Investigations on the effect of nozzle angle and air flow rate during nanofluid Minimum Quantity Lubrication milling of Aerospace alloy Al7075-T6

Harshit B Kulkarni¹, Pratik P Khandare¹, Pranesh G Parvatikar¹, Pranil G Pawar¹, Rajanikant Tiwari¹, Mahantesh M Nadakatti¹, Anand S Deshpande¹, and Raviraj M Kulkarni²

¹Department of Mechanical Engineering, Centre for Nanoscience and Nanotechnology, KLS Gogte Institute of Technology, Udyambag, Belagavi, Karnataka India.
²Department of Chemistry, Centre for Nanoscience and Nanotechnology, KLS Gogte Institute of Technology, Udyambag, Belagavi, Karnataka India.

Email: hbkulkarni@git.edu

Abstract: Present day industries are focusing upon finding various methods and techniques to implement sustainable manufacturing, which is ‘the need of the hour’. With increase in global competition, industries are striving hard to reduce the machining costs, which is a major contributor for ‘manufacturing cost per part’, in an industry. Conventional method of using large quantity of coolant/cutting fluids in several liters per hour, to cool machining zone is causing enormous concern. Strict Government regulations are necessitating industries to replace flood-coolant assisted machining by new techniques like ‘Minimum Quantity lubrication’ (MQL) coolant supply technique. The present work deals with investigating the effect of varying nozzle angle and air-flow rate during MQL assisted surface milling of aerospace aluminum Al7075-T6 alloy, using uncoated carbide tool. Three methods of coolant supply namely Dry, MQL and nanofluid MQL (nano particles suspended oil with MQL) are experimented. Cutting speed [150m/min, 208m/min, 264 m/min], feed rate [95 mm/min, 110 mm/min, 125 mm/min] and depth of cut [0.5 mm, 1.3 mm, 2 mm] are chosen as process variables. Two nozzle angles 25° and 50°, with 1.5 kg/cm² and 3 kg/cm² air flow rates were investigated. Best results were obtained for air flow rate of 1.5kg/cm². Optimum nozzle angle was found to be 25°. To obtain lowest temperature and reduced heat generation, nanofluid MQL machining is a feasible option. With regards to MQL technique, for obtaining better surface finish with reduced surface roughness of the work piece (Al7075-T6), nanofluid MQL technique is best.

1. INTRODUCTION

The term machining plays a significant role in shaping the components ranging from soft to hard. Over the years with the advancement in machine tool technology, various challenges are overcome. However, for machining of harder and difficult to cut, materials like aerospace alloys, it still remains a challenge with regards to the cost of machining. Around the globe, industries are striving, to find methods to reduce the cost of machining without compromising on quality of machined product. One of the challenges to reduce cost is that, associated with excess use of cutting fluid/coolant. Machining of hard and difficult to cut components, generally leads to increased cutting temperatures at the metal working zone, demanding high quantity cooling supply. This increases the cost of coolant. Conventional coolant supply techniques like flood coolant system, do not suffice the need, since they do not reach exact cutting area. The fluid supplied is reported to evaporate much before the metal cutting zone, due to increased cutting temperature. Thus, heat generated increases causing adverse effects on tool and work[1] after machining.
One of the solutions to effectively reduce the coolant costs is minimizing coolant quantity by effective utilization of coolant by directing it through a converging channel, at the exact work-tool interface. This unique feature, led to the concept of “Minimum Quantity Lubrication” or “Near Dry Machining”, currently being investigated by several researches all over the globe. MQL technique is being accepted for the fact that with MQL system the machine floor space remains almost clean, with clean and dry chips, further eliminating post processing of chips. MQL supplies coolant in form of mist [oil and compressed air] focused through a nozzle normally ranging from 50 to 500 ml/hour [2][3]. This MQL system is eco friendly since cool ant usage is minimal with least disposal and contamination issues. MQL system have replaced those situations where dry machining is not feasible. This method cools the tool-work and acts as both cooling agent and lubricant [4]. Experimental investigations on using MQL technique further lead to certain challenges of heat dissipation for aggressive materials. Few researchers so pined that MQL oil mist with compressed air failed to obtain the desired cooling effect for hard materials like aerospace alloys. These necessitated researchers to find coolants that have better cooling ability even though used in small quantity.

