

Performance Evaluation and Economic Analysis of Minimum Quantity Lubrication with Pressurized/Non-Pressurized Air and Nanofluid Mixture

M. Amrita, R. R. Srikant, A. V. Sita Rama Raju

Abstract—Water miscible cutting fluids are conventionally used to lubricate and cool the machining zone. But issues related to health hazards, maintenance and disposal costs have limited their usage, leading to application of Minimum Quantity Lubrication (MQL). To increase the effectiveness of MQL, nanocutting fluids are proposed. In the present work, water miscible nanographite cutting fluids of varying concentration are applied at cutting zone by two systems A and B. System A utilizes high pressure air and supplies cutting fluid at a flow rate of 1ml/min. System B uses low pressure air and supplies cutting fluid at a flow rate of 5ml/min. Their performance in machining is evaluated by measuring cutting temperatures, tool wear, cutting forces and surface roughness and compared with dry machining and flood machining. Application of nanocutting fluid using both systems showed better performance than dry machining. Cutting temperatures and cutting forces obtained by both techniques are more than flood machining. But tool wear and surface roughness showed improvement compared to flood machining. Economic analysis has been carried out in all the cases to decide the applicability of the techniques.

Keywords—Economic analysis, Machining, Minimum Quantity lubrication, nanofluid.

I. INTRODUCTION

WATER emulsifier oils are widely used in machining processes due to their excellent cooling properties. But their disposal has caused issue of environmental and economic concern as they are classified among hazardous waste by many countries and hence their disposal cost is expensive. This accelerated the research in minimizing use of cutting fluids, among which Minimum Quantity Lubrication (MQL) is prominent. Many researchers [1]–[3] reported that MQL showed better performance than dry machining. Few reported that MQL performed better than flood machining also [4]–[6]. Superior properties of nanofluids compared to basic fluids have been explored in different applications in engineering and medical fields. Few researchers have also explored the application of nanofluids to machining [7]–[9]. Application of emulsifier based nano cutting fluid at minute flow rate near

1ml/min to machining has not been reported till date to the best of author's knowledge. In the present work, cutting fluid is applied at cutting zone by two techniques. Their performance in machining is evaluated by measuring cutting temperatures, tool wear, cutting forces and surface roughness and also compared with dry machining and wet machining.

II. EXPERIMENTATION

Nanographite (C, <80 nm, 99.9%, natural graphite, hydrophobic) is purchased from Nanoshel (Washington, USA). It is functionalized and dispersed in water miscible cutting fluid (20:1) in different weight percentages (0.1wt%, 0.3wt%, 0.5wt%) using sonicator. Cutting fluid is applied at the cutting zone using two systems A and B. System A has separate fluid and air output adjustment arrangement, which uses high pressure air and supplies cutting fluid at a flow rate of 1ml/min. Pressure in the air line from compressor was maintained constant at 75psi using a pressure regulator. Cutting fluid was applied at 1ml/min by setting pulse generator to 40, brass adjustment knob to full stroke and air metering screw to $\frac{3}{4}$ revolution. Fig. 1 shows the experimental set up. System B uses an air atomizing nozzle which utilizes low pressure air of 3 psi to pull and atomize cutting fluid, which is fed under gravity, at a flow rate of 5ml/min. Fig. 2 shows the schematic diagram of mist generation using air atomizing nozzle i.e. System B. Turning operation was performed on AISI1040 steel rod with cemented carbide tool at constant cutting conditions: cutting velocity 40 m/min, feed 0.14 mm/rev and depth of cut 1mm while using both techniques. Performance of different techniques of MQL application is evaluated by measuring cutting forces using Kistler Dynoware system and cutting temperature using embedded tool thermocouple. End of thermocouple was maintained at a distance of 5mm from the cutting edge. Cutting was interrupted at regular interval of time and tool wear was measured using Olympus Metallurgical microscope and surface roughness was measured using SurfTest SJ-301 analyzer. Their performance is compared with dry and flood machining.

Economic analysis is also performed for both systems and compared with dry and flood machining. Experimentation data is used to perform economic analysis. Power consumed was determined using cutting forces obtained during machining.

