL or CMQL is a technique in which cold air is used as lubricant carrier. Cold air carries the atomized lubricant into the machining zone. The cool air causes extra cooling effect in addition to the lubrication film provided by the lubricant.

In an attempt to improve the cooling efficiency of the conventional MQL process, Saberi et al. [41] employed a vortex tube for delivering lubricant into the machining zone. A vortex tube is a small pipe without any mechanical parts in which the input compressed air is split into two parts. One end of the vortex tube discharges cold air, and other end discharges hot air. This cold air is used for carrying the atomized lubricant. From the experiments, it was found that using this technique, the heat transfer coefficient was higher than the conventional MQL system. However, they also reported that lubricant has no effect in cooling with this method; yet, the lubricant in the MQL spray was able to reduce the grinding forces. They also reported that best surface finish is found in flood method of grinding than the MQL method of delivery because poor effectiveness of air in carrying away the heat generated and due to the circular profile of the grinding wheel which distorts the jet flow of air–lubricant mixture.

Stachurski et al. [42] used similar technique of using cold compressed air with MQL in sharpening by grinding the hobbing cutter. In a different approach, the authors used separate delivery of cold air into the machining zone in addition to the lubricant spray. They reported that among MQL, MQL + CCA and conventional flood method, MQL + CCA method gave best surface finish indicating its effectiveness over other methods and also reducing the quantity of cutting fluid required. Not only this, the cutting edges were free of defect with MQL + CCA method of delivery. The results indicate that coupling conventional MQL with cooled air approach is a better alternate than using only the conventional MQL system in machining.

Benjamin et al. [43] combined cold air through vortex tube and conventional MQL method of lubricant delivery in milling titanium alloy Ti-6Al-4V. The authors reported better lubrication in terms of reduced friction in machining with the combined method than with single MQL stream. The chips produced with the combined method of fluid delivery were also thinner and with less radius of curvature indicating less coefficient of friction at the tool chip interface. It was found from the experimental results that the combined technique was able to reduce the cutting forces by an average of 7% thereby saving on the input power requirement during machining. Too wear studies on the cutting tools showed impressive results. Tool life was found to increase by 43%. Moreover, the wear with conventional MQL was 502 microns, whereas with the combined technique, the wear was only 404 microns and no evidence of diffusion on the rake face which was found to be prominent with the conventional MQL method.

In another study done on titanium (Grade-II), Singh and Sharma [44] used vortex tube method for delivering cold and compressed air in the machining zone combined with lubricant. From the results, it was found that there is a reduction of 15% in surface roughness. Not only had this, cutting forces and tool wear also reduced with

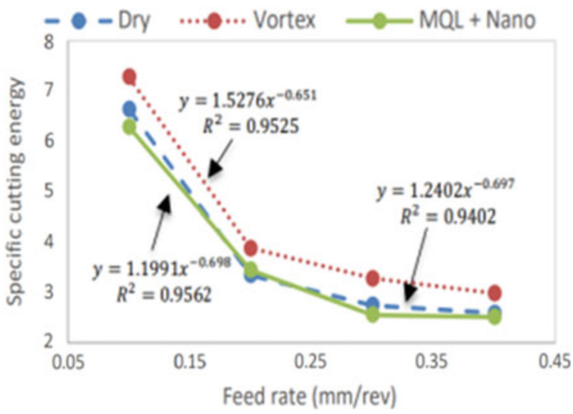

Fig. 4 Specific cutting energy with different fluid delivery method at different feed rate [46]

the combination method employed by the authors. This was due to better cooling achieved with the combination method in comparison with the MQL method alone. Salaam et al. [45] proposed the use vortex tube for generating cold air for assisting the conventional MQL proves in order to improve its effectiveness. They claim that this combined method will have higher pressure than the conventional MQL method and will also help in improving the machining efficiency. However, Ali et al. [46] reported that using hybrid method did not reduce the specific cutting energy required in the machining operation. Figure 4 clearly shows that even at different feed rate the highest specific cutting energy is with the hybrid method of fluid delivery.

Jiang et al. [47] compared the effectiveness of cold air with mist. The performance was compared with cold air without mist, and they observed a reduction in the cutting forces in the cold air with lubricant mist. Better temperature control is observed in both the cases than dry machining.