According to the principles of heat transfer enhancement theory, ‘solids have higher heat transfer ability than gases & liquids’ Keeping this as the base, researchers started investigations on suspension so fultrafine nano meter sized metallic particles in existing coolants to enhance its thermal conductivity. This led to the concept of nanofluid MQL machining. Adding small amounts of nano particles to the coolant used for MQL has reported to enhance the thermal conductivity of the coolant significantly. Several researchers have been experimenting on this new method that is yielding better results [5]. Nano fluid coolants have high heat carrying capacity, high dispersion stability and eliminates the accumulation of particles. Several researchers have experimented the use of nanofluids for metal machining. Cong Mao et al. [6] carried experiment on grinding to study performance of spray parameters using nanofluid MQL on hardened AISI52100 steel with depth of 0.1mm & 0.2mm /rev cutting speed. The tool used was aluminum oxide grinding wheel of abrasive size 100(WA100).

Investigations found that the application of nano fluid mist is affected, when the direction of MQL nozzles praying angle changes. Mist size increase as spraying distance increase, while mist velocity decreases when spraying direction changes. Hence, shorts pray distance is better than long spray distance. Patricia and Paul[7] established a model on geometrical analysis to find the desired surface roughness during face milling of Al 7075-T7351 on a CNC (Computer Numerical Control) high speed vertical machining center using variables such as feed per tooth, tool nose radius, axial depth of cut and cutting speed. The research work was useful for development to surface roughness prediction models as a fundamental variable in mechanical part surface integrity. Using model allows for experiments of trial and error and looking for optimal variable for different roughness value.

The model developed is easy to use, it has 98 percent accuracy, and it not only allows the roughness value to be obtained, but also the profile development of the 2D surface roughness. Xia J et al. [8] investigated the effect of cutting performances of MQL in terms of cutting temperature, cutting force & residuals tress. It was found that cutting temperature, cutting force and residual stress can be affected by cutting fluid on the surface of work piece which depends on thermal stress and application of cutting fluid. Jules K et al. [9] carried out turning operation on 7075-T6 aluminum alloy in MQL and dry condition using Mecagreen 550 lubricant coolant. The cutting speed varied from 79m/ min to 661m /min, while feed rate varied from 0.0508 mm /rev to 0.2845 mm/rev. The authors noticed that surface finish depends mainly on feed rate, while particle emission depends cutting and lubrication conditions.

Sener K et al. [10] investigated the impact of milling variable on the tool wear on constant chip volume removed from ANOVA (analysis is of variance), during Friction of Al7075 and MMC (Metal Matrix Composite). Feed, cutting depth (axial) and milling speed affected the milling(friction) force with percentage contribution of 23.23%, 65.51% and 8.61% was respectively for Al7075 and 14.22%, 70.48% and 11.26% respectively for SiC (Silicon Carbide) composite foam. It was found that for both
the workpiece materials the most significant parameter for milling force was axial cutting depth. Feed affected the most with percentage contribution of 79.31% followed by cutting depth (axial) in the MMC milling process. Good cutting efficiency was shown by carbide uncoated tool with machining speed below 220 m/min in finish milling of workpiece material Al7075, but is not efficient in MMC’s milling. Ugochukwu et al. [11] conducted experiment for comparative analysis of Aluminum (Al) surface by end milling for both MQL and dry methods. Material used was Aluminum 6061 of size 200mm*50mm*50mm blocks in CNC milling machine system. Thirty samples were cut for MQL and 30 samples for dry condition using a 12mm diameter HSS milling cutter. Response Surface Methodology (RSM) and statistical (ANOVA) was employed in the experiment. Surface roughness (Ra) value for MQL condition were lower when compared to dry condition by 20% reduction. They found that for spindle speed of 2000 rpm and depth of cut of 20mm, minimum surface roughness obtained was about 0.58 μm for dry, whereas for feed of 100 mm/min and depth of cut (radial) of 1.5mm for this surface roughness was 0.5μm for MQL. Manish Kumar Gupta and PK Sood [3] carried out an investigation on machining comparison of aerospace materials considering MQL cutting fluid as beneficial for machining two Aero engine alloys (Inconel-800 and titanium-2) in which machining performance of titanium alloy was far better as compared to Inconel alloy. Machining of titanium and Inconel alloy under MQL condition broke the chips into small fragments, whereas for machining of titanium and Inconel alloy under wet and dry conditions produces continuous chips. Mohammadhreza S at el. [12] performed experimental investigations on lubrication properties of CuO nano fluid with AISI 1045 hardened steel in MQL grinding. Investigations concluded that tangential force and force ratio of AISI hardened steel with CuO nano fluid in MQL grinding were found to be lower than flood cooling. The magnitude of sliding force found varying with concentration of CuO nanoparticles. Cagri V.Y at el. [13] milled base superalloy under MQL parameters (flow rate, oil type, milling type, nozzle type and spray distance,) and concluded that coolant flow rate was one of the main factors affecting cutting force and tool life. It was observed that by increasing flow rate the values of both cutting force and tool life were improved. Salah G et al. [14] performed experimental evaluation of cutting fluid when machining of Ti-6Al-4V using vegetable oil. It was found to be performing better when compared with conventional system, which significantly reduced cutting fluid consumption up to 42%, tool flank wear with percentage contribution of 46.77%, cutting force with percentage contribution of 16.40%, and burr formation with percentage contribution of 31.70%. H. Hegabat at el. [15] implemented sustainable process parameters during cutting of Inconel 7118 with two nano-additives namely MWCNTs (Multi walled carbon nano tubes) and Al2O3 (aluminum oxide) nanoparticles. The sustainability assessment results showed promising improvements using MQL nano fluids when compared to MQL technique. It showed that nano-additive splayed an important role increase in nano-additives concentration decreased the induced friction. Manish K.G et al. [16] emphasized on strategies of cooling lubrication to improve surface roughness and tool wear in CNC turning for Al7075-T6 alloy under 4 different cooling environments i.e., dry cooling (DC), nitrogen cooling (N2), nitrogen MQL (N2-MQL) and Ranque-Hilschvor texture NMQL (R-N2MQL). Parameters chosen were cutting speed between 160 m/m in and 320 m/min and feed rate between 0.05 mm/rev and 0.15 mm/rev. The nodes N2C, N2MQL and R-N2MQL are proved to be necessary for sustainable machining of Al7075-T6 and the tool wear reduced by101-118% using right cooling/lubrication and cutting parameters. Harshit B.K et al. [17] investigated DOE based experiments on surface milling of Al7075-T6 aerospace alloy possessing high strength and light weight. Surface milling experiments were conducted using Vulcan Strub Oil Futura nano fluid coolant on aluminum slab of 300*200*10 mm3 with 12 mm diameter carbide uncoated end mill cutter on vertical machining centre.

Outcome of investigations revealed that MQL method of coolant supply during surface milling was found to be useful in terms of reducing coolant consumption from 50 L/hour to 60 L/hour to 50-500 mL/hour. Anuj K.S et al. [18] made research for improving machining performance using nanoparticles enriched cutting fluid in MQL system by listing out properties of different nanoparticles compared to all other experiments carried out by different authors. They also listed out different nanoparticles used in other processes such as milling, turning and grinding etc, and conducted a general comparison.
Study concluded that nanoenriched fluids exhibit better properties tribologically when compared to base fluid. About 2% of Al2O3 (30nm) added in paraffin oil generates smallest surface roughness of 0.1 μm. Harshit B. K. et al. [19] performed studies on enhancement of thermal conductivity studies by coating Al2O3 with thin shell of copper suspended in Nanofluid coolant. The coating of Al2O3 nano particles enhanced the heat carrying capacity of base fluid and resulted in thermal conductivity rise of 23.39% when 0.3% of Al2O3@Cu nano particles by weight was added to selected coolant.

2. EXPERIMENTATION

2.1. Equipment, work-tool and machining parameters

The present investigation deals with surface milling tests (operation) performed on the Al7075-T6 alloy. The work piece is in rectangular shape having dimensions of 200mm*420mm and depth of cut of 10mm. Chemical compositions of Al7075-T6 alloy are listed in table 1.

| Element | Mn   | Si    | Cu   | Mg    | Fe   | Ti  | Cr   | Zn   | Al   |
|---------|------|-------|------|-------|------|-----|------|------|------|
| weight% | 0.0189 | 0.0526 | 1.3518 | 2.318 | 0.1053 | 0.015 | 0.2243 | 5.3536 | Balance |

Experiments were performed on vertical milling machine V645 Max power as shown in figure 1.

Uncoated carbide end mill cutter of four flute having diameter of 12mm cutting tool was used for machining. The experiments were performed for three types of coolant supply methods namely dry, MQL & Nanofluid MQL using KENCO (‘Krishna Engineering company’) make, mist coolant system of 5 litre tank capacity MQL system as shown in figure 2.
The machining parameters selected for experiment were spindle speed (150 m/min, 208 m/min and 264 m/min), feed (125, 110, 95) mm/min and depth of cut (0.5 mm, 1.3 mm, 2 mm) and output parameters to be determined were surface roughness (µm) and surface temperature (°C). Since temperature prevalent at the interface of work tool affects the surface finish of machined component, present research has selected temperature as one of response. Readings are obtained using infrared thermal gun-IR of measuring range (30°C to 500°C) for temperature as shown in figure 3 and the Surface roughness \( R_a \) was measured by Telesurf Surfcom roughness tester as shown in figure 4.

2.2. Nanoparticle Synthesis and Nanofluid preparation

ZnO is for medusing chemical reduction method. Most popular methods of ZnO nano particle is chemical precipitation, in which two reaction reagents are involved such as Zinc nitrate \([\text{Zn(NO}_3\text{)}_2]\) or Zinc sulphate \([\text{ZnSO}_4]\), Zinc acetate \([\text{Zn(CH}_3\text{COO)}_2\text{H}_2\text{O}]\), and solution of precipitate such as Ammonium hydroxide \([\text{NH}_3\text{H}_2\text{O}]\) Or sodium hydroxide \([\text{NaOH}]\). The precipitate is added drop wise to dissolve z in cuntil it reaches to pH level of about 10. Then, complete mixture of these solution will form a white intermediate of zinc hydroxide this is converted to ZnO after heating at high temperature [20]. Further, 10 grams of ZnO nano particles are mixed with 1-litre of cool an oil, the total weight percentage of the nano particle was 0.01% addition.

2.3. DOE (Design of Experiments)

DOE based investigations with nanofluid MQL machining, were conducted with statistical technique ANOVA to find the significance of air flow rate and nozzle angle. The selected range of variables were of air flow rates (1.5 kg/cm\(^2\), 3 kg/cm\(^2\)) and nozzle angles (25°, 50°). The design matrix with selected range of speed, feed and depth of cut are as shown in table 2. Coolant used for experiment was Vulcan Strub Oil Futura (Swiss Tribology) and the nano particles used for Nanofluid MQL method is ZnO in powder form. 3-level, 3-factor, full factorial design with two replicates was conducted. The cutting tool (uncoated carbide) was fixed on the spindle of the VMC machine, work piece (Al7075-T6) was clamped on the vice and then mounted on top of the work table of the VMC machine. Then the CNC part programming is fed in and specific command for milling was given to the VMC machine. Then the CNC part programming is fed in and specific command for milling was given to the VMC machine. ZnO nano particles in powder form is added and mixed in the tank for Nano + MQL system. The nozzle of MQL system produces the aerosol mist as the coolant. At first Dry machining then MQL machining, finally Nano + MQL machining was carried out for different nozzle angle and air flow rates. A sample of 5 readings from each set of milling operation (dry, MQL and nanofluid MQL) are shown in table 3.
### RESULTS AND DISCUSSION

**Table 2.** Design matrix for experiment using 3-level, 3-factors full factorial analysis.

| Factor       | Unit | L1 | L2 | L3 |
|--------------|------|----|----|----|
| Cutting speed (V) | m/min | 150 | 208 | 264 |
| Feed rate (f)   | mm/min | 95  | 110 | 125 |
| Depth of cut (d) | mm    | 0.5 | 1.3 | 2  |

**Table 3.** Sample readings for all three types of coolant supply. [5 readings for each coolant type]

| Std Order | Run Order | PtType | Blocks | Cutting speed | Feed | DOC | Temperature | Ra(Surface Roughness)(µm) |
|-----------|-----------|--------|--------|--------------|------|-----|-------------|--------------------------|
| 9         | 1         | 1      | 1      | 150          | 125  | 2   | 33.6        | 0.36                     |
| 12        | 2         | 1      | 1      | 208          | 95   | 2   | 44.3        | 0.32                     |
| 16        | 3         | 1      | 1      | 208          | 125  | 0.5 | 29.6        | 0.41                     |
| 24        | 4         | 1      | 1      | 264          | 110  | 2   | 38.3        | 0.31                     |
| 10        | 5         | 1      | 1      | 208          | 95   | 0.5 | 30.5        | 0.34                     |
| 9         | 1         | 1      | 1      | 150          | 125  | 2   | 35          | 0.28                     |
| 12        | 2         | 1      | 1      | 208          | 95   | 2   | 37.8        | 0.19                     |
| 16        | 3         | 1      | 1      | 208          | 125  | 0.5 | 24.8        | 0.45                     |
| 24        | 4         | 1      | 1      | 264          | 110  | 2   | 32.6        | 0.14                     |
| 10        | 5         | 1      | 1      | 208          | 95   | 0.5 | 28.5        | 0.15                     |
| 9         | 1         | 1      | 1      | 150          | 125  | 2   | 35.5        | 0.33                     |
| 12        | 2         | 1      | 1      | 208          | 95   | 2   | 35.4        | 0.19                     |
| 16        | 3         | 1      | 1      | 208          | 125  | 0.5 | 32.4        | 0.12                     |
| 24        | 4         | 1      | 1      | 264          | 110  | 2   | 36.5        | 0.16                     |
| 10        | 5         | 1      | 1      | 208          | 95   | 0.5 | 25.8        | 0.17                     |

**Figure 5.** Plot of temperature Vs Cutting speed and depth of cut (Dry)

**Figure 6.** Plot of temperature Vs Cutting speed and depth of cut (MQL)
From the results obtained it is noted that depth of cut and cutting speed are significant factors for heat generation. From the graph in figure 5, during dry milling, it is observed that as the depth of cut and cutting speed increases, friction at the work tool interface increases leading to significant rise in temperature up to a maximum of 42.5°C. From figure 6, during MQL milling, it was observed that feed has less significance than cutting speed and the temperature values are lower compared to during dry machining. Aerosol mist directed at the work tool interface with MQL system assists in carrying the heat. For nanofluid MQL milling as represented in figure 7, the temperature values are still over than those for MQL with a maximum of 37.5°C. This is attributed to the fact that, rolling action of billions of nano particles contributes to Brownian motion that transfers heat quickly through fluid. Suspension of solid nanometer sized particles leads to enhanced heat carrying capacity, due to increased thermal conductivity of the coolant [19]. Hence the temperature values are lowered at work tool interface with effective cooling. Figure 9 and figure 10 represent the effect of cutting speed on surface roughness in case of MQL and nanofluid MQL milling. From the obtained results, it was found that depth of cut and cutting speed are significant factors, for increasing the surface roughness of the workpiece. From Figure 8 as the feed rate and cutting speed increases, the surface roughness values decrease. Same trend is observed for MQL and nanofluid-MQL milling.

4. CONCLUSION

The introduction of MQL has improved the machining performance during surface milling of aerospace aluminum alloy Al7075-T6. Significant reduction in coolant consumption was reported.
parameters investigated were air flow rate and the nozzle angle orientation. Best results were obtained at an air flow rate of 1.5 kg/cm² and optimum nozzle angle was 25°, for effective machining. To obtain lowest temperature and reduced heat generation, nano fluid MQL machining is a feasible option. For obtaining lowerest temperature and reduced heat generation, nano fