An assessment of environmentally conscious lubrication techniques in grinding: use of minimum quantity lubrication, solid lubricants and cryogenic cooling

Mayur A. Makhesana* and Kaushik M. Patel

Mechanical Engineering Department,
Institute of Technology,
Nirma University,
Ahmedabad 382481, India
Email: mayur.makhesana@nirmauni.ac.in
Email: kaushik.patel@nirmauni.ac.in
*Corresponding author

Abstract: The quality of work piece produced by the grinding operation greatly depends upon the heat generated due to friction and high specific energy of surface. The heat generated due to friction not only affects the integrity of work piece surface but also limits the applicability of the work piece material being ground. To overcome the effects of high heat generation in grinding, cooling and lubrication is generally provided. In this study, an effort is made to review the status on various newer, efficient and environment conscious lubrication techniques in grinding operation. It includes the method of minimising quantity of lubricants, application of solid lubricants and cryogenic cooling such techniques can reduce the cost and environmental hazards in grinding process and also leads towards the cleaner production. The performance and limitations of these methods of lubrication are highlighted here. The review also suggests some of the possible avenues of future research in cutting fluid application for grinding process.

Keywords: grinding; environmentally conscious lubrication techniques; minimum quantity lubrication; MQL; solid lubricants.

Reference to this paper should be made as follows: Makhesana, M.A. and Patel, K.M. (2018) 'An assessment of environmentally conscious lubrication techniques in grinding: use of minimum quantity lubrication, solid lubricants and cryogenic cooling', *Int. J. Sustainable Manufacturing*, Vol. 4, No. 1, pp.23–38.

Biographical notes: Mayur A. Makhesana is working as an Assistant Professor in Mechanical Engineering Department and pursuing a PhD at Nirma University. His research interests include conventional and advanced machining processes, sustainable manufacturing and cleaner production. He has research publications in various national and international journals and conference proceedings.

Kaushik M. Patel is working as a Professor in Mechanical Engineering Department at Nirma University. His research interests include conventional and advanced manufacturing processes. He has several research publications in various national and international journals and conference proceedings.

1 Introduction

Grinding is considered as a precision machining process which can produce components and parts with close tolerance and smooth surface finish. Grinding is also recognised as a method to grind very hard and brittle materials such as ceramics in order to achieve high surface quality and process efficiency with lower cost (Zhang and Peng, 2000). Grinding however is a highly energy intensive material removal process. The thermal energy associated in grinding is higher than any other alternative methods such as metal cutting. Moreover, the higher the process temperature in grinding area has an additional risk of thermally inducing damage, and has a profound influence on the surface integrity of the component. Grinding and many other finishing and cutting processes require use of cutting fluids in operation (Yildiz and Nalbant, 2008). If the fluid is not used for cooling, the heat generation increases and as a result the process temperature increases (Yerkes and Dorian, 1999).

Thus, the technical review is started with application of cutting fluid in grinding and its related health and environmental issues. These are discussed in subsequent sections.

2 Cutting fluid application in grinding

Cutting fluids are used in grinding by delivering fluid into the grinding area to reduce wheel wear, achieve smooth surface finish, protect the work piece against thermal damage and carry away the chips (Rowe et al., 1995; Morgan et al., 2008). Lubrication and cooling can be provided by cutting fluids and also the listed effects can be eliminated (Batako et al., 2005; Shaw, 1996). Lubrication reduces the heat generation and friction, grinding power required, grinding wheel wear and increases surface quality (Marinescu, 2004; Rowe, 2009).

Various methods have been reported for the fluid delivery in grinding but the mostly used and common technique is application of fluid with low velocity and high-volume (Rowe, 2009; Brinksmeier et al., 1999a). The fluid loses its properties with prolonged use and becomes waste. It has been reported that the application of fluids accounts for an extensive proportion of the total manufacturing cost (Brinksmeier et al., 1999b). The costs attributed to the use of machining fluids not only comprise the initial purchase and delivery logistics but also the storage, energy consumption, treatment, filtration, and the end of life disposal. The costs of cooling can be around 17% of a total component production cost; however storage and disposal costs are around 54% of cooling costs (Byrne and Scholta, 1993; Klocke and Eisenblätter, 1997). And for these reasons it is required to minimise the use of grinding fluids. Therefore the choice of grinding fluid cannot be made on the lower initial cost, but the total process economy and environmental requirements should be considered which leads to clean production.

3 Health and environmental concerns with cutting fluids

Grinding is known as one of the most environmental unfriendly manufacturing processes as it generates high amount of mist which can cause health problems to workers (Chen et al. 2002a). From measurements of the mist concentration and droplet size distribution on the shop floor for grinding, Chen et al. (2002b) found that the amount of mist generated in grinding is much more than in turning. Large numbers of workers are working in industries and around the machines but the effects of these cutting fluids and mist generated on the workers' health is generally ignored. The inherent high cost of disposal or recycling of the grinding fluid is often accepted as a necessary cost of doing business. Further, owing to strict environmental regulations, the cost of disposal or recycling of these fluids continues to rise (Howes et al., 1991; Byrne and Scholta, 1993).

Government regulation, environmental protection, public awareness, and the need for cost-reduction and cleaner production lead the manufacturing industries to take initiatives towards the development of clean processes. Grinding with no fluid has its own limitations and effects on the process (Klocke and Eisenblätter, 1997; Malkin and Guo, 2008). The grinding with no lubrication or cutting fluid causes higher heat and friction generation, thus increases the wheel wear and also affects the work surface integrity and surface finish achieved. (Marinescu et al., 2007; Ebbrell et al., 2000).

Moreover, the consideration about service life of grinding fluid is very important as the economic aspects about the use of various alternatives can be concluded. Studies have been reported on the eco-efficiency of grinding processes.