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Tool wear obtained at the end of machining was used to estimate tool life and number of tools consumed per year. Assumptions for economic analysis are taken as in [12]. Total amount spent in machining per year is calculated using (1):

$$C_{total} = A + B + C \quad (1)$$

where

$$A = A1 + A2 + A3 + A4 + A5 + A6$$

$$B = (B1 + B2 + B3 + B4) * \text{Cost of Power} * 12$$

$$C = C1 + C2$$

A is amount spent on purchase and disposal of cutting fluid, purchase and surface treatment of nanopowder and water consumed/year

- A1 = Cost of oil consumed
- A2 = Cost of water used
- A3 = Labor cost for cleaning the sump and charging of

sump after each change (in case of Flood lubrication)

- A4 = Cost of nanographite consumed
- A5 = Cost of surface treatment of nanographite
- A6 = Cost of disposal of used cutting fluid

B is cost of power consumed /month:

- B1 = Power consumed (kWh) by Lathe/month
- B2 = Power consumed by pump /month
- B3 = Power consumed by compressor/month
- B4 = Power consumed by Sonicator/month

C is amount spent on tools/year

- C1 = Cost of tools = $y * N$
- C2 = Cost of regrinding = $x * N$
- N = Number of tool changes = (T_{ac}/T)
- T_{ac} = actual cutting time,
- T = Tool life
- x = cost of regrinding
- y = Cost of insert/no. of cutting edges (Cemented Carbide tool)



Fig. 1 Experimental set up with Coolubricator system

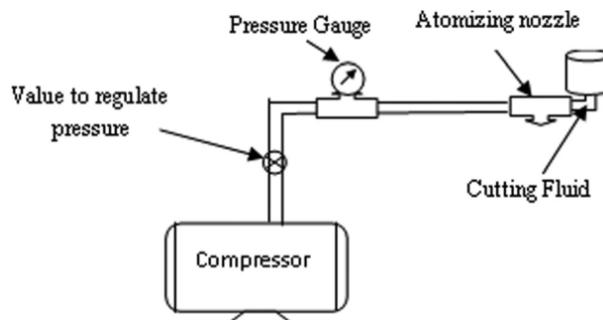


Fig. 2 Schematic diagram for mist generation using air atomizing nozzle

III. RESULTS AND DISCUSSION

Machining performance of different systems (A&B) of MQL application are evaluated by measuring cutting forces, cutting temperatures, surface roughness and tool wear. Machining is performed using emulsifier cutting fluid and emulsifier based nanographite cutting fluids with varying concentration. Flow rate of 1ml/min is obtained by using System A and flow rate of 5ml/min is obtained using System B. Care should be taken while using System B to maintain constant flow rate.

A. Cutting Temperature

Cutting temperature generated near cutting zone was measured using embedded tool thermocouple. Fig. 3 shows the variation of cutting temperature with machining time for dry machining, flood machining, MQL application at 1ml/min using System A and MQL application at 5ml/min using System B for emulsifier cutting fluid and emulsifier based nanographite cutting fluids with varying concentration .

