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Study of Turning process with Minimum Qquantity Lubrication (MQL) using Nano-cutting fluids

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ABSTRACT

The cutting fluid is important in any metal cutting operation, for chilling the cutting tool and the surface of the work piece, by lube the tool-work piece interface and removing chips from the cutting zone. Freshly, many researchers have been focusing on Minimum Quantity Lubrication (MQL) among the many methods existing on the aapplication of the coolant as it reduces the usage of coolant by jetting a mixture of compressed air and cutting fluid in an improved way instead of flood cooling. The MQL method has been incontestable to be appropriate as it fulfills the requirement of 'green' machining. In the current study, firstly, various lubrication methods were introduced which are used in machining processes, and then, basic machining processes used in manufacturing industries in turning. The comprehensive reappraisal of various Nano fluids (NFs) used as lubricants by different researchers for machining process is presented. Based on the studies, it can be concluded that utilizing NFs as coolant and lubricant lead to lower tool temperature, tool wear, higher surface quality, and less biology dangers. However, the high cost of nanoparticles, need for devices, agglomeration, and deposit are still challenges for the NF applications in metalworking operations. At last, the article identifies the opportunities for using NFs as lubricants in the future. It should be stated that this work offers a clear guideline for utilizing MQL and MQL-nanofluid approaches in turning processes. This guideline shows the physical, tribological, and heat transfer mechanisms associated with employing such cooling/lubrication approaches and their effects on different machining quality characteristics such as tool wear, surface integrity, and cutting forces.

Keywords: Cutting fluid, Lubricants, Minimum Quantity Lubrication (MQL), Machining process, Nano fluids.

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1. INTRODUCTION

Growing the heat dissipation area is an essential requirement during the cutting processes as it could offer effective results in terms of cutting tool life, energy consumption, and production rates. The conventional technique for increasing the heat dissipation for several industrial applications has focused on increasing the heat exchanging area; however, it associates with a problem of the thermal management system size. Conventional cutting fluids have played a cardinal role in reducing the induced surface roughness, extended tool wear, and improving the overall machinability for difficult to cut materials. However, the immoderate use of mineral based cutting fluids is hazardous for soil and water, and it results in multifarious health and ecological complexities. The global consumption of mineral-based non-biodegrad able cutting lubricants was 12,726 million tons in 2015with annually 1% increment in consumption depicting the alarming situation. In addition, the continuous reduction of natural energy resources with the danger of loss proportion varies between 12 and 60% of natural lubricants in the planetary and aquatic ecosystem. Therefore, introducing new environmental lubrication and cooling techniques is extremely required especially in improving the machining performance of difficult to-cut materials. Many environmental lubrication technologies were presented such as minimum quantity lubrication (MQL), cryogenic technology, as well as dry cutting. Eliminating the use of cutting fluids can be performed using dry cutting technology; however, dry cutting is associated with some problems such as short tool life and poor surface quality .Another environmental friendly technology is MQL where a fine mist is applied to the cutting zone using the optimal amount of cutting fluid with compressed air. Furthermore, the cryogenic technique is considered as another effective alternative for enhancing the machinability and dissipating the generated heat at the cutting zone as it affects the properties of the cutting tool and work piece using a super cold medium with liquefied gasses at a temperature lower than 120 K (e.g., liquid nitrogen: LN2) .In addition, using nano fluids (NFs) in machining process could offer promising advantages to face the challenge of the heat dissipation when machining difficult-to-cut materials as nano-cutting fluids can provide a highly observed thermal conductivity in comparison with the base fluids. Moreover, they have superior cooling characteristics due to their advanced capabilities to extract the generated heat. A nano fluid is defined as a new fluid result from the dispersion of non-metallic/metallic nano-additives with size less than 100 nm into the base fluid. Nano-additives are categorized into many types which are metallic, mixing metallic, non-me tallic, carbon, and ceramic nano-particles .Various advantages of using NFs through different applications have been presented as follows and High heat transfer surface between additives and fluids because of the high specific surface area of nano fluid and Saving power consumed in the intensification of pure liquid since NFs can offer the desired heat transfer properties. Surface wettability and heat transfer properties can be controlled by changing the nano-additives concentrations. Previous studies have focused on modeling ,analysis ,and heat transfer enhancement using nano-fluids.