An approach has been made to evaluate the environmental and cost impact of a grinding process when changing the applied cutting fluid by calculating the respective impacts and eco-efficiency. Winter and Herrmann (2014) have used two conventional fluids, a mineral-based emulsion and grinding oil in grinding, and compared with an alternative cutting fluid. It has been concluded that the cutting fluid composition has a major influence on the technological, environmental and cost impact and therefore on the eco-efficiency of the grinding process.

A study has been reported to improve eco-efficiency of grinding by observing the influence of non-miscible mixable grinding oil and water-miscible polymer dilution on the grinding process by Winter et al. (2014). Based on the results it was reported that for the environmental and economic impacts, grinding oil is a less favourable option. Though, for other objectives and constraints, the grinding oil proves to be a better choice than polymer dilution, owing to a lower grinding wheel wear.

Quantifying eco-efficiency based on a ratio between life cycle costs and life cycle assessment is proposed by different authors. Huppes and Ishikawa firstly proposed the framework of evaluating eco-efficiency with the LCC/ LCA approach (Huppes and Ishikawa, 2005). The life cycle analysis case study of a non-cylindrical grinding process has been reported by Murray et al. (2012). The scope of this study was the production of 5,000 parts by using an averaged production rate. The analysis did not consider the variation of process parameters and the influence on environmental impact.

4 MQL technique in grinding

Minimum quantity lubrication (MQL) is the way to achieve nearly dry machining (NDM), it uses the cutting fluid in optimised and minimum quantities. Such techniques consume much less cutting fluid than conventional fluid cooling. (Machado and Wallbank, 1997; Rahman et al., 2002).

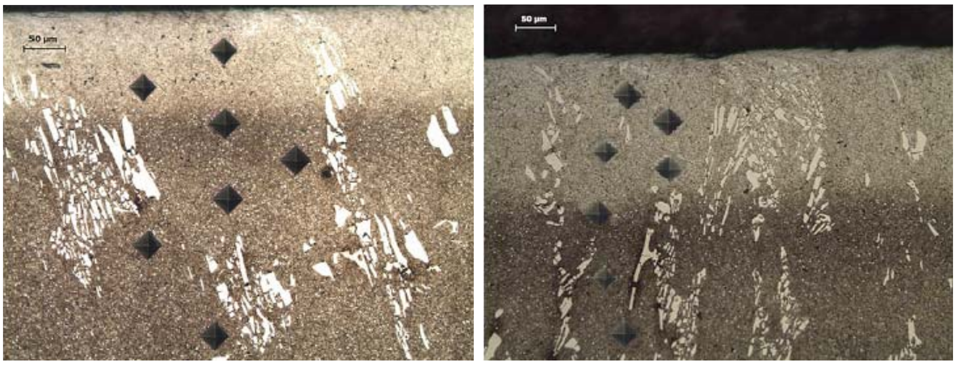
In MQL a small quantity of fluid via an aerosol is supplied to the machining area. The mixture of air and oil can be prepared in a tank or on the nozzle tip (Klocke et al., 2000). The amount of fluid required can be found based on the width of wheel. It is suggested as

1 L/min of fluid per 1 mm of wheel width (Barczak et al., 2010). In general, MQL fluid usage and supply is typically 30–100 ml/h (Weiner et al., 2004).

The study and comparison of the costs of storage and disposal of fluids in fluid delivery and MQL application in BMW company was reported by Dorr and Sahm (2000). It was revealed that up to 22% of cost saving by using MQL technique.

The use of MQL has been reported at rates between 20 to 140 ml/h, and 4 bar air pressure, to compare the effects of the tribological conditions when grinding titanium (Ti-6Al-4V) (Sadeghi et al., 2009). Aluminium oxide (Al_2O_3) wheels were used at a wheel speed of 15 m/s, work speed of 40 m/s, and depth of cut of 0.007 mm. Considerable reduction in cutting forces was obtained when applying MQL, as compared to cutting with flood cooling. In addition, better performance was reported when the MQL fluid was synthetic oil rather than a vegetable oil. In terms of surface roughness, MQL grinding can achieve similar results as flood cooling. The comparison of different MQL oil flow rates showed that an optimal flow rate exists; 60 ml/h, in that case.

Figure 1 Microphotograph (200X) of the steel structure, (a) after grinding with the new MQL-CO_2 technology (b) after conventional grinding (see online version for colours)



(a) (b)

Note: Experiments carried out with work piece speed v_w = 2 m/min, depth of cut a_e = 30 mm.

Source: Sanchez (2010)

Another approach to eliminate the use of cutting oil in grinding was reported by Sanchez (2010). The methodology applies MQL and low temperature CO_2 system that reduces the amount of lubricant required. In those experiments a reduced wheel wear and improved surface quality was found, as the frozen oil creates a layer around abrasive grits. Similar structure of base material was obtained in the micrograph as shown in Figure 1 in case of MQL-CO_2 application and the conventional grinding.

However the reduced cooling effect was observed as compared to normal cooling but no thermal damage reported in work piece surface. However it is required to reduce the costs associated with CO_2 consumption. By using CFD the nozzle design can be optimised to mix CO_2 and other gases.

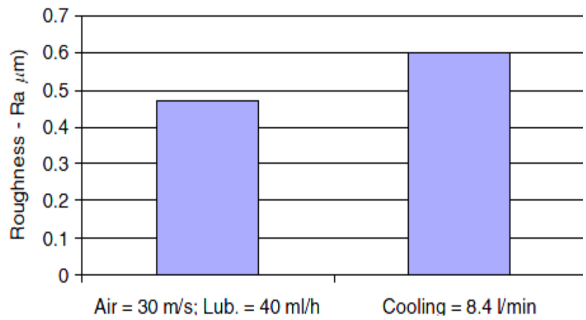
Emami et al. (2014) have studied and analysed the performance of four types of lubricants, namely mineral, hydrocracked, synthetic, and vegetable oils, are evaluated with regard to the reduction in specific energy required, cutting force and improved surface finish in MQL grinding of Al_2O_3 engineering ceramic. The parameters considered were depth of cut, feed rate and abrasive grain size for minimal cutting force, surface finish value and specific energy for the study and optimisation. The analysis of variance (ANOVA) was performed to find the significant parameters affecting the grinding force, specific grinding energy and surface finish.