3.2 Cryogenic MQL

Cryogenic machining refers to machining done at very low temperatures. Owing to the low lubricity problem of cryogenic gases but good thermal properties, researches have use several cryogens combined with MQL method.

Shokrani et al. [13] used a double nozzle system for delivering liquid nitrogen cryogen with MQL lubricant at different cutting speeds, feed and depth of cut. The results show that cryogenic gas combined with lubricant has a significant effect on the life of the cutting tool. The life of the cutting tool was found to have increased significantly under the hybrid cooling environment. However, in this study, it was found that the lubricant also plays a role in heat carrying capacity which was not observed when machining with cold air assisted MQL. From the surface roughness data, it was found that the machining environment affected the quality of surface achieved in machining. The surface roughness achieved was comparable to that achieved with MQL. Cryogenic MQL technique thus increases the tool life in addition to providing a better surface finish and very low rise in temperature.

Hanenkamp et al. [48] used carbon dioxide in combination with atomized lubricant in milling operation of Ti6Al4V. In a strikingly different approach, the authors used different types of lubricants in addition to the carbon dioxide as cryogen. The results clearly show that the combination of cryogenic technique with MQL performs better than the conventional flood method of cooling. Comparison of surface roughness achieved with the different types of lubricants used in the machining operations revealed a striking fact that it is the presence of lubricant that controls the quality of the machined surface. This was evident because the cryogen used in each case was the same, but the lubricant employed was different, and different surface roughness values were achieved. The lowest surface roughness values were achieved with the ester + additive lubricant. Figure 5 shows the surface integrity with different methods of fluid delivery.

Tool	KM Drill Ø 4,5 mm	**Material**	50CrMo4
Coating	TiAlN	**Drilling depth l**	30 mm
Wet	Oil 110 bar	**Cutting speed v_c**	90,5 m/min
MQL	5,4 bar	**Feed f**	0,20 mm
MQL+CO_2	8 kg/h + 90 ml/h	**Length of cut**	21 m

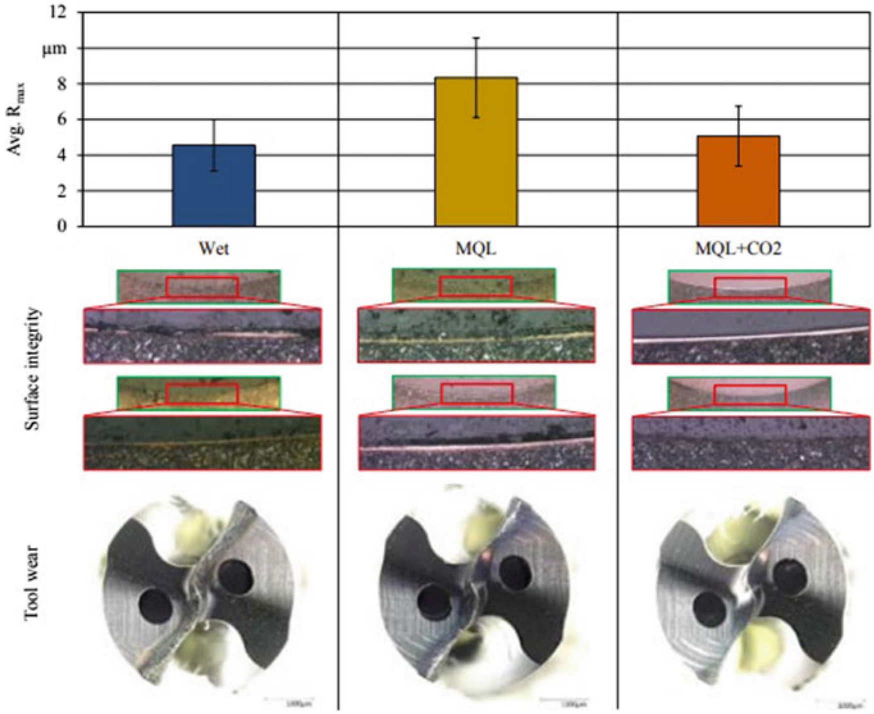

Fig. 5 Surface integrity with different fluid delivery methods [48]

Grguras et al. [49] used cryogenic MQL by premixing the lubricant in liquid carbon dioxide in machining. The experiments were done on milling TI6Al4V with carbide tool. The results indicate that cryogen oil solution was able to increase the tool life by more than 200%. The authors also reported that this method of mixing the lubricant in the carbon dioxide cryogen is also a simpler method because only a single nozzle is required in machining.