Examples of several applications, which implemented the nano fluid technology to improve its thermal, rheological, and stability properties, are cooling of electronics, engine cooling, solar water heating, cooling of welding, engine trans mission oil, nuclear systems cooling, and NFs in different cutting operations .Furthermore, previous studies employed MQL-nano fluid technology using nano-tubes and nano-particles, and both scenarios showed better results (e.g., tool wear, power consumption, surface roughness) in comparison with the classical MQL .The MQL-nano fluid approach achieves two main advantages: applying sustainable technique since MQL consumes less amount of oil and enhancing the process performance as the nano-additives improve heat and transfer characteristics .After a careful review of the open literature, it is found that no study offers a clear and comprehensive review of the effects as well as the mechanisms associated with MQL and nano-fluids in machining processes. Thus, the main goal of this work focuses on reviewing and analyzing the work done using MQL, NFs as well as the integrated approach of MQL-nano fluid in different machining operations with a various cutting tool and work piece materials. This work does not only show what other researcher did in the filed, but also discusses the mechanisms (i.e., tribological and heat transfer) of MQL-nano fluid approach, and how physically these mechanisms affect the machining process performance. Regarding the current work, it is mainly focused on reviewing the mechanisms associated with the application of MQL and MQL-nano fluid during machining operations (i.e., drilling, milling, turning, and grinding). These mechanisms include physical aspects, tribological behavior, as well as heat transfer effects of such cooling/lubrication techniques on the over machining performance. The performance of the machining processes includes several quality characteristics such as tool wear, surface quality, and cutting forces. Furthermore, the current comprehensive review provides important information about the nano-fluid preparation and the stability of the resultant mist from MQL-nano fluid technique.

2. MINIMUM QUANTITY LUBRICATION (MQL)

Farther advancement is required to replace the flood cooling with fully matured dry machining, while the reduction in cutting fluids is the requirement of this era. The emergence of near-dry machining (NDM) or micro-quantity lubrication (MQL) has possibly reduced the drawbacks aforementioned with dry or flood cooling . The MQL concept was proposed about 15 years ago to accommodate the strict environmental protection policies, operator health, and 7~17% of the cost in total machining cost. The successful application of MQL has been reported in turning , The MQL resulted in improved surface finish, chip breakability, less cutting forces, and better tool life. Minimum quantity lubrication (MQL) refers to a mixture of compressed air with less amount of oil in the form of fine drops forming a spray pulverized on the cutting region

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The flow rate of oil is in the range between 0.01 and 2 l/h instead of the 50–1000 l/h in the case of conventional lubrication/cooling systems. In addition, the flow rate of MQL equal to 1 ml/h is named micro-lubrication lubrication (μLL). The MQL system contains a compressor, fluid reservoir, the fluid supplying pump, air-oil mixing chamber, nozzle, and external pipes for air and oil supply. As the quantity of liquid is very low in MQL and μLL, they are named near-to-dry machining (NDM). However, if the requirement is cooling containing slight lubrication is named minimum quantity cooling (MQC). Main products used for machining with MQL system are fatty alcohols and synthetic esters (vegetable oils chemically modified). Fatty alcohols mainly act more like lubricants; however, cooling is required more than the lubrication effect. Numerous MQL benefits against other lubrication/cooling systems are less cutting fluid consumption, cost and tool wear, enhancement of surface roughness, and decrease in environmental and worker health hazards and good lubrication than that of conventional lubrication/cooling system , as the cutting fluid used in such fewer quantity results in eliminating the lubricant disposal problems. Furthermore, convection and evaporation heat transfer mode in MQL and highpressure liquid effectively breaking the evaporation zone have made attractive in machining. Also, chips formed are not mixed with cutting fluid, which is easy to recycle .

Sharma et al.have presented a review of the MQL system in different machining processes, showing that the MQL system might be a promising alternative to the use of cutting fluids. MQL is used focusing on the lubricant properties rather than coolant properties; heat removal is achieved mainly by the compressed air .Varadarajan et al. proposed improved machinability through MQL owing to Rebinder effect. The Rebinder effect is significant due to the fact that small particles penetrate the work piece surface and help their plastic flow at the back surface of the chip. It was concluded that the rebinder effect in MQL is the key phenomenon behind machining improvement . Furthermore, some authors have studied that minimum quantity lubrication technique in combination with cooled air can enhance cooling and lubricating performance during machining steel and difficult-to-machine materials.

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2.1 Types of MQL techniques

There are two types of MQL cooling:

- External MQL cooling/lubrication technique (Fig.1).
- Internal MQL cooling/lubrication technique.

The external MQL is the application of fine cool mist through an external nozzle. The external MQL is very common in a research study. Numerous researchers have reported
the application of external MQL in machining .

The lubricant is supplied through an external supply system. The design of the MQL system is given in Fig.1 The external MQL system provides a mixture of air and oil in aerosol form. The aerosol is a fine suspension of air and liquid particles dispersed through the air. The aerosol is normally generated through named "atomization" that converts the liquid into mist or spray through the nozzle. The external supply of aerosol has two options:

The MQL system with ejector-type nozzle: oil and air are supplied separately to the ejector nozzle and aerosol forms after exiting from the nozzle. The MQL system with conventional type nozzle: aerosol is prepared by mixing oil and air and supplied in a
mixture. The internal MQL system contains aerosol supply in internal passage to supply mist. The internal type of MQL system has also been reported by various researchers . In
internal MQL, there are two options:

The MQL system with external atomizer: the external atomizer is commonly used to prepare aerosol and supplied through internal tunnels/channels in the tool.

The MQL system with internal atomizer inside spindle: internal atomizer mixed the air-oil and supplied through tunnels in tools (see Fig.1).

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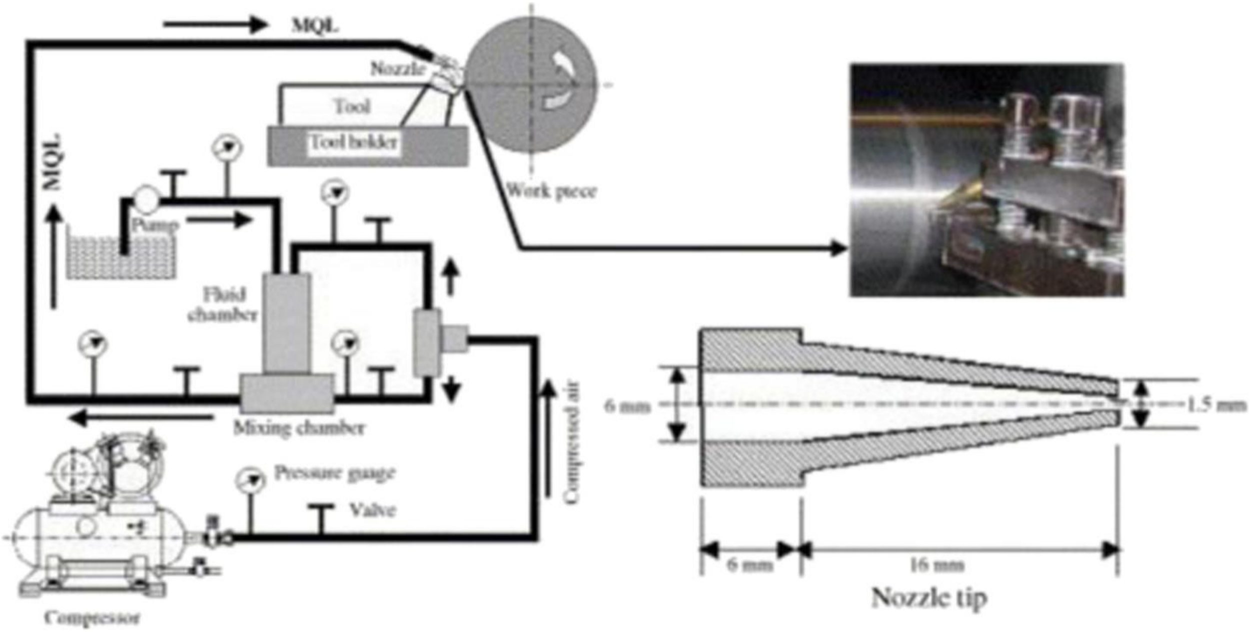

Fig.1 External MQL supply system

The MQL-based fine mist has been identified as much effective for cooling and lubrication. The cool air-based and coolair couples with MQL were applied as a coolant in finish turning of Inconel alloy. Results concluded that the 77% and 125% improvements under cool-air and cool-air couples with MQL, respectively, were observed compared to dry machining. Kamata and Obikawa have varied the cutting fluid
flow rate from 16.7 to 31.7 ml/h to identify the effect of tool coatings under MQL-finish turning of Inconel-718. It was concluded that TiAlN-coated carbide tools have improved
tool life and surface finish with the increased fluid flow rate.
However, PVD coating TiN/AlN did not extend the tool life, but the better surface finish was observed . Similarly, the effect of cutting speed, feed rate, and variation of MQL-flow rate in turning process of brass material with cemented carbide inserts (K10). Findings have concluded that surface finish was improved under higher cutting speed, less feed rate, and a higher level of MQL flow rate .Davim et al. Comparedthe cutting power, surface roughness, specific cutting force, and chip formation under variation of MQL flow rate in finish turning of brass material. A slight increase in cutting power was observed at a flow rate of 50 ml/h. However, at 200 ml/h, the specific cutting force was lowest, and surface roughness was also decreased with the increase in flow. In comparison of MQL with flood (2000 ml/h), similar or better results were identified at same cutting conditions .Pervaiz et al. experimentally investigated the effectiveness of MQCL under machining of Ti-6Al-4V. Authors have compared it with flood cooling in the viewpoint of surface quality and tool wear mechanism. Results have suggested that a vegetable oil with sub-zero cold air can be an alternative to conventional flood cooling at relatively high flow rates (60– 70 ml/h) to achieve a reliable machining performance.

It is a consensus that during the high-speed machining of hard materials like titanium alloys having poor thermal conductivity, high reactivity leads to high machining temperature that accelerates tool wear. In high-speed machining of difficult-to-cut material under MQL fine mist provides rather than excellent cooling. Gurraj et al. have used Ranque–Hilsch vortex tube (RHVT)-assisted MQL to achieve lubrication as well as the cooling effect in the turning of difficult-to-cut material titanium (grade 2). Findings have shown that vortex tube-assisted MQL (V-MQL)-assisted turning has reduced 15% of surface quality, cutting force, and tool wear compared to MQL under all the experiments.
The effectiveness of MQL in perspective of oil and oilwater film through rapeseed oil and synthetic ester during the rough turning of aluminum. The rapeseed oil-based MQL provided less lubrication. However, synthetic esterbased MQL provided lubrication, tool damage, and high surface roughness. The synthetic ester with water-based MQL outperformed regarding less tool damage, high lubrication, The cutting forces underand excellent smooth surface.

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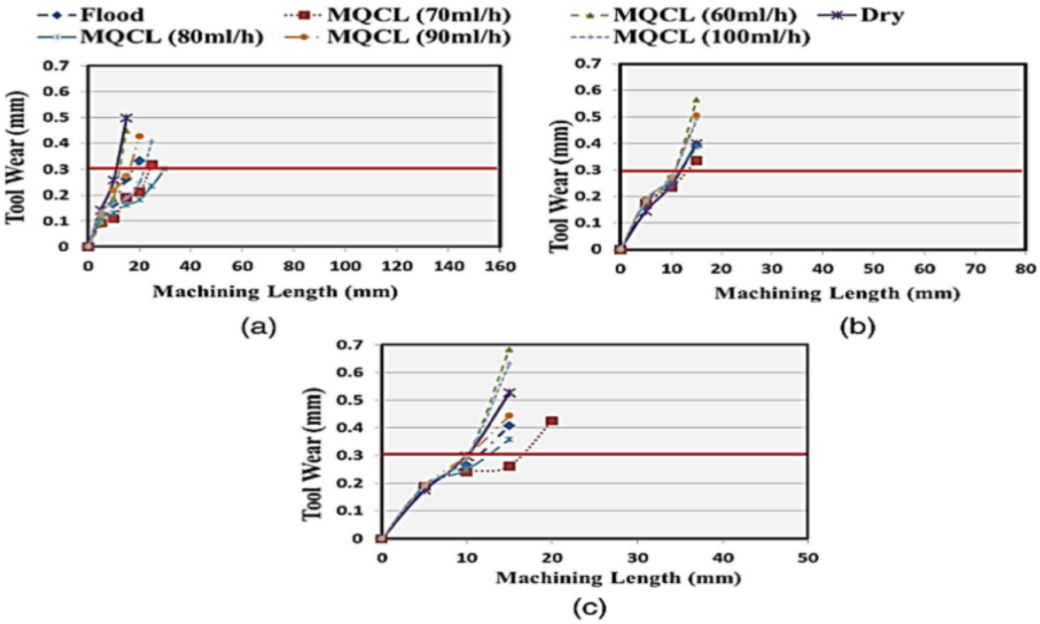

Fig. 1:Tool flank wear at a spindle speed of 150 m/min (a). At feed rate of 0.1 mm/rev (b). At feed rate of 0.2 mm/rev (c). At feed rate of 0.3 mm/rev

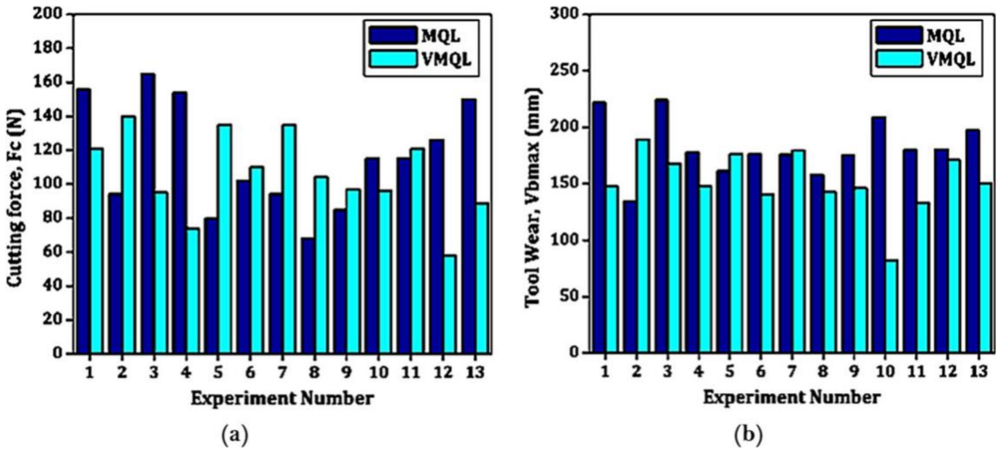

Fig. 2:.Comparison of V-MQL and MQL of cutting force.b.V-MQL and MQL of cutting force for tool wear, Vbmax

Comparison of V-MQL and MQL of cutting force.b V-MQL and MQL of cutting force for tool wear, VbmaxMQL were evaluated less than dry but higher than flood cooling during the finish turning of steel alloys. At lower cutting speed, MQL provided enough lubrication. However, at higher speed, cutting forces decreased due to an elevation of temperature. MQL reduced main cutting force efficiently among three components of cutting forces. The similar results were reported by many other researchers regarding the finish turning of steel alloys. The high-pressure MQL mist penetrates and decreases the temperature. At low cutting speed, MQL is more effective as compared to high cutting speed. The effectiveness of MQL at low cutting speed can be associated with the provision of cooling/lubrication through capillary tubes and plastic shearing region for more time. At high-speed cutting, temperature elevation is due to a reduction in time to dissipate hea . In addition, hard turning (> 47HRC) with coated carbide tools at relatively higher cutting speeds (100–170 m/min) and feed rate (0.16– 0.24 mm/rev) was performed with low MQL flow rate (10– 100 ml/h) to evaluate tool life. Findings have depicted longer inverse relation of cutting speed and feed with the tool life under all the conditions. Similarly, hard turning (> 55HRC) was performed to verify the performance of coated carbide tools (AlTiN, TiAlN/TiSiN, and AlTiCrN) under dry and MQL cooling to evaluate tool life and tool wear. Experimental observations have underscored 20–25% longer tool life under MQL compared to dry turning. It is pertinent to mention that the effect of cutting speed was higher compared to the feed rate. Figure depicts the tool life under the different cutting environment with three types of coated tools and type of wear on the cutting tool.

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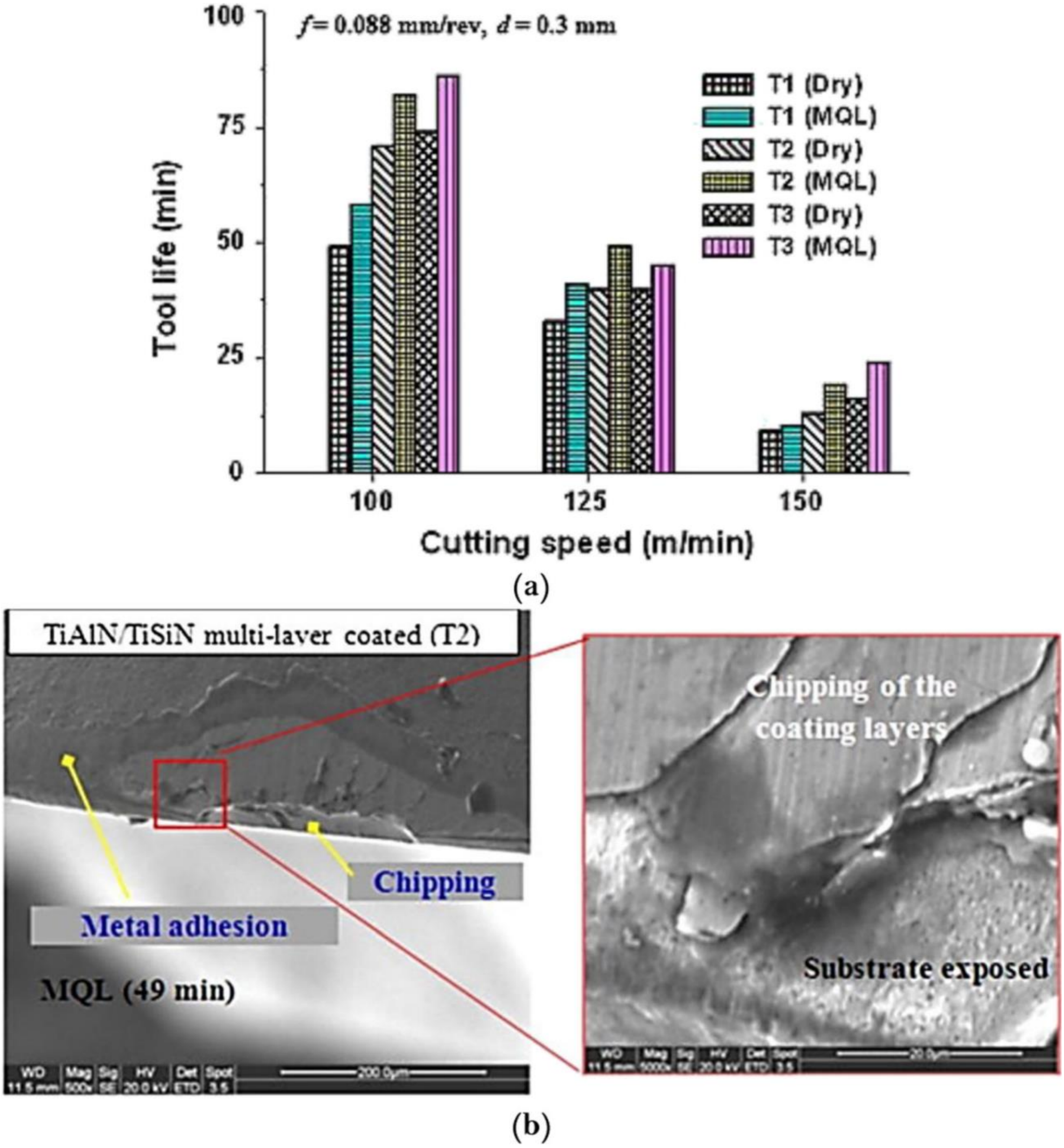

Fig. 3:Tool life of three different coating carbide tools under dry, MQL mode.(b). SEM image of tool wear on rake and clearance face of coated cutting insertt.

3. NANO-CUTTING FLUIDS

NFs are a type of fluids that contain nanoparticle sizes from 1 to 100 nm suspended in the base fluid. These metallic or metallic oxide particles increase the convection and conduction in fluids for efficient heat transfer from the cutting zone. In the last few decades, nanotechnology advancement has led to a new type of coolant named NFs. In NFs, nanoparticles are suspended to modify the desideratum properties of fluids. Some common type of nanoparticles, such as Graphene particles, Al2O3 particles, multiwall carbon nanotubes (MWCNT's), carbon nanoparticles. These NFs are diluted with nanoparticles that were developed with an objective of increasing the heat transfer rate in fluids, which is now a separate field as "nanotechnology." Compared to conventional fluids, NFs contain the following superior properties such as: High heat transfer surface area that transfers heat more between fluid particles. Brownian motion of particles and dispersion stability. Removed pumping energy compared to conventional liquids. No particle clogging with predominant system miniaturization.

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3.1 Mechanism of MQL-Nano fluid

Numerous researchers have revealed the effectiveness of the integrated approach of MQL-NFs on machining characteristics in turning operations. The suspended nano-additives with multifarious sized in the base oil depicted enhanced heat transfer coefficient that transferred a considerable amount of heat from the machining zone. Moreover, the enhanced tool life was linked with the MQL-based NFs since the nano-additives worked as spacers at the work piece-tool interface to reduce the considerable coefficient of friction. Accordingly, the main cutting force, tool wear, and surface roughness performance measures were reduced. Theintegratednano-additive-based MQL mechanism and key ad vantages have been summarized in the open literature.

A combination of nano-additives and high-pressure air atomized in MQL nozzle provided a fine mist. The impinged droplets on the tool and work piece surfaces formed a tribo-film that enhanced the tribological properties such as friction or lubrication.

The high concentration of multifarious sized nanoparticles increased the overall nano-additives performed a key role as a spacer at close and wider contact between tool

andwork piece surface. The existence of nano cutting fluid in narrow toolworkpiece interface due to high-pressure of MQL system provided direct contact resistance which helped to form a chemical reaction on the surface of the work piece . The overall increased number of particles made a thin protective tribo-film on the turned surface.

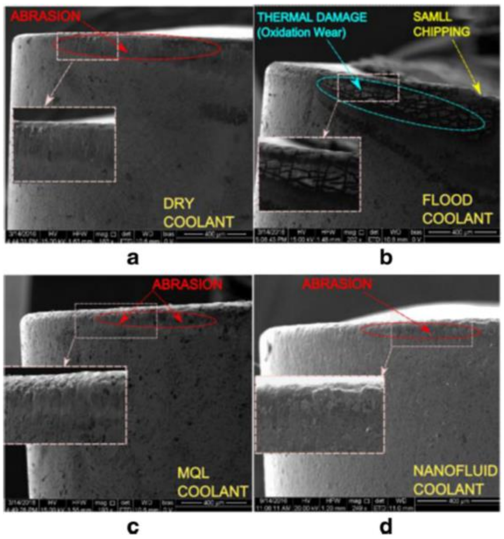

Fig. 4: SEM images of inserts after machining at V = 110 m/min and f = 0.3 mm/rev under different coolant strategies