5 Influence of nozzle design and Jet velocity in MQL grinding

The variation in nozzle design and location influences the efficiency of lubrication. Webster et al. (2002) proposed the use of coherent jet nozzles. The benefits of coherent jet nozzles are the capability to focus on the cutting zone, accurate velocity with respect to wheel velocity and reduced air entrainment in the cutting fluid.

The effects of grinding parameters on ABNT 4340 steel using MQL method were reported by Silva et al. (2005, 2007). The analysis was carried out to study the effect and behaviour of the MQL method and to compare the same with fluid cooling method. A specially designed nozzle was used to supply optimum quantity of fluid, which supplied the least amount of required oil in compressed air flow. The possibility of application of MQL in grinding was explored and discussed. Surface roughness, residual stresses, micro structure and micro hardness were analysed in order to conclude the effect of MQL method in grinding.

Figure 2 Roughness after 90 cycles with the Al_2O_3 grinding wheel (see online version for colours)



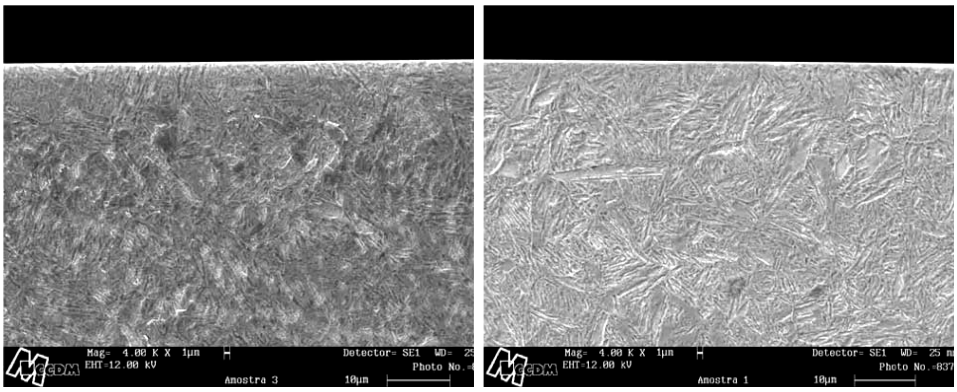
Note: v_s =30 m/s; v_f = 1 mm/min; t_s = 10 s; a = 100 µm.

Source: Silva et al. (2007)

It is also observed in Figure 2 that the roughness values were significantly reduced in MQL method, maybe due to very good property of lubricity.

The comparison of microstructures presented in Figure 3 shows that there is not any significant change or effect of MQL as compared to conventional cooling in the surface integrity of material.

Figure 3 Subsurface microstructures obtained after 90 cycles (v_s = 30 m/s; v_f = 1 mm/min and a = 100 µm) 4.000X, (a) conventional cooling (b) MQL (air = 30 m/s and lubri. = 40 ml/h)

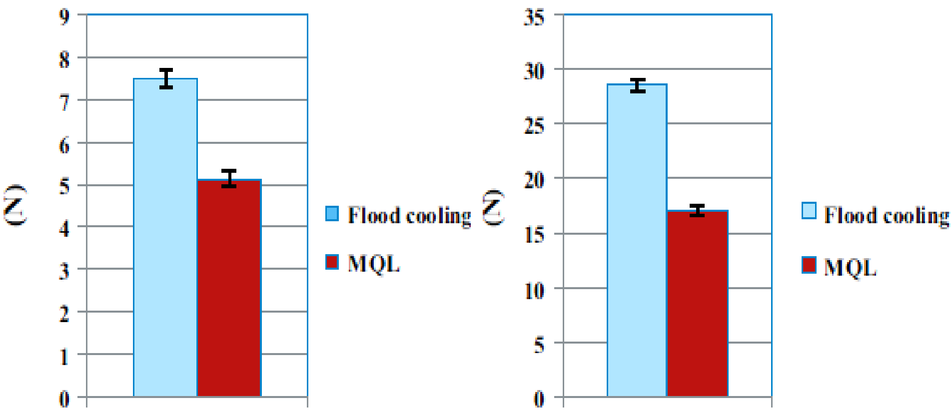


(a) (b)

Source: Silva et al. (2007)

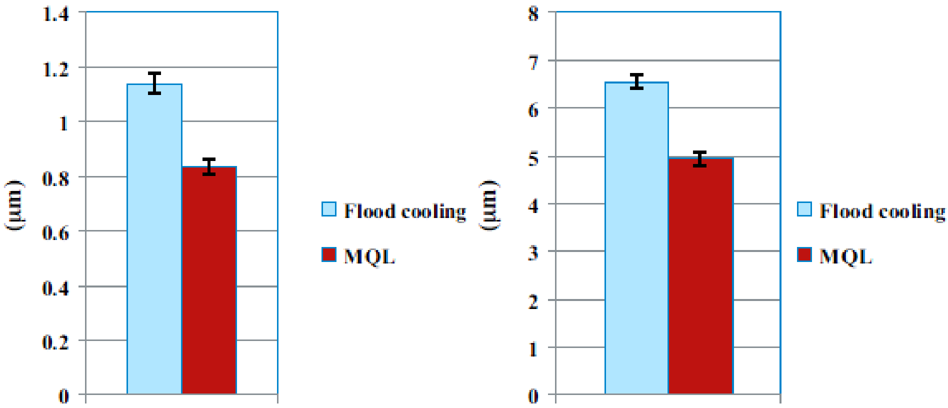
A theoretical and experimental investigation was carried out on the spray atomisation and various delivery parameters in the grinding process of Al_2O_3 engineering ceramics (Emami et al., 2013). The carrier gas velocity, liquid droplet size and liquid droplet velocity were considered as spray atomisation characteristics and the MQL delivery parameters were nozzle angle, nozzle distance, lubricant flow rate and gas flow rate in the case of Al_2O_3 ceramics grinding. Results were compared as shown in Figure 4 for the effects of nozzle distance on tangential force, normal force and surface roughness. And it was concluded the superiority of MQL over fluid cooling in grinding.