Pereira et al. [50] used carbon dioxide MQL in machining Inconel 718. They made a plug and play type adapter. From results, it is seen that the tool wear obtained with this hybrid method was close to that achieved with the flood method of cooling which indicates the effectiveness of this method as a potential alternative to the conventional flood cooling method.

Kim et al. [51] used chilly carbon dioxide gas with MQL lubricant in milling titanium alloy. The experimental results obtained clearly establish the effectiveness of hybrid MQL over the conventional MQL process. The hybrid method produced less cutting forces and resulted in lower coefficient of friction and also increased the tool life. Another outcome of this research translates the effect of lubricant delivered in the chip–work interface is that the authors found an improvement in the surface finish with an increase in the concentration of the lubricant.

Damir et al. [52] tested the effectiveness of cryogenic MQL in machining aerospace alloy. The authors used liquid nitrogen as the cryogen and a lubricant for MQL spray. The comparison was made with flood method, cryogen only, MQL only and hybrid method. Initially, the tool wear rate was almost the same for every method. But as the machining advanced towards, lowest amount of tool wear was obtained with the hybrid method. This was due to better cooling achieved with the cryogen system coupled with the MQL system. Also, the components machined with the hybrid delivery method showed less amount of residual stress than other techniques.

3.3 Electrostatic MQL

Electrostatic MQL is a strikingly new type of MQL process. In this method, fine mist of oil, either positively or negatively charged, is directed into the machining zone. Huang et al. [53] used an external system to charge the oil before atomizing them through an air compressor system and then directed the electrostatically charged oil particles into the machining zone. The benefit achieved out of electrostatically charging the oil is reduction in the wetting angle which translates into better spreadability. Also, as the oil particles are charges, it would be attracted to the neutral workpiece surface easily. Oil particles charged up electrostatically have lower surface tension which helps in easy transportation in the cutting zone thereby enabling better lubricity and higher performance than the conventionally used lubricant. From the experimental results, it was also found that positively charges oil has better lubrication properties than the negatively charges oil and the degree of polarity also affects the lubrication performance. The electrostatic MQL resulted in reduction in the wear of the cutting tool due to increase in the wetting properties, spreadability and reduction in surface tension. Similarly, in another study done on stainless steel, Xu et al. found similar results in decrease in tool wear [54]. The experimental results indicate the effectiveness of electrostatic MQL over the conventional MQL system and also indicate the viability of this method as an alternative to the conventional MQL method of cutting fluid delivery.

Jamil et al. [55] used electrostatically charges lubricant in machining aluminium alloy 6061T6. The authors used negatively charged castor oil as the lubricant in turning the aluminium 6061T6. The authors report that the negatively charged oil particles are accelerated towards the positively charged workpiece. The positive charge near the chip–workpiece region creates a suction pressure near the zone and helps in the capillary suction of the charges oil. This results in a deeper penetration into the cutting zone than the conventional MQL method and results in better performance and machining quality in terms of reduced tool wear.

Lv et al. [56] used grapheme nano platelets via the electrostatic MQL process. The focus of the researchers was to study the extent of penetration and the deposition property endowed due to the electrostatic charging. The experimental results showed an improvement in the penetration and the deposition in the metallic surface of the workpiece. The improvement in the properties was due to decrease in the wetting angle which resulted in better spreadability which is seen in other cases also. Electrostatically charged particles are able to make a better tribo film because they penetrate easily between the mating surfaces.

Xu et al. [57] used electrostatic MQL strategy in grinding operation of die steel. They reported that the dominant mechanism of action was capillary action. They also observed that 4kv electrostatic voltage was able to reduce the cutting forces significantly. This was attributed to the fact that the electrostatically charges lubricant particles were able to spread easily and resulted in better lubrication and reduced cutting temperature.

Su et al. [58] used charges nanoparticles in the lubricant and used this in the MQL system and found that electrostatically charged nanoparticles mixed lubricant with MQL is better than simply electrostatically charged lubricant with MQL. However, the drawback was that the nanoparticle charges resulted in higher mist concentration than that with the simple lubricant charges electrostatically and delivered via MQL. The authors recommend both these methods as an alternative to the conventional MQL method without electrostatic charging.

4 Conclusion and Future Scope

MQL method is no doubt a good alternative to the conventional flood method of fluid delivery. However, currently many advancements have been seen in the delivery method of cutting fluids. Following can be concluded from the literature:

1. MQL method is better than conventional flood delivery method.

2. The method of cutting fluid delivery affects the machining quality.
3. MQL still suffers from the cooling ability drawback as the volume used is very low.
4. Hybrid MQL techniques have shown better results than conventional MQL method.
5. Additional methods add up to the cost of conventional MQL as extra set-up is costly.
6. It is recommended that MQL method can be combined with flood delivery method in order to improve the heat carrying effectiveness of the method.

References

1. Adler DP, Hii W-S, Michalek DJ, Sutherland JW (2006) Examining the role of cutting fluids in machining and efforts to address associated environmental/health concerns. Mach Sci Technol 10(1):23–58
2. Astakhov VP, Joksch S (2012) Metalworking fluids (MWFs) for cutting and grinding: fundamentals and recent advances. Elsevier
3. Çakīr O, Yardimeden A, Ozben T, Kilickap E (2007) Selection of cutting fluids in machining processes. J Achiev Mater Manuf Eng 25(2):4
4. Abukhshim NA, Mativenga PT, Sheikh MA (2006) Heat generation and temperature prediction in metal cutting: a review and implications for high speed machining. Int J Mach Tools Manuf 46(7–8):782–800
5. Bartz WJ (2001) Ecological and environmental aspects of cutting fluids. Tribol Lubr Technol 57(3):13
6. Weisenberger BL (1976) Cutting oils and coolants are chief culprits in worker skin problems. Occup Health Saf Waco Tex 45(5):16
7. Grattan CEH, English JSC, Foulds IS, Rycroft RJG (1989) Cutting fluid dermatitis. Contact Dermat 20(5):372–376
8. Ellis EG (1967) LUBRICANTS: an industrial health hazard? Ind Lubr Tribol 19:141–145
9. Grijalbo L, Fernandez-Pascual M, García-Seco D, Gutierrez-Mañero FJ, Lucas JA (2013) Spent metal working fluids produced alterations on photosynthetic parameters and cell-ultrastructure of leaves and roots of maize plants. J Hazard Mater 260:220–230
10. Najiha MS, Rahman MM, Yusoff AR (2016) Environmental impacts and hazards associated with metal working fluids and recent advances in the sustainable systems: a review. Renew Sustain Energy Rev 60:1008–1031
11. King N, Keranen L, Gunter K, Sutherland J (2001) Wet versus dry turning: a comparison of machining costs, product quality, and aerosol formation. SAE Technical Paper
12. Marksberry PW, Jawahir IS (2008) A comprehensive tool-wear/tool-life performance model in the evaluation of NDM (near dry machining) for sustainable manufacturing. Int J Mach Tools Manuf 48(7–8):878–886
13. Shokrani A, Al-Samarrai I, Newman ST (2019) Hybrid cryogenic MQL for improving tool life in machining of Ti-6Al-4V titanium alloy. J Manuf Process 43:229–243
14. Klocke F, Eisenblätter G (1997) Dry cutting. CIRP Ann 46(2):519–526
15. Rubio EM, Camacho AM, Sánchez-Sola JM, Marcos M (2006) Chip arrangement in the dry cutting of aluminium alloys. J Achiev Mater Manuf Eng 16(1–2):164–170
16. Debnath S, Reddy MM, Yi QS (2014) Environmental friendly cutting fluids and cooling techniques in machining: a review. J Clean Prod 83:33–47
17. Hörner D (2002) Recent trends in environmentally friendly lubricants. J Synth Lubr 18(4):327–347