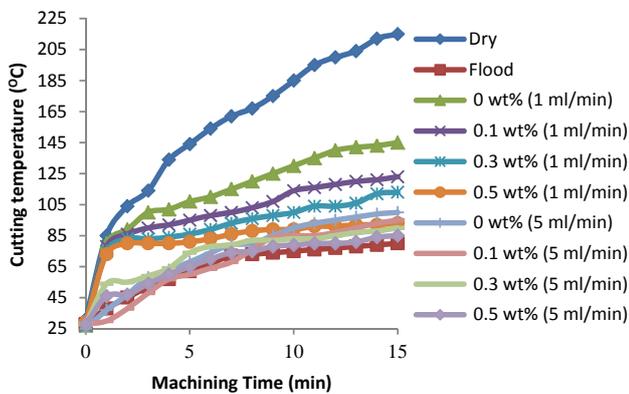


Fig. 3 Variation of cutting temperature with machining time

Maximum temperature was recorded in dry machining. Temperature generated near cutting zone was effectively removed by flood cooling followed by MQL application using System B followed by MQL application using System A. As in flood cooling, the cutting zone is completely covered with cutting fluid which constantly removes heat generated, the temperature measured was found to be less. With System A, use of cutting fluid has decreased by 80% compared to System B. Due to this, the effectiveness in cooling the cutting zone has also reduced. Percentage reduction of maximum cutting temperature obtained with System B w.r.t that obtained with System A was found to be 31%, 22%, 20% and 8% for 0wt%, 0.1wt%, 0.3wt% and 0.5wt% respectively. Percentage reduction in maximum cutting temperature with System A and System B with respect to dry machining is shown in Table I. Percentage reduction in temperature was found to increase with increase in percentage of concentration of nanographite in cutting fluid in both MQL techniques. But this reduction was found to be more with use of System A than use of System B. This may be due to use of high pressure air in System A which atomizes each droplet of cutting fluid causing

its effective entry into the cutting zone. As graphite is a good solid lubricant and also has good thermal conductivity, its entry along with cutting fluid into the cutting zone may have effectively removed the cutting temperature generated.

TABLE I
PERCENTAGE REDUCTION IN MAXIMUM CUTTING TEMPERATURE WITH RESPECT TO DRY MACHINING

	% reduction w r t dry machining	
	Using System A (1ml/min)	Using System B (5ml/min)
0 wt%	32.56	53.49
0.1 wt%	42.79	55.81
0.3 wt%	47.44	58.14
0.5 wt%	56.74	60.47

B. Cutting Forces

Cutting forces i.e. main cutting force (F_z), feed force (F_y) and thrust force (F_x) generated during machining operation are measured online using Kistler Dynamometer. Feed force and thrust force generated are very less as compared to main cutting force. Resultant cutting force (F_r) is measured using (2):

$$F_R = \sqrt{F_x^2 + F_y^2 + F_z^2} \quad (2)$$

Fig. 4 shows the variation of resultant cutting force (F_r) with machining time for dry machining, flood machining, MQL application at 1ml/min using System A and MQL application at 5ml/min using System B with emulsifier cutting fluid and emulsifier based nanographite cutting fluids of varying concentration. Maximum cutting force was observed with dry machining. Cutting forces obtained from MQL application using System A (1ml/min) was found to be less compared to dry machining. The entry of minute droplets of emulsifier cutting fluid in the cutting zone may have reduced the frictional forces existing there, thereby reducing the resultant cutting force. Cutting forces obtained from MQL application using System A (1ml/min) was found to be more than that obtained from MQL application using System B (5ml/min). The reason may be that the quantity of cutting fluid supplied by System A could not provide lubrication as that provided by cutting fluid supplied using System B. For both MQL application techniques, cutting forces were found to decrease with increase in concentration of nanographite. This may be due to increase in lubricating properties with increase in concentration of nanographite in cutting fluid. This may have reduced the frictional forces and in turn reduced the cutting forces.

C. Tool Wear

Machining was interrupted at regular intervals of time and maximum flank wear of the tool was measured using Olympus Metallurgical microscope. Fig. 5 shows the tool flank wear observed at the end of 35 min for dry machining, wet machining, MQL application at 1ml/min using System A and MQL application at 5ml/min using System B with emulsifier cutting fluid and emulsifier based nanographite cutting fluids of varying concentration. Fig. 6 shows the variation of tool

flank wear with time for all cases except for dry machining. Curve for dry machining is not shown as its inclusion would mingle all other curves closely making it difficult to compare