Figure 4 Comparison of MQL and flood cooling in Al_2O_3 ceramics grinding, (a) tangential force (b) normal force (c) surface roughness Ra (d) surface roughness Rz (see online version for colours)



(a) (b)

Figure 4 Comparison of MQL and flood cooling in Al_2O_3 ceramics grinding, (a) tangential force (b) normal force (c) surface roughness Ra (d) surface roughness Rz (continued) (see online version for colours)



(c) (d)

Source: Emami et al. (2013)

Another work has been reported on effect of nozzle spraying direction during surface grinding of hardened AISI 52100 steel (Mao et al., 2013). An angular position of the nozzle towards the grinding wheel provided the optimal grinding performance. Grinding forces, surface roughness and grinding temperature were reduced with increase in air pressure.

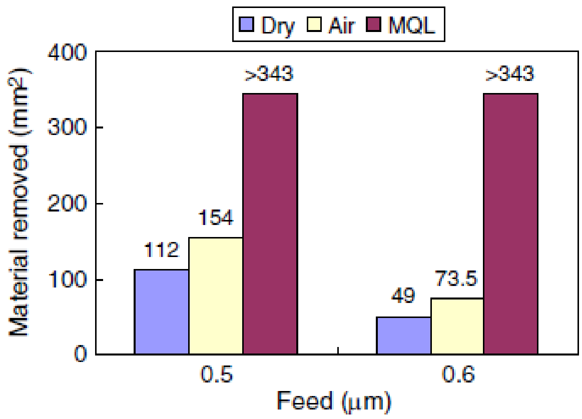
6 Influence on wheel wear, power, forces and process temperature in MQL grinding

The MQL method with ester oil in internal cylindrical grinding has been reported by Hafenbraedl and Malkin (2001). The experiments were conducted to cut AISI 52100 hardened steel with oil flow rate of 12 ml/h mixing with 69 kPa compressed air. From results it was concluded that the use of MQL provides efficient lubrication, required grinding power and specific energy and also reduction in grinding wheel wear.

The comparison of three cooling methods, conventional flood cooling, dry grinding and grinding with MQL, was attempted and studied by Barczak et al. (2010). Common steels EN8, M2 and EN31 were ground with a general purpose alumina wheel. They found that MQL can deliver better performance than flood cooling for the considered parameters and conditions. The parameters considered were power, specific forces (tangential and normal force), grinding temperature and surface roughness of work piece.

The suitability of MQL in micro grinding for the parameters effective tool life and surface roughness and the effect of various parameters of grinding and lubrication was analysed by Li and Lin (2012). Some experiments on dry grinding were also conducted. It was observed that the MQL in micro grinding process improves the amount surface finish and reduces tool wear. Experimental results shows that if higher surface finish and reduced wheel wear are required then the chip removal should be also smooth and efficient at the grinding zone in process. It was reported to increase tool life by seven times.

Figure 5 Tool life for different oil flow rates (see online version for colours)



Notes: Spindle speed = 39,000 rpm, oil flow rate = 1.88 ml/h, and air flow rate = 30 L/min.

Source: Li and Lin (2012)

Work has been reported on a new technique to obtain the value of temperature generated and energy distribution in work piece (Hadad and Sadeghi, 2012). Dry, fluid grinding and MQL method were considered for experiments. Embedded thermocouple was used to get temperature distribution in subsurface of 100Cr6 hardened steel material. The effects of parameters such as air pressure, oil mist flow rate, and oil droplet properties were studied in MQL grinding.

A newer grinding method which is efficient in cooling and environmentally safe was developed by considering the effect of grinding parameters and hardness of material on the basis of the grinding forces required and surface quality values (Tawakoli et al., 2009). They used an Al_2O_3 wheel in grinding soft and hardened steels, at removal rates in the range of 0.21 and 1.04 mm^3/min, with MQL at 66 ml/h and air pressure of 4 bar. Because plastic deformation takes place at the contact zone, the surface roughness is reduced and qualities are increased when MQL method is applied in grinding of 100Cr6 hardened steel.

7 Solid lubricant technique in grinding

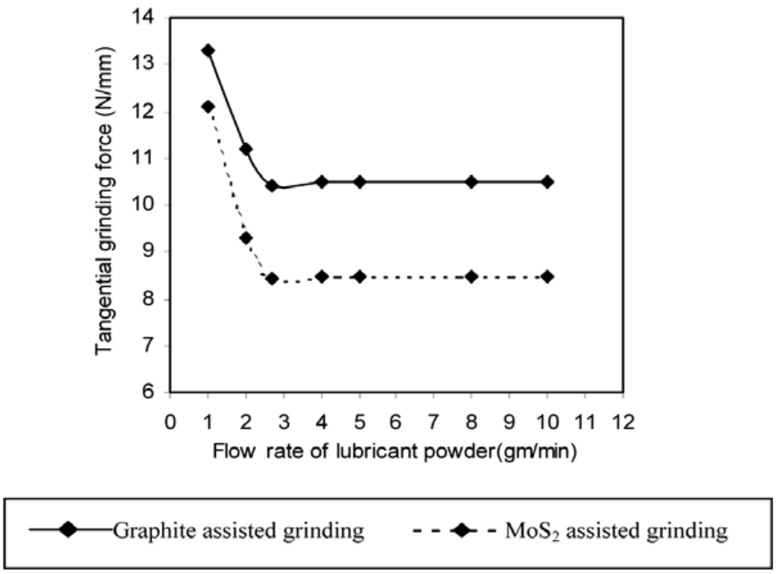
Solid lubricant assisted machining is one attempt to avoid the use of cutting fluids. Venu Gopal and Venkateswara Rao (2004) used graphite as a solid lubricant in grinding process which led to a decrease in heat generation. And it was noted that the entire improvement in the process was because of graphite. The most dominant factors affecting the grinding forces were studied by conducting the experiments with dry and graphite assisted grinding. It was reported that the tangential force and the percentage area of surface damage were reduced significantly when compared to dry grinding. Graphite and molybdenum disulphide (MoS_2) are the widely used solid lubricants. Boron nitride, polytetrafluoroethylene (PTFE), talc, calcium fluoride, cerium fluoride and tungsten disulphides can be used as solid lubricants. It is also concluded that too wear is less with the use of solid lubricants (Lathkar and Bas, 2000).