4. FUTURE CHALLENGES

The widespread use of coolant lubricants in machining processes since long has kept them dominant over MQL that remained a marginal technique. Thus, very few machinists worked with MQL and have known how the concept behind this technology, while many never enjoyed most of the benefits are associated with MQL. From an industrial point of view where the efficiency of the production process is the main task, less familiarity with such beneficial technology could pose a potential threat of downtime and complications. The fear-associated MQL due to less familiarity might be the greatest challenge for MQL technique in getting dominantover conventional coolants. Next challenge is that the use of nano fluid in MQL is difficult because of some reasons: (i) NFs differ with simple solid-liquid mixtures. Some special conditions in NFs are required, such as uniform and stable suspension, low clustering of particles, etc. To achieve these special conditions, different ways are used. The main problems for preparing of a nano fluid are its clustering, changing in pH of solution suspension, using

surfactants, disperser, or vibrators can be used. (ii) More investigations are still required to understand and optimize the effects of nano-additives size and concentration on the machining performance in order to achievea balance between the induced nano-additives wear and overall frictional behavior as similarly discussed by Hegab et al. (iii) More investigations are still required to investigate the tribological and heat transfer mechanisms associated with the application of hybrid NFs in machining processes.

(iv) The cost of nanoparticles and manufacturing cost of nano fluid both are quite high.

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(v) A clear assessment model is required to evaluate the effectiveness of using MQL-nano fluid during machining difficult-to-cut materials. This model should not only include the machining quality characteristics, but also the main pillars for sustainable machining (i.e., waste management, energy consumption, personal health and safety, and environmental impact). A previous sustainability assessment algorithm can be used to accomplish this part. (vi) Moreover, more efforts should be added to the cost of nanoparticles and preventing them from sedimentation.

5. CONCLUSIONS

Torrent coolant is one of the best cooling/lubrication technique; nevertheless, it shows different drawbacks such as negative effects on the health of workers, severe environmental effects, and high machining cost. To overcome these drawbacks, efforts have been developed to provide another alternative. There is a need to apply various techniques, like machining without cutting fluid use or dry machining, to restrict the extravagant usage of cutting fluid as lubricants in machining processes. However, dry machining cannot be preferably recommended in most of the machining operations. Reasons can be found in the excessive heat generated in the process, which deteriorates the frictional behavior at the work piece -tool as well as the tool performance. In certain machining situations where dry machining is not possible either technically or economically, then a new technique named as minimum quantity lubrication (MQL) can be preferred for spraying cutting fluid lubricant over the work piece -tool interface using optimized way. Various researchers showed that Nano fluid with MQL is an appropriate method for offering better machining performance as well as reducing the environmental and operator hazards. However, MQL heat capacity is not that much compared to flood coolant. In the current review paper, different types of lubrication methods (e.g., dry machining, minimum quantity lubrication, solid lubrication, cryogenic cooling, gaseous cooling, sustainable cutting fluids, and NFs) used in machining process were firstly introduced in which nan fluid is best suited. Thus, an extensive focus was provided about the preparation and stability of nano fluid. Afterward, a brief study about nano fluid used as cutting fluid in machining operations (e.g., grinding, milling, turning, and drilling) used in manufacturing industries was presented and discussed. This review article shows that nano fluid with the MQL technique is one of the best-suited methods for lubrication as it showed better results in terms of tool temperature, tool wear, surface quality, as well as environmental aspects. The novelty of this work lies in offering a clear guideline for utilizing MQL and MQL-Nano fluid approaches in machining processes. This guideline shows the physical, tribological, and heat transfer mechanisms associated with mploying such cooling/ lubrication approaches and their effects on different machining quality characteristics such as tool wear, surface integrity, and cutting forces. In terms of the future work, more investigations are still required to understand and optimize the effects of nano-additive size and concentration on the machining performance in order to achieve a balance between the induced nano-additive wear and overall frictional behavior. Moreover, more investigation are still required to understand thetribological and heat transfer mechanisms associated with the implementation of hybrid NFs in machining processes.

REFERENCES

1. He, J., Pei, H., Chu, Y., Wang, S. and Wang, G., “MQL Application in high-speed turning bearing steel”, Applied Mechanics and Materials, 2014, 490-491, 306- 310.

2.Sharma, J. and Sidhu, B.S., “Investigation of effects of dry and near dry machining

on AISI D2 steel using vegetable oil”, Journal of Cleaner Production, 2014, 66, 619-623.

3.Roy, S. and Ghosh, A., “High-speed turning of AISI 4140 steel by multi-layered TiN top-coated insert with minimum quantity lubrication technology and assessment of near tool-tip temperature using infrared thermography”, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 2014, 0954405413514570.

4.Amrita, M., Srikant, R. R. and Sitaramaraju, A. V., “Performance evaluation of nanographite-based cutting fluid in machining process”, Materials and Manufacturing Processes 2014, 29(5), 600-605.

5.Prasad, M.M.S., Srikant, R.R., “Performance evaluation of nano graphite inclusion in cutting fluids with MQL technique in turning of AISI 1040 steel”, Int. J. Res. Eng. Technol. 2 (11), 2013, 381e393.

DOI:10.31695/IJASRE.2023.9.12.3

6.Itoigawa, F., Childs, T.H.C., Nakamura, T., Belluco, W., "Effects and mechanisms in minimal quantity lubrication machining of an aluminium alloy", Wear 260, 2013, 39e344.

7.Hadad, M. and Sadeghi, B. Minimum quantity lubrication-MQL turning of AISI

4140 steel alloy. Journal of Cleaner Production 2013, 54, 332-343.

8.Khandekar, S., Sankar, M. R., Agnihotri, V. and Ramkumar, J., "Nano-cutting fluid for enhancement of metal cutting performance", Materials and Manufacturing Processes, 2012, 27, 963–967.

9.Rao, S.N., Satyanarayana, B., "Experimental estimation of tool wear and cutting temperatures in MQL using cutting fluids with CNT inclusion. Int. J. Eng. Sci. Tec, 2011.

10.Vasu, V. and Reddy, G.P.K., "Effect of minimum quantity lubrication withAl2O3 nanoparticles on surface roughness, tool wear and temperature dissipation in machining Inconel 600 alloy", Journal of Nanoengineering and Nanosystems, 2011, 225(1), 3-16.

11. Bhogare R.A. and B. Kothawale 2013 A review on applications and challenges of nano fluids as coolant in automobile radiator. Int J Sci Res Publ, 3(8)

12. Khan AM, Jamil M, UlHaq A, Hussain S, Meng L, He N (2019) Sustainable machining. Modeling and optimization of temperature and surface roughness in the milling of AISI D2 steel. Industrial Lubrication and Tribology 71(2):267–277

13. Sanchez JA, Pombo I, Alberdi R, Izquierdo B, Ortega N, Plaza S, Martinez-Toledano J (2010) Machining evaluation of a hybrid MQL-CO2 grinding technology. J Clean Prod 18(18):1840–1849

14. Eltaggaz A, Hegab H, Deiab I, Kishawy HA (2018) Hybrid nano fluid-minimum quantity lubrication strategy for machining austempered ductile iron (ADI). Int J Interactive Des Manuf (IJIDeM) 12(4):1273–1281

15. Eltaggaz A, Zawada P, Hegab HA, Deiab I, Kishawy HA (2018) Coolant strategy influence on tool life and surface roughness when machining ADI. Int J AdvManufTechnol 94(9-12):3875–3887

16. Hegab H, Kishawy H (2018) Towards sustainable machining of Inconel 718 using nano-fluid minimum quantity lubrication. J Manuf Mater Process 2(3):50

17. Khan A, Jamil M, Mia M, Pimenov D, Gasiyarov V, Gupta M, He N (2018) Multi-objective optimization for grinding of AISI D2 steel with Al2O3 wheel under MQL. Materials 11(11):2269

18. Boubekri N, Shaikh V (2015) Minimum quantity lubrication (MQL) in machining: Benefits and drawbacks. J IndIntellInf 3:3

19. Sampaio MA, Machado AR, Laurindo CAH, Torres RD, Amorim FL (2018) Influence of minimum quantity of lubrication (MQL) when turning hardened SAE 1045 steel: a comparison with dry machining. Int J AdvManufTechnol 98(1-4):959–968

20. Tosun N, Huseyinoglu M (2010) Effect of MQL on surface roughness in milling of AA7075-T6. Mater Manuf Process 25(8):793– 798

21. Tasdelen B, Wikblom T, Ekered S (2008) Studies on minimum quantity lubrication (MQL) and air cooling at drilling. J MaterProcessTechnol 200(1-3):339–346

22. Tawakoli T, Hadad M, Sadeghi MH, Daneshi A, Sadeghi B (2011) Minimum quantity lubrication in grinding: effects of abrasive and coolant–lubricant types. J Clean Prod 19(17-18):2088–2099

23. Madanchi N, Kurle D, Winter M, Thiede S, Herrmann C (2015) Energy efficient process chain: The impact of cutting fluid strategies. Procedia CIRP 29:360–36

DOI:10.31695/IJASRE.2023.9.12.3