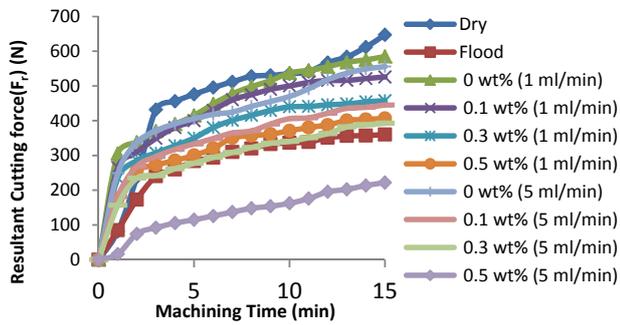


Fig. 4 Variation of resultant cutting force (F_r) with machining time

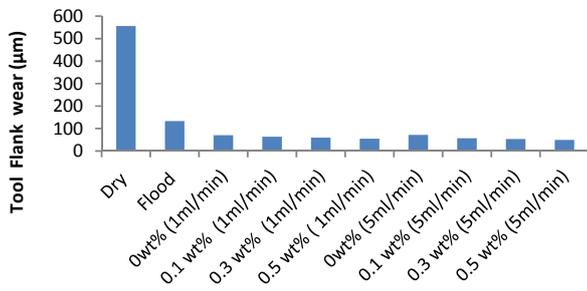


Fig. 5 Tool flank wear observed at the end of machining for all cases

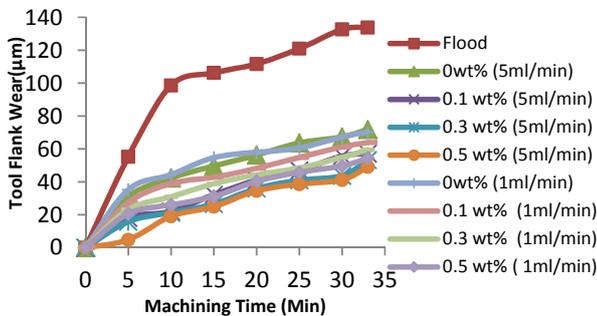
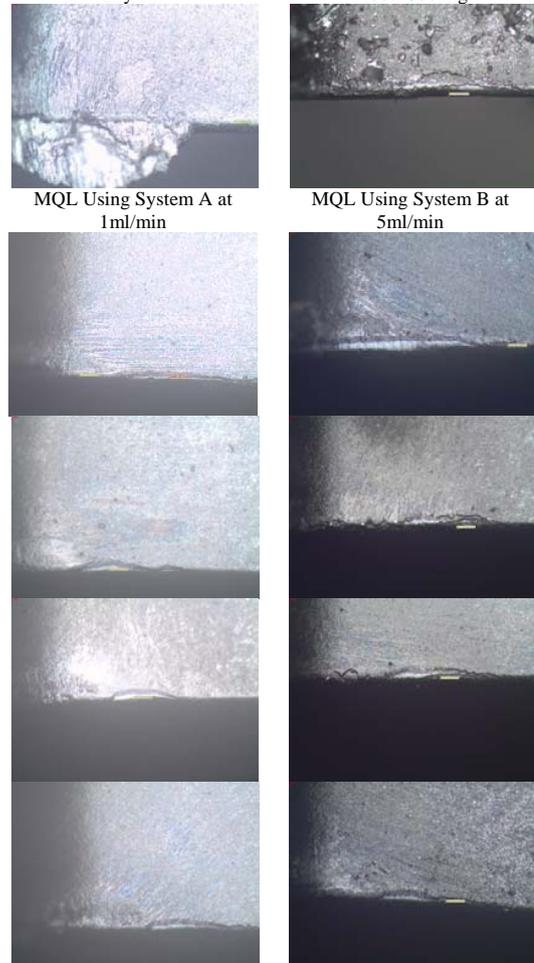


Fig. 6 Variation of tool flank wear with machining time for flood machining, MQL application (System A) (1ml/min) and MQL application (System B) (5ml/min) with different concentration of nano cutting fluids

Table II shows the tool wear photos at the end of machining. Maximum tool flank wear was observed with dry machining. Tool flank wear observed with MQL applications using both techniques is found to be less compared to flood machining. In MQL application, aerosolization of cutting fluid using air may have caused their easy entry into the cutting zone causing better lubrication and cooling at tool tip and hence reducing the tool wear. The increase in tool wear in flood machining may also be due to accelerated wear of cutting tool due to thermal shock. In both MQL application

techniques, tool wear was found to decrease with increase in concentration of nanographite in cutting fluid. This may be due to increase in thermal conductivity [10] and lubricating properties i.e. wear preventive property and extreme pressure capability [11] with addition of nanographite in cutting fluid.