18. Katna R, Singh K, Agrawal N, Jain S (2017) Green manufacturing—performance of a biodegradable cutting fluid. Mater Manuf Process 32(13):1522–1527
19. Katna R, Suhaib M, Agrawal N (2020) Nonedible vegetable oil-based cutting fluids for machining processes – a review. Mater Manufact Process 35(1):1–32
20. Katna R, Suhaib M, Agrawal N, Singh K, Jain S, Maji S (2019) Green machining: studying the impact of viscosity of green cutting fluid on surface quality in straight turning. J Phys Conf Series 1276:012036
21. Agrawal N, Katna R (2019) Assessment of cutting forces in machining with novel neem oil-based cutting fluid. In: Applications of computing, automation and wireless systems in electrical engineering (pp 859–863). Springer, Singapore
22. Katna R, Suhaib M, Agrawal N, Jain S, Singh K, Maji S (2020) Experimental study on effect of green cutting fluid and surfactant on temperature in turning operation. In: Emerging trends in mechanical engineering (pp 437–449). Springer, Singapore
23. Dhar NR, Kamruzzaman M, Ahmed M (2006) Effect of minimum quantity lubrication (MQL) on tool wear and surface roughness in turning AISI-4340 steel. J Mater Process Technol 172(2):299–304
24. Dhar NR, Islam MW, Islam S, Mithu MAH (2006) The influence of minimum quantity of lubrication (MQL) on cutting temperature, chip and dimensional accuracy in turning AISI-1040 steel. J Mater Process Technol 171(1):93–99
25. Kamata Y, Obikawa T (2007) High speed MQL finish-turning of Inconel 718 with different coated tools. J Mater Process Technol 192–193:281–286
26. Kaynak Y (2014) Evaluation of machining performance in cryogenic machining of Inconel 718 and comparison with dry and MQL machining. Int J Adv Manuf Technol 72(5):919–933
27. Tasdelen B, Thordenberg H, Olofsson D (2008) An experimental investigation on contact length during minimum quantity lubrication (MQL) machining. J Mater Process Technol 203(1):221–231
28. Filipovic A, Stephenson DA (2006) Minimum quantity lubrication (mql) applications in automotive power-train machining. Mach Sci Technol 10(1):3–22
29. Silva LR, Corrêa ECS, Brandão JR, de Ávila RF (2013) Environmentally friendly manufacturing: Behavior analysis of minimum quantity of lubricant—MQL in grinding process. J Clean Prod
30. Chetan SG, Rao PV (2016) Environment friendly machining of Ni–Cr–Co based super alloy using different sustainable techniques. Mater Manuf Process 31(7):852–859
31. Lee P-H, Nam TS, Li C, Lee SW (2010) Environmentally-friendly nano-fluid minimum quantity lubrication (MQL) meso-scale grinding process using nano-diamond particles. In: 2010 international conference on manufacturing automation, pp 44–49
32. Murthy KS, Rajendran I (2012) Optimization of end milling parameters under minimum quantity lubrication using principal component analysis and grey relational analysis. J Braz Soc Mech Sci Eng 34(3):253–261
33. Tosun N, Huseyinoglu M (2010) Effect of MQL on surface roughness in milling of AA7075-T6. Mater Manuf Process 25(8):793–798
34. Boubekri N, Shaikh V (2015) Minimum quantity lubrication (MQL) in machining: benefits and drawbacks. J Ind Intell Inf 3(3)
35. Nguyen TK, Do I, Kwon P (2012) A tribological study of vegetable oil enhanced by nano-platelets and implication in MQL machining. Int J Precis Eng Manuf 13(7):1077–1083
36. Lawal SA, Choudhury IA, Nukman Y (2013) A critical assessment of lubrication techniques in machining processes: a case for minimum quantity lubrication using vegetable oil-based lubricant. J Clean Prod 41:210–221
37. Rotella G, Dillon OW, Umbrello D, Settineri L, Jawahir IS (2014) The effects of cooling conditions on surface integrity in machining of Ti6Al4V alloy. Int J Adv Manuf Technol 71(1):47–55
38. Khan MMA, Mithu MAH, Dhar NR (2009) Effects of minimum quantity lubrication on turning AISI 9310 alloy steel using vegetable oil-based cutting fluid. J Mater Process Technol 209(15):5573–5583