8 Influence on heat generated, cutting forces and surface finish in solid lubricant assisted grinding

Shaji and Radhakrishnan (2003) tried to develop solid lubricant moulded grinding wheels with different bonds in order to provide effective a solid lubrication process. Heat generated at the grinding area was reduced with the use of graphite as solid lubricant. The grinding wheels with resin bonding were effectively made and it has improved the process performance. Shaji and Radhakrishnan (2002) made an investigation on surface grinding using graphite as solid lubricant. They found a reduction in temperature, grinding force and energy and improved surface finish by developing the new set up.

Agarwal and Rao (2007) used graphite and molybdenum disulphide as solid lubricants, in order to reduce heat generated and friction in grinding. They have developed a set up for the application of solid lubricants and studied the effects of solid lubricants on tangential grinding force, specific energy and surface roughness while grinding SiC. The tangential grinding force as shown in Figure 6 was compared and found to be less with the application of MoS_2 assisted grinding.

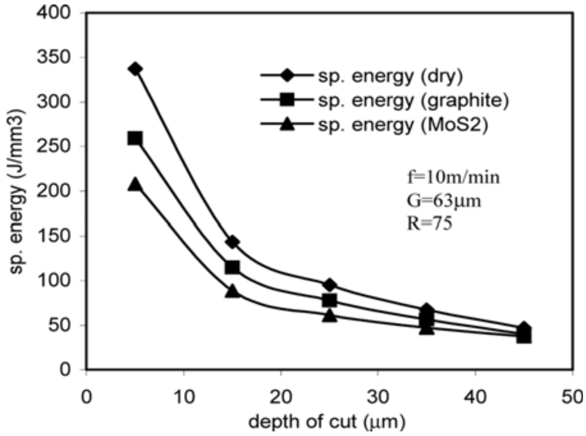
Figure 6 Variation of tangential grinding force with flow rate at selected level of depth of cut (d), feed rate (f), grit size (G) and grit density (R)



Source: Agarwal and Rao (2007)

The variation of specific energy with dry grinding, grinding with graphite and MoS_2 lubricants was studied and it was found that specific energy value was less in case of solid lubricants as compared to dry grinding.

Figure 7 Variation of specific energy with depth of cut for different grinding environments



Source: Agarwal and Rao (2007)

9 Cryogenic cooling technique

The liquid nitrogen (LN_2) when applied at –196°C to the cutting zone in order to reduce the heat generated in cutting or grinding is known as cryogenic cooling (Evans, 1991). This is an efficient and effective way to reduce the temperature between tool and work piece surface while machining.

Researchers have applied and studied the effects of liquid nitrogen on the grinding process (Chattopadhyay et al., 1985) and reported the improved surface finish value of the specimen grounded with the use of liquid nitrogen as compared to use of soluble oil. In adding, extreme cooling is reported in process and it has progressive effect on the tool life, because the grits remains sharp after even repeated use.

The application of cryogenic cooling has been reported in grinding for different steels and the liquid nitrogen jet enabled substantial reductions in grinding temperature, grinding forces, and surface residual stress in high speed steel, plus a better mode of chip formation and better surface quality (Paul et al., 1993; Paul and Chattopadhyay, 1995).

Similarly, a study has been reported on the effect of cryogenic cooling on grinding forces (Paul and Chattopadhyay, 1996b). The components of grinding forces and their dependencies on various parameters have been discussed. It was reported that the cryogenic cooling reduced the grinding forces substantially for all the materials undertaken throughout the infeed range due to favourable mode of chip formation, retention of grit sharpness, inert atmosphere, less primary ploughing, less secondary ploughing, etc.

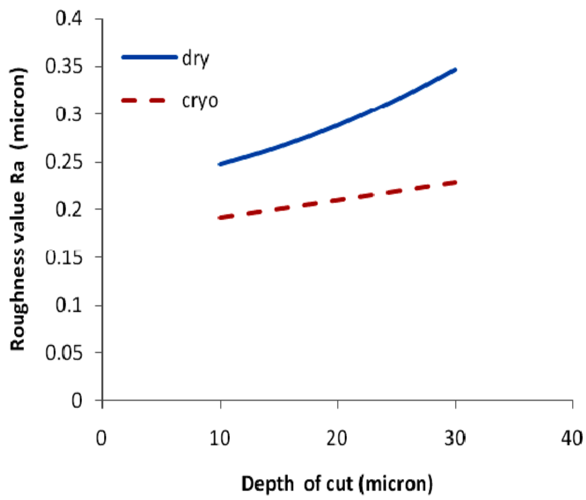
Application of cryogenic cooling was reported in grinding to control the grinding zone temperature (Paul and Chattopadhyay, 1996a). The method substantially reduced the grinding zone temperature and kept the temperature well below the critical range sensitive for steel, whereas flood cooling could not control the grinding zone temperature and lost its effectiveness at higher infeed.

Hong (2001) proposed a method of lubrication by using minimum amount of liquid nitrogen (LN_2) with the help of a specially designed micro-nozzle to apply it. It was found that with the arrangement of these two micro-nozzles, most efficient cooling was achieved by using the lowest LN_2 flow rate. They have also concluded that while machining of Ti-6Al-4V by liquid nitrogen the tool life increases significantly.

