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Minimum Quantity Lubrication (MQL) During Conventional Machining Operations: A Review

Sukhdev Gangwar[1], Dr. P.Sudhakar Rao[2]

[1] *M.E Scholar, Department of Mechanical Engineering, NITTTR Chandigarh,*
[2] *Assistant Professor, Department of Mechanical Engineering, NITTTR Chandigarh,*

Abstract— In machining operation lubrication is very epochal phenomenon, which requires a lubricant, generally liquid, to reduce the friction and the generated heat at the tool- workpiece interface. MQL is the technique of lubrication in which very less amount of lubricant is used with high pressure air and it is injected at the cutting zone with the help of nozzle. Fumes formed during the flood cooling cause harm to the environment but in MQL the amount of fumes is very low due to use of very small amount of lubricant in comparison to former one. Due to less amount of lubricant used there is reduction of cost of lubrication. In this work we are going to review one of the lubricating methods, called minimum quantity lubrication (MQL) which is also known as near dry machining.

Keywords— Minimum Quantity Lubrication, Conventional Machining, Nano-Fluids, Tool Wear, Surface Finish.

I. Introduction

Cutting fluids are used in machining operations to reduce the cutting temperature and the forces in cutting operation, but application of cutting fluids causes generation of harmful fumes and causes health as well as environmental issues. In order to resolve this issue now a days researchers are looking for MQL. This method first time came into picture during 1993, that time it was used for lubrication of bearings [1]. In 1997, MQL was first time used for machining for grinding process. Earlier MQL was restricted to only contact lubrication but after 2000s MQL has attracted researchers attention towards machining operation that too specially for difficult to machine materials. With the ongoing research many new technologies arise such as nano-fluid MQL and MQL with cooled air. Till now lot of work has been done on the MQL with nano-fluids and cooled air. The focus of research on MQL is mainly on grinding (29%), milling (26%), turning (24%) and drilling (21%) [2]. It has been seen that MQL has proven better in comparison to other cooling technique economically too, because of lesser consumption of cutting fluid and easier management of the chips.

For any lubrication system properties of lubricant are major concern. MQL fluid should have biodegradability, high lubrication capacity and high stability. According to the properties of the cutting fluid vegetable oils and synthetic ester are found to be most common due to their higher biodegradability [3][4][5]. It was found from some studies that synthetic ester is superior to the vegetable oil [6]. In MQL another medium is required to effective transport of cutting fluid into the cutting zone. Generally pressurised air is taken as this medium, but now a days some researchers used cooled air for this medium to enhance cooling abilities [7][8].From the previous research carried out in the domain of manufacturing it was found that there are two types of MQL delivery systems are being used one is external delivery system and other is internal delivery system. Figure 1 shows the different types of MQL system used.

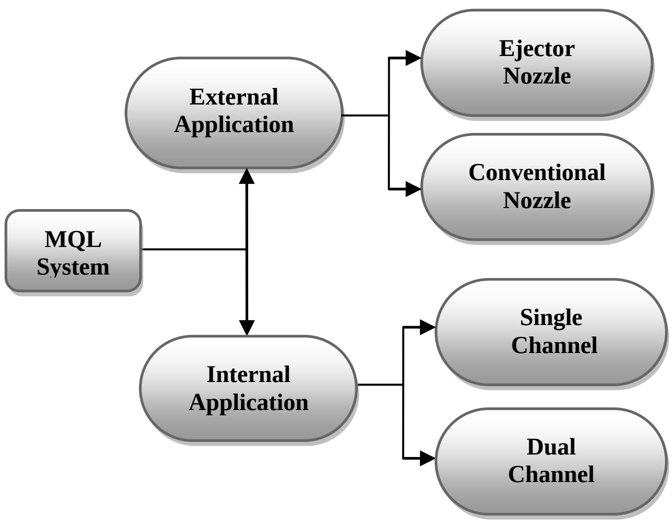

Fig.1. Types of MQL System

In external application external nozzles are used to feed mixture of compressed air and lubricating oil into the cutting zone. External application of MQL uses ejector and conventional nozzle. In ejector nozzle separate ejectors are used to supply compressed air and oil then they get mixed at the exit of the nozzle. Whereas in conventional nozzle air and oil are mixed in external atomizer then the mixture is supplied to the conventional nozzle, as shown in Fig.2.

In case of internal application system it is also known as through-tool system because in this case cutting fluid is delivered through the spindle. It has configurations of single channel and dual channel. In single channel, air and oil are mixed before the spindle and then supplied to the cutting zone through cutting tool. Whereas in case of dual channel two paths are used to supply air and oil then mixture is made in the before tool holder, as shown in Fig.3.