TABLE II
TOOL WEAR PHOTOS AT THE END OF MACHINING



D. Surface Roughness

Surface finish is an important parameter as it determines the performance and service life of machined component. Surface roughness of the machined component is measured at the end of machining using Surftest SJ-301 analyzer. Fig. 7 shows the surface roughness (R_a) for all cases.

Surface roughness was found to be maximum with dry machining. This may be due to more tool wear leading to sliding of blunt edge along the work piece. Surface roughness obtained with both MQL application techniques using conventional emulsifier cutting fluid were found to be slightly more than that obtained with flood machining. This may be either due to application of cutting fluid with pressure, which hits the workpiece with force causing more surface roughness or due to use of reduced quantity of cutting fluid which could

not provide sufficient lubrication between the tool work and tool chip interfaces as provided by flood cooling. Surface roughness was found to be decrease with use of nanographite cutting fluid in both MQL application techniques and this decrease was found to be more with increase in concentration of nanographite in cutting fluid. This shows that additions of nanographite in cutting fluid has improved its lubricating and wear preventive properties thereby decreasing tool wear and hence decreasing surface roughness.

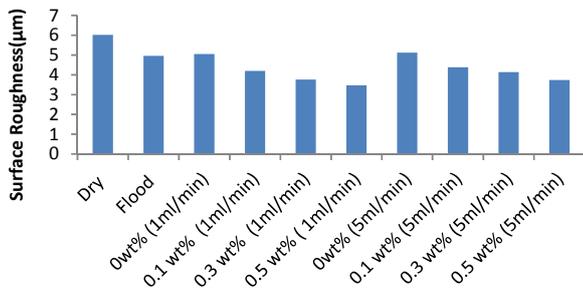


Fig. 7 Variation of surface roughness for all cases

E. Economic Analysis

Economic analysis is performed for machining using both MQL techniques and compared with dry and flood machining. Fig. 8 shows the amount spent/year in dollars on oil, nanopowders and water. It shows that no amount is spent in this category for dry machining. MQL application using System B with emulsifier cutting fluid and 0.1wt% and 0.3wt% nanographite emulsifier cutting fluid are found to be economically better than flood machining. High cost of nanoparticles has caused application of 0.5wt% nanographite emulsifier cutting fluid using System B to be more expensive than flood machining. MQL application using System A with emulsifier cutting fluid as well as nanographite emulsifier cutting fluids are found to be economically better than flood machining and MQL application using System B. This is due to minute flow rate obtained using System A, which limits the use of cutting fluid and nanoparticles. Fig. 9 shows the amount spent/year in dollars on power consumption. It is found that amount spent in this category is least in dry machining as power is consumed only during machining process. Amount spent in power consumption is found to be more with both MQL techniques compared to flood machining. This is because of increased power consumption due to use of compressor and sonicator. Fig. 10 shows the amount spent /year in dollars on tools utilized. It shows that maximum amount is spent in dry machining due to more utilization of tools as tool wears rapidly with dry machining. Amount spent in this category is found to be less with both MQL techniques compared to flood machining, as tool wear obtained with flood machining is found to more than that obtained with MQL applications. Amount spent on tools is found to be slightly more with MQL application using System A (1ml/min) as compared to MQL application using System B (5ml/min). With both techniques, amount spent is found to

decrease with use of nanographite in cutting fluid and this decrease is found to be more with increase in concentration of nanographite in cutting fluid. Fig. 11 shows the total expenditure/year in dollars for all cases of machining. Total expenditure is found to be less with use of MQL application using System A (1ml/min) with conventional as well as nano cutting fluids, followed by MQL application using System B (5ml/min) with conventional as well as 0.1 and 0.3wt% nano cutting fluid compared to flood machining.

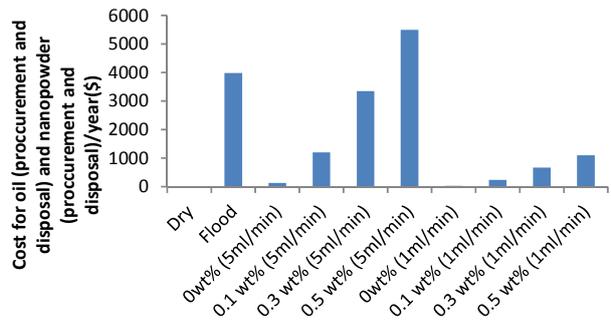


Fig. 8 Amount spent /year (Dollars) on oil, nanopowders and water

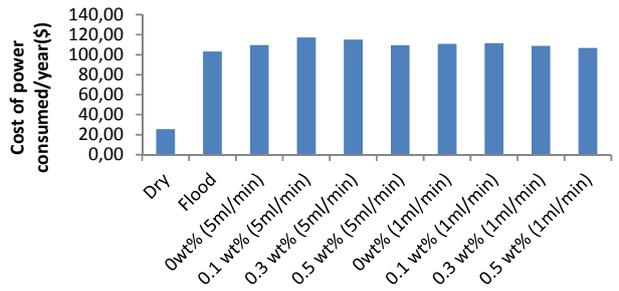


Fig. 9 Amount spent /year (Dollars) on Power Consumption

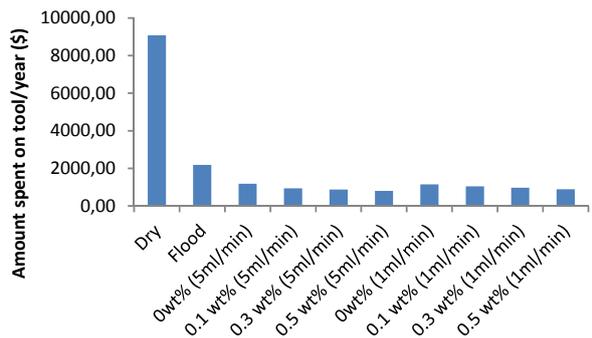


Fig. 10 Amount spent /year (Dollars) on Tools

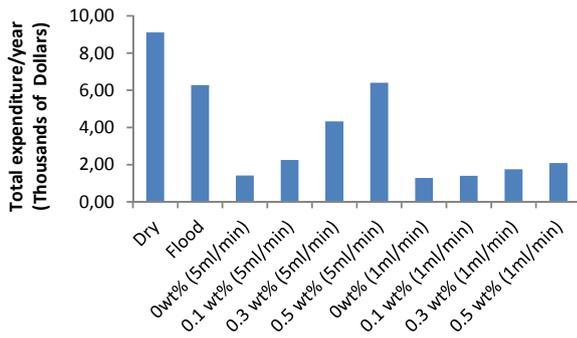


Fig. 11 Total Expenditure /year (Thousands of Dollars)

IV. CONCLUSION

1. Cutting temperature near cutting zone is found to be more with both MQL applications compared to flood machining. MQL application using System B (5ml/min) showed better cooling compared to MQL application using System A (1ml/min).
2. Maximum percentage reduction in cutting temperature was found with nanographite emulsifier cutting fluid used in System A and System B, which was found to be 56.74% and 60.47% compared to dry machining.
3. Cutting forces are found to be more with both MQL applications compared to flood machining. But MQL application with higher concentration of nanographite has provided better lubrication reducing cutting forces and nearing flood application.
4. Tool wear obtained with both MQL techniques are found to be less as compared to flood and dry machining and it further decreased with use of nanographite in cutting fluid.
5. Surface roughness was found to be less with use of nanographite emulsifier based cutting fluid in both MQL applications compared to flood machining. Surface roughness was found to decrease with increase in concentration of nanographite in emulsifier cutting fluid with both MQL applications.
6. MQL application using System A was found to be economically better than MQL application using System B with emulsifier based cutting fluids as well as corresponding emulsifier based nanographite cutting fluid. Both MQL application techniques are found to be economically better than dry and flood machining.

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