The sub-cooled jet of air for cryogenic cooling was used by Ramesh and Yeo (2003) instead of studying LN_2 for economic and environmental friendly cooling. A decrease in grinding force was found when a jet of air at 0.35°C and 0.3 MPa was applied to the grinding zone as compared to normal coolants.

Singh et al. (2010) investigated the grindability of composite ceramic material by considering various parameters affecting the process. It was reported that the specific grinding energy required in cryogenic grinding is less than in dry grinding. And hence improvement in process efficiency is also reported. The surface roughness value was obtained for dry and cryogenic grinding, and the value was lower in the case of cryogenic grinding.

Figure 8 Roughness value (Ra) with depth of cut (see online version for colours)

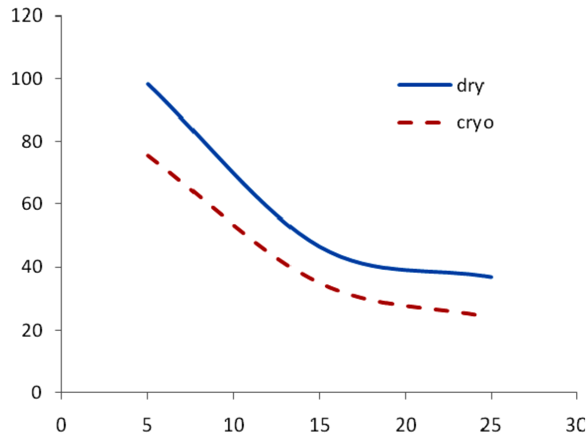


Source: Singh et al. (2010)

It was also observed that the specific grinding energy required in case of cryogenic cooling is reasonably low as compared to dry grinding.

The effect of cryogenic cooling and sol-gel (SG) alumina wheel on grinding performance of AISI 316 stainless steel was reported by Manimaran and Pradeep Kumar (2013). The SG alumina grinding wheel, with a self-sharpening characteristic was used the experiments in dry, wet and cryogenic cooling environments. The results were a reduction of about 32% in the grinding forces, 30%–49% improvement in the surface roughness, and 45%–49% lower temperature even at higher material removal rates with the application of cryogenic cooling.

Figure 9 Specific energy required in grinding (see online version for colours)



Source: Singh et al. (2010)

Work was also carried out to evaluate the effect of the application of liquid nitrogen in cryogenic grinding process and the improvements in the grinding force and surface roughness (Manimaran et al., 2014). Grinding tests were conducted on stainless steel 316 material in three environments, namely, dry, wet and cryogenic cooling. As compared to dry and wet cooling, a 37% and 13% reduction in the grinding forces resulted from using cryogenic cooling. The surface roughness under cryogenic cooling was found to produce 59% and 32% lower values than dry and wet cooling.

10 Conclusions and future research

It is a difficult task to select and rank a suitable lubrication method in grinding as it is greatly affected by grinding conditions, grinding wheel material and material of work piece. However, the review of the literature and work done in related areas shows the potentiality of application of MQL technique in grinding as compared to fluid cooling method. MQL technique is economic as compared to wet cooling, when the cost of lubricant and storage of large amount of lubricant is considered.

It was also observed that MQL method seems effective when applied with vegetable oil-based lubricant and other lubricants. It not only improves the grinding performance but also meets the environmental requirements and leads to the cleaner production. However, it is required to assess the effects from variables like types of workpiece material, grinding process, wheel material and grinding conditions in determining the performance ability of MQL technique in grinding.

The MQL application in grinding has improved the value of surface finish, reduced the heat generation and better lubrication in process. Further it is also analysed that there is no significant effect observed on surface integrity of work material.

Still it needs to address the application of MQL technique in grinding process to determine the grinding ratio, roughness values and wheel wear rate, as only a few studies are available on this technique. The generation of mist particles from the lubricant and their characteristics need to be investigated for grinding processes and conditions.

The application of solid lubricants has come up with another alternative solution to fluid cooling. However, it is required to select and apply right lubricant for given application. The use of solid lubricant gives an improvement in surface finish, and reductions in heat generation and friction and wear rate. It is also required to design and develop a proper and efficient lubricant delivery system to achieve desirable results.

In case of cryogenic cooling, it was reported the improvement in productivity. In this technique, the regulation of flow rate and pressure of liquid nitrogen are critical factors in order to get continuous flow of liquid nitrogen without over-cooling the workpiece. It is observed that with the use of liquid nitrogen the problem of disposal is eliminated as it evaporates in atmosphere after use. It is also required to regulate the supply of liquid nitrogen at the machining area in order to avoid the over-cooling. Cryogenic cooling has proved its effectiveness by improvements in process performance and quality.

References

Agarwal, S. and Rao, P.V. (2007) 'Performance improvement of sic grinding using solid lubricants', *Machining Science and Technology*, Vol. 11, No. 1, pp.61–79.

Barczak, A.D., Batako, L. and Morgan, M.N. (2010) 'A study of plane surface grinding under minimum quantity lubrication (MQL) conditions', *International Journal of Machine Tools & Manufacture*, Vol. 50, No. 1, pp.977–985.

Batako, A.D., Rowe, W.B. and Morgan, M.N. (2005) 'Temperature measurement in high efficiency deep grinding', *International Journal of Machine Tools and Manufacture*, Vol. 45, No. 11, pp.1231–1245.

Brinksmeier, E., Heinzel, C. and Wittmann, M. (1999a) 'Friction, cooling and lubrication in grinding', *Annals of the CIRP*, Vol. 48, No. 21, pp.581–598.

Brinksmeier, E., Walter, A., Jansen, R. and Diersen, P. (1999b) 'Aspects of cooling lubrication reduction in machining advanced materials', *Proceedings of the Institution of Mechanical Engineers*, Part B, Vol. 213, No. 8, pp.769–778.

Byrne, G. and Scholta, E. (1993) 'Environmentally clean machining processes-a strategic approach', *CIRP Ann. Manufacturing Technology*, Vol. 42, No. 1, pp.471–474.