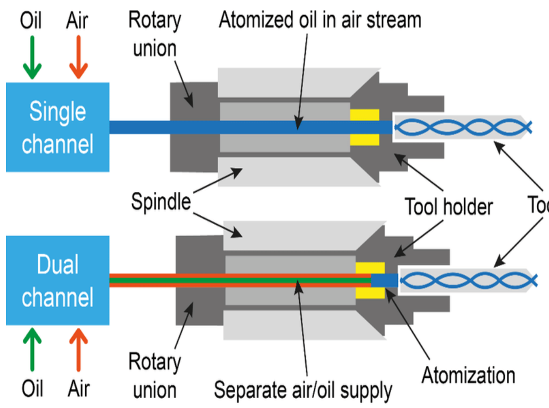

Fig.2. External Delivery Systems [2]

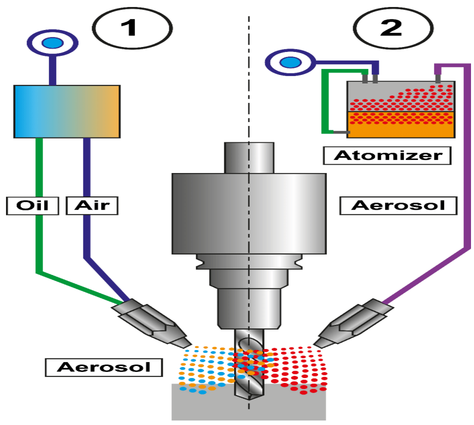

Fig.3. Internal Delivery Systems [2]

II. PRINCIPLE OF MQL

As the name suggests MQL is the method of lubrication in which very small quantity of lubricant is used. In this method of lubrication cutting fluid is injected to the cutting zone at high pressure so that it can reach the cutting zone properly. The cutting fluid forms a layer around the tool just like an insulating layer; this layer also reduces the coefficient of friction between tool and work-piece. Due to this layer there is reduction in cutting force, friction force, and it provides the insulation between tool and work-piece. In MQL, the cutting fluid is used in atomised form and cooling action is done by the evaporative action. In MQL, cutting fluid is used completely and the chips obtained are nearly dry that's why it is also known as near dry machining [9].

III. MQL IN DIFFERENT MACHINING OPERATIONS

Many researches have been done before and some of them are discussed here:

Sreejith [10] studied the same effect on turning of Al6061. He also investigated that there was higher adhesion in MQL than flood cooling. Further studies on the above problem were done by **Yan** *et al.* [11] and suggested that use of diamond like coating and use of diamond coating on the cutting tool reduces the chances of adhesion because of its low coefficient of friction and low affinity towards aluminium. Studies were also done to investigate the tool wear with MQL. **Tsao** [12] found that milling of Al6061 PT 651 using sulphurous boric acid ester as cutting fluid reduces the average flank wear by 12.5%. **Lacalle** *et al.* [13] recommended in his work that MQL for high speed milling of Al alloy will result in lesser tool wear. **Diciuc** *et al.*[14] worked on milling Al 7175 and found that lowest surface roughness is achieved in case of MQL.

Sohrabpoor *et al.* [15] conducted experiments on the turning of AISI4340 stainless steel in four cooling conditions i.e. dry, air cooling, wet and MQL (used soluble oil as the cutting fluid) and their results showed better performance during MQL with respect to surface roughness and flank wear due to heat reduction at the tool chip interface as the mist produced in MQL has higher interface penetration ability compared to wet cooling. Experiments conducted by **Dhar** *et al.* [16] supported the above results in turning of AISI4340 and AISI1040 steels i.e. reduction in heat generation, resulted in maintaining the sharpness of cutting edge and leads to longer tool life, lesser tool wear, better surface finish and better tolerances. It was also observed that chips produced by turning AISI 1040 steel with MQL were smooth, light in colour and did not have traces of built-up-edge. **Rahman** *et al.* [17] during milling of ASSAB HH718 steel resulted in reduced flank wear under MQL conditions especially at lower feed, cutting speed and depth of cut. It was also observed that orientation of nozzle plays an important role in evaluating tool wear. It was also observed that there was no effect of cooling condition on the surface quality during milling operation.

Priarone *et al.*[18] conducted experiments on turning and milling of Ti-48Al-2Cr-2Nb alloy under different cooling conditions (wet, dry and MQL), it was observed that there was significant improvement in surface finish only and ideal cooling conditions in terms of tool wear were obtained by wet cooling. **Park** *et al.* [19] studied the flank wear in different cooling conditions which showed that there was lesser wear in case of wet cooling compared to MQL and dry cooling. They also compared the results of consumption of electric power in eco-friendly machining technologies (MQL, cryogenic machining with liquid nitrogen, combination of MQL with cryogenic and laser assisted machining) along with dry and flood cooling. Their results showed that there was very less consumption of power in MQL (1.53 kW) where as wet machining consumed maximum electric power i.e. 2.75 kW. They also suggested that lower consumption of power in MQL was because of minimum tool wear. **Wang** *et al.* [20] performed experiments on continuous and interruptive turning of Ti-6Al-4V alloy which showed that positive results were obtained especially for two slots interrupted cutting and continuous turning at high speed and feed rates due to better lubrication ability as compared to flood cooling. **Boswell and Islam** [21] concluded by their experiments that cold water produces better surface finish and cryogenic cooling improved the tool life during turning of Ti alloy compared to that of MQL .Some experiments of **Boswell** *et al.* [22] showed that there was reduction in surface roughness and cutting force by 38% and 59% respectively while using MQL in comparison to dry machining.

Thamizhmanii and Hasan [23] compared vegetable oil based MQL and dry milling of Inconel 718 with super hard cobalt tool and reported that the tool travelled longer under MQL with the flow rate of 37.5 ml/hr. This flow rate provided the optimum surface roughness and flank wear with 43.75% increase in tool life. **Bhowmick and Alpas** [24] found positive results by using low-friction type diamond like coating (DLC) coating drills under the MQL with a flow rate of 30 ml/hr. **Fox** *et al.* [25] used different coatings with MQL for drilling of aluminium silicon B319 cast alloy and found that there was huge increase in tool life with diamond coated and low hydrogen DLC for drilling 500 holes. **Davim** *et al.* [26] used uncoated K10 carbide drill as tool and emulsion as cutting fluid for MQL and found positive results against the flood cooling. **Pieri and Strinati** [27] used coated and uncoated tool with MQL (mineral oil) and flood cooling (emulsion oil) and noticed similar results in both the cases for tool flank wear. They also noticed that diamond coated tool require higher feed force. **Shingarwade** and **Chavan** [28] in drilling of AISI 1040 steel resulted in improved quality and reduction in cutting temperature by 10% while drilling with HSS tool under MQL at tool chip interface. **Zeilmann** *et al.* [29] performed experiments on AISI P-20 steel with carbide drills under different cooling condition using emulsion (continuous drilling), dry and MQL (pecking cycle). Pecking cycle conditions were 1.5 mm advance with retreatment of hole and it was used to avoid formation of micro chips and it also helped in chip evacuation. During their experiments they found that in the beginning, the emulsion and MQL have similar behavior, but at the end, plastic deformation is more in case of emulsion because cutting fluid was difficult to reach the cutting zone. **Heinemann** *et al.* [30] also found positive results in deep drilling with increase in tool life. **Meena and Mansoori** [31] performed drilling of Austempered ductile iron (ADI) under different lubricating conditions like dry, flood and MQL and found that MQL has positive effects on average torque, surface roughness; thrust force and width of flank wear. **Rahim and Sasahara** [32] used palm oil and synthetic ester as base oil for MQL in drilling of Ti-6Al-4V and found that there was good improvement in tool life i.e, around 306% in both the cases. In another study **Zeilmann and Weingaertner** [33] found that in drilling of Ti-6Al-4V with internal MQL has resulted in reduction of the maximum temperature by 50% in comparison to external MQL.

From the above researches, we found that MQL has positive impact on tool wear, cutting forces and cutting power in different machining operation. MQL also results in good surface finish as well as it lowers the cutting temperature at tool chip interface, if we apply some conditions on the operation. Generally it was found that MQL is better than the dry machining in all cases but it has some shortcomings, in case, when it is compared with the flood cooling. In case of difficult to cut materials MQL has given good results in terms of tool life and tool wear. MQL allows the machining of materials at higher cutting speeds. So we can conclude that MQL is effective in the machining operation and there are areas where this method can be improved to overcome its shortcomings.