39. Sharma VS, Singh G, Sørby K (2015) A review on minimum quantity lubrication for machining processes. Mater Manuf Process 30(8):935–953
40. Tai BL, Stephenson DA, Furness RJ, Shih AJ (2014) Minimum quantity lubrication (MQL) in automotive powertrain machining. Procedia CIRP 14:523–528
41. Saberi A, Rahimi AR, Parsa H, Ashrafijou M, Rabiei F (2016) Improvement of surface grinding process performance of CK45 soft steel by minimum quantity lubrication (MQL) technique using compressed cold air jet from vortex tube. J Clean Prod 131:728–738
42. Stachurski W, Sawicki J, Wójcik R, Nadolny K (2018) Influence of application of hybrid MQL-CCA method of applying coolant during hob cutter sharpening on cutting blade surface condition. J Clean Prod 171:892–910
43. Mark Benjamin D, Sabarish VN, Hariharan MV, Samuel Raj D (2018) On the benefits of sub-zero air supplemented minimum quantity lubrication systems: an experimental and mechanistic investigation on end milling of Ti-6-Al-4-V alloy. Tribol Int 119:464–473
44. Singh G, Sharma VS (2017) Analyzing machining parameters for commercially puretitanium (Grade 2), cooled using minimum quantity lubrication assisted by a Ranque-Hilsch vortex tube. Int J Adv Manuf Technol 88(9):2921–2928
45. Salaam H, Taha Z, Tuan Ya TMYS (2012) Minimum quantity lubrication (MQL) using Ranque-Hilsch vortex tube (RHVT) for sustainable machining. Appl Mech Mater 217–219:2012–2015
46. Mahboob Ali MA, Azmi AI, Khalil ANM (2018) Specific cutting energy of Inconel 718 under dry, chilled-air and minimal quantity nanolubricants. Procedia CIRP 77:429–432
47. Jiang F, Li J, (Kevin) Rong Y, Sun J, Zhang S (2008) Study of cutting temperature in cold-air milling of Ti6Al4V alloy. In: Mitsuishi M, Ueda K, Kimura F (eds) Manufacturing systems and technologies for the new frontier. Springer, London, pp 371–376
48. Hanenkamp N, Amon S, Gross D (2018) Hybrid supply system for conventional and CO_2/MQL-based cryogenic cooling. Procedia CIRP 77:219–222
49. Grguraš D, Sterle L, Krajnik P, Pušavec F (2019) A novel cryogenic machining concept based on a lubricated liquid carbon dioxide. Int J Mach Tools Manuf 145:103456
50. Pereira O et al (2015) The Use of Hybrid CO_2 + MQL in machining operations. Procedia Eng 132:492–499
51. Kim JS, Kim JW, Lee SW (2017) Experimental characterization on micro-end milling of titanium alloy using nanofluid minimum quantity lubrication with chilly gas. Int J Adv Manuf Technol 91(5–8):2741–2749
52. Damir A, Shi B, Attia MH (2019) Flow characteristics of optimized hybrid cryogenic-minimum quantity lubrication cooling in machining of aerospace materials. CIRP Ann 68:77–80
53. Huang S, Lv T, Wang M, Xu X (2018) Enhanced machining performance and lubrication mechanism of electrostatic minimum quantity lubrication-EMQL milling process. Int J Adv Manuf Technol 94(1–4):655–666
54. Xu X, Huang S, Wang M, Yao W (2017) A study on process parameters in end milling of AISI-304 stainless steel under electrostatic minimum quantity lubrication conditions. Int J Adv Manuf Technol 90(1):979–989
55. Jamil M, Khan AM, He N, Li L, Zhao W, Sarfraz S (2019) Multi-response optimisation of machining aluminium-6061 under eco-friendly electrostatic minimum quantity lubrication environment. Int J Mach Mach Mater 21(5–6):459–479
56. Lv T, Huang S, Liu E, Ma Y, Xu X (2018) Tribological and machining characteristics of an electrostatic minimum quantity lubrication (EMQL) technology using graphene nano-lubricants as cutting fluids. J Manuf Process 34:225–237
57. Xu X et al (2019) Capillary penetration mechanism and machining characteristics of lubricant droplets in electrostatic minimum quantity lubrication (EMQL) grinding. J Manuf Process 45:571–578
58. Su Y, Lu Q, Yu T, Liu Z, Zhang C (2019) Machining and environmental effects of electrostatic atomization lubrication in milling operation. Int J Adv Manuf Technol 104(5):2773–2782