Chattopadhyay, A.B., Bose, A. and Chattopadhyay, A.K. (1985) 'Improvements in grinding steel by cryogenic cooling', *Precision. Engineering*, Vol. 7, No. 2, pp.93–98.

Chen, Z., Yamaguchi, H. and Liang, S.Y. (2002a) 'Predictive modeling of cutting fluid aerosol in grinding process', *Transactions of the North American Manufacturing Research Institution, Society of Manufacturing Engineers*, Vol. 25, No. 1, pp.277–285.

Chen, Z., Liang, S.Y. and Yamaguchi, H. (2002b) 'Predictive modeling of cutting fluid aerosol generation in cylindrical grinding', *Society of Manufacturing Engineers*, Vol. 160, No. 1, pp.1–8.

Dorr, J. and Sahm, A. (2000) 'The minimum quantity lubricant evaluated by the users', *Machines and Metals Magazine*, Vol. 418, No. 1, pp.20–39.

Ebbrell, S., Woolley, N.H., Tridimas, Y.D., Allanson, D.R. and Rowe, W.B. (2000) 'The effects of cutting fluid application methods on the grinding process', *Int. J. Mach. Tools Manuf.*, Vol. 40, No. 2, pp.209–223.

Emami, M., Sadeghi, M.H. and Sarhan, A.A.D. (2013) 'Investigating the effects of liquid atomization and delivery parameters of minimum quantity lubrication on the grinding process of Al_2O_3 engineering ceramics', *Journal of Manufacturing Processes*, Vol. 15, No. 3, pp.374–388.

Emami, M., Sadeghi, M.H., Sarhan, A.D. and Hasani, F. (2014) 'Investigating the minimum quantity lubrication in grinding of Al_2O_3 engineering ceramic', *Journal of Cleaner Production*, Vol. 66, No. 1, pp.632–643.

Evans, C. (1991) 'Cryogenic diamond turning of stainless steel', *CIRP Ann. Manuf. Technol.*, Vol. 40, No. 1, pp.571–575.

Hadad, M.J. and Sadeghi, B. (2012) 'Thermal analysis of minimum quantity lubrication-MQL grinding process', *International Journal of Machine Tools & Manufacture*, Vol. 63, No. 1, pp.1–15.

Hafenbraedl, D. and Malkin, S. (2001) 'Technology environmentally correct for internal cylindrical grinding', *Machines and Metals Magazine*, No. 426, pp.40–55.

Hong, Y.S. (2001) 'Economical and ecological cryogenic machining', *J. Manuf. Sci. Eng.*, Vol. 12, No. 1, pp.331–338.

Howes, T.D., Toenshoff, H.K. and Heuer, W. (1991) 'Environmental aspects of grinding fluids', *CIRP Ann. Manuf. Technol.*, Vol. 40, No. 2, pp.623–629.

Huppes, G. and Ishikawa, M. (2005) 'A framework for quantified eco-efficiency analysis', *J. Ind. Ecol.*, Vol. 9, No. 4, pp.25–41.

Klocke, F. and Eisenblätter, G. (1997) 'Dry cutting', *CIRP Ann. e Manuf. Technol.*, Vol. 46, No. 2, pp.519–526.

Klocke, F., Beck, T., Eisenblatter, G. and Lung, D. (2000) 'Minimal quantity of lubrication (MQL) – motivation, fundamentals, vistas', *12th International Colloquium*, pp.929–942.

Lathkar, G.S. and Bas, U.S.K. (2000) 'Clean metal cutting process using solid lubricants', *Proceedings of the 19th AIMTDR Conference*, Narosa Publishing House, IIT Madras, pp.15–31.

Li, K-M. and Lin, C-P. (2012) 'Study on minimum quantity lubrication in micro-grinding', *Int. J. Adv. Manuf. Technol.*, Vol. 62, No. 1, pp.99–105, DOI 10.1007/s00170-011-3789-1.

Machado, A.R. and Wallbank, J. (1997) 'The effect of extremely low lubricant volumes in machining', *Wear*, Vol. 210, Nos. 1–2, pp.76–82.

Malkin, S. and Guo, C. (2008) *Grinding Technology*, Industrial Press, New York.

Manimaran, G. and Pradeep Kumar, M. (2013) 'Effect of cryogenic cooling and sol-gel alumina wheel on grinding performance of AISI 316 stainless steel', *Archives of Civil and Mechanical Engineering*, Vol. 13, No. 3, pp.304–312.

Manimaran, G., Pradeep Kumar, M. and Venkatasamya, R. (2014) 'Influence of cryogenic cooling on surface grinding of stainless steel 316', *Cryogenics*, Vol. 59, No. 1, pp.76–83.

Mao, C., Zou, H., Huang, X., Zhang, J. and Zhou, Z. (2013) 'The influence of spraying parameters on grinding performance for nanofluid minimum quantity lubrication', *The International Journal of Advanced Manufacturing Technology*, Vol. 64, Nos. 9–12, pp.1791–1799.

Marinescu, I.D., Hitchiner, M., Uhlmann, E., Rowe, W.B. and Inasaki, I. (2007) *Handbook of Machining with Grinding Wheels*, CRC Press, Atlanta GA.

Marinescu, I.D., Rowe, W.B., Dimitrow, B. and Inasaki, I. (2004) *Tribology of Abrasive Machining Process*, William Andrew Publishing, Norwich, New York.

Morgan, M.N., Jackson, A.R., Baines-Jones, V., Batako, A., Wu, H. and Rowe, W.B. (2008) 'Fluid delivery in grinding', *Annals of the CIRP*, Vol. 57, No. 1, pp.363–366, doi: 10.1016/ j.cirp.2008.03.090.

Murray, V.R., Zhao, F. and Sutherland, J.W. (2012) 'Life cycle analysis of grinding: a case study of non-cylindrical computer numerical control grinding via a unit process life cycle inventory approach', *Proc. Inst. Mech. Eng. Part B: J. Eng. Manufacture*, Vol. 226, No. 10, pp.1604–1611.