IV. ADVANCEMENT IN MQL

We have seen in all of the above research that MQL has proved good alternative for cooling and lubrication in machining, but still there are chances of improvement in MQL. In order to improve the performance of MQL, further researches were done which resulted in its advancement. These advancement in MQL are discussed below:

Fig 4. shows the advancements done in the field of MQL which majorly comprise the use of additives and cooled air. In case of additives, nano-particles and ionic liquids were used and in case of cooed air and gases the RHVT cooled air, cryogenic cooled air and supercritical CO_2 were used. In former method, suspension of nano-particles with base oil was used for lubrication purposes. Inclusion of nano-particles changes the properties of lubricant and assists in the improvement in machining. Most widely studied nano-particles are Al_2O_3, TiO_2 and MoS_2 etc. Ionic fluids used in MQL are low melting organic salts. These salts attracted the attention of researchers because of their low volatility. **Devis** *et al.* [34] found positive impacts on tool wear during machining of titanium in comparison to other lubrication methods. **Pham** *et al.* [35] examined surface roughness and found positive results too while research was done on machining on aluminium alloy. **Stepnowski** *et al.* [36] found that these liquids are toxic, which restrict their use for lubrication purposes.

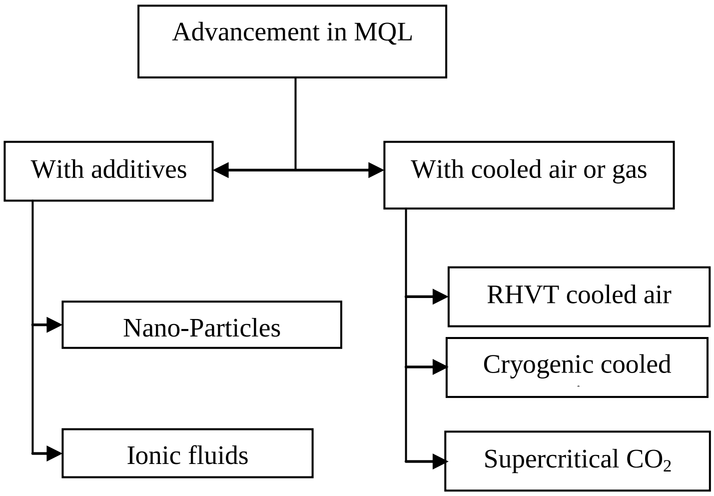

Fig.4. Advancement in MQL

In order to obtain better cooling properties in MQL, cooled air and gases were used by researchers in different ways among which one of them is RHVT (Ranque-Hilsch Vortex Tube) cooled air. **Dutta** *et al.* [37] mentioned that in RHVT, compressed air flows through nozzles and the hot and cold air gets separated in different tubes. And this compressed air with the lubricant is used for the lubrication in MQL. Decrease in cutting temperature was observed by **Selek** *et al*.[38], which resulted in minimization of built-up-edge formation and hence reduction in tool wear. **Kırmacı** [39] mentioned that its main advantage is that it does not require any chemical or electricity for its functionality hence it is cost effective too. Similarly, CMQL (Cryogenic Minimum Quantity Lubrication) is done to reduce the cutting temperature by cooling the work-piece. Experimental work carried out by **Zhang** *et al.* [40] suggested that although RHVT and cryogenic are similar techniques but the transportation of cold air makes them different as in CMQL it uses refrigeration system whereas **Kim** *et al*. [41] used vortex tube. **Yuan** *et al*. [42] suggested that CMQL gave positive results with different machining processes such as CMQL resulted in significant decrease in cutting temperature, surface roughness, tool wear and cutting forces. In order to improve the effectiveness with cooled air, MQL was used with super-critically cooled CO_2. **Stephenson** *et al*. [43] used this combination and observed that by this combination a frozen layer of lubricating oil is formed at cutting zone which resulted in positive results such as in turning of Inconel 750 resulted in increase of heat dissipation and increase in tool life with MRR (Material Removal Rate). Although the use of CO_2 gave better results but being a green house gas increase in its concentration may result in increase in global temperature. To resolve this issue **Mon** *et al*. [44] suggested the reuse of CO_2.

V. CONCLUSIONS

Above reviewed literature gives basic information about the minimum quantity lubrication system and suggests that it has been proven a mile stone in the field of machining operations to overcome several problems occurring during the machining operations. It has been also seen from the review that MQL is more effective than dry machining in every aspect, but it is could not overshadow the flood lubrication owing to its inability to reduce the temperature at cutting zone as compared to the flood lubrication. To overcome these limitations some advancements were done in the field of MQL like use of additive and cooled air and gas which improved the performance of MQL. The inspiration for the present study arises from the ecological considerations of MQL since higher quantity of lubricant cause air pollution. MQL is also found to be economic in comparison to flood lubrication since due to lesser utilization of lubricant, easier disposal of lubricant and chip management reduces cost of machining. It can be concluded that MQL is ecologically and economically advisable technique along with its better results on machining parameters to obtain accurate and highly finished surfaces with higher tool life.

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