Paul, S. and Chattopadhyay, A.B. (1995) 'A study of effects of cryo-cooling in grinding', *Int. J. Mach. Tools Manufact.*, Vol. 35, No. 1, pp.109–117.

Paul, S. and Chattopadhyay, A.B. (1996a) 'Determination and control of grinding zone temperature under cryogenic cooling', *Int. J. Mach. Tools Manufact.*, Vol. 36, No. 4, pp.491–501.

Paul, S. and Chattopadhyay, A.B. (1996b) 'The effect of cryogenic cooling on grinding forces', *Int. J. Mach. Tools Manufact.*, Vol. 36, No. 1, pp.63–72, p.199.

Paul, S., Bandyopadhyay, P.P. and Chattopadhyay, A.B. (1993) 'Effect of cryo-cooling in grinding steels', *J. Mater. Proc. Technol.*, Vol. 37, Nos. 1–4, pp.791–800.

Rahman, M., Kumar, A.S. and Salam, M.U. (2002) 'Experimental evaluation on the effect of minimal quantities of lubricant in milling', *Int. J. Mach. Tools Manuf.*, Vol. 42, No. 5, pp.539–547.

Ramesh, K. and Yeo, S.H. (2003) 'Ecological grinding with chilled air as coolant', *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, Vol. 217, No. 3, pp.409–419.

Rowe, W.B. (2009) *Principles of Modern Grinding Technology*, William Andrew Publishing, Norwich, NY.

Rowe, W.B., Black, S.C.E., Mills, B., Qi, H.S. and Morgan, M.N. (1995) 'Experimental investigation of heat transfer in grinding', *Annals of the CIRP*, Vol. 44, No. 1, pp.329–332.

Sadeghi, M.H. et al. (2009) 'Minimal quantity lubrication-MQL in grinding of Ti-6Al-4V titanium alloy', *International Journal of Advanced Manufacturing Technology*, Vol. 44, Nos. 5–6, pp.487–500.

Sanchez, J.A., Pombo, I., Alberdi, R., Izquierdo, B., Ortega, N., Plaza, S. and Martinez-Toledano, J. (2010) 'Machining evaluation of a hybrid MQL-CO2 grinding technology', *Journal of Cleaner Production*, Vol. 18, No. 18, pp.1840–1849.

Shaji, S. and Radhakrishnan, V. (2002) 'An investigation on surface grinding using graphite as lubricant', *International Journal of Machine Tools & Manufacture*, Vol. 42, No. 6, pp.733–740.

Shaji, S. and Radhakrishnan, V. (2003) 'An investigation on solid lubricant moulded grinding wheels', *International Journal of Machine Tools & Manufacture*, Vol. 43, No. 9, pp.965–972.

Shaw, M.C. (1996) *Principles of Abrasive Processing*, Oxford Science Publications, Clarendon Press, Oxford.

Silva, L.R., Bianchi, E.C., Catai, R.E., Fusse, R.Y., Franc, T.V. and Aguiar, P.R. (2005) 'Study on the behaviour of the minimum quantity lubricant-MQL technique under different lubrication and cooling conditions when grinding ABNT4340 steel', *J. Braz. Soc. Mech. Sci. Eng.*, Vol. 27, No. 2, pp.192–199.

Silva, L.R., Bianchi, E.C., Fusse, R.Y., Catai, R.E., Franc, T.V. and Aguiar, P.R. (2007) 'Analysis of surface integrity for minimum quantity lubricant – MQL in grinding', *International Journal of Machine Tools & Manufacture*, Vol. 47, pp.412–418.

Singh, V., Ghosh, S. and Rao, P.V. (2010) 'Grindability improvement of composite ceramic with cryogenic coolant', *Proceedings of the World Congress on Engineering*, WCE, London, UK, Vol. 2.

Tawakoli, T., Hadad, M.J., Sadeghi, M.H., Daneshi, A., Stockert, S. and Rasifard, A. (2009) 'An experimental investigation of the effects of work piece and grinding parameters on minimum quantity lubrication – MQL grinding', *International Journal of Machine Tools & Manufacture*, Vol. 49, No. 12, pp.924–932.

Venu Gopal, A. and Venkateswara Rao, P. (2004) 'Performance improvement of grinding of SiC using graphite as a solid lubricant', *Materials and Manufacturing Processes*, Vol. 19, No. 2, pp.177–186.

Webster, J., Brinksmeier, E., Heinzel, C., Wittman, M. and Thoens, K. (2002) 'Assessment of grinding fluid effectiveness in continuous-dress creep feed grinding', *CIRP Annals*, Vol. 48, No. 2, pp.581–598.

Weiner, K., Inasaki, I., Sutherland, J.W. and Wakabayashi, T. (2004) 'Dry machining and minimum quantity lubrication', *CIRP Annals – Manufacturing Technology*, Vol. 53, No. 2, pp.511–537.

Winter, M. and Herrmann, C. (2014) 'Eco-efficiency of alternative and conventional cutting fluids in external cylindrical grinding', *Procedia CIRP*, Vol. 15, No. 1, pp.68–73.

Winter, M., Li, W., Kara. S. and Herrmann, C. (2014) 'Determining optimal process parameters to increase the eco-efficiency of grinding processes', *Journal of Cleaner Production*, Vol. 66, No. 1, pp.644–654.

Yerkes, K.L. and Dorian, J. (1999) 'Micro-cooler for chip-level temperature control', *Aero System Power Conference*, Arizona, pp.1401–1404, pp.1–9.

Yildiz, Y. and Nalbant, M. (2008) 'A review of cryogenic cooling in machining processes', *Int. J. Mach. Tools Manuf.*, Vol. 48, No. 9, pp.947–964.

Zhang, B. and Peng, X. (2000) 'Grinding damage prediction for ceramics via CDM model', *Journal of Manufacturing Science Engineering*, Vol. 122, No. 2, pp.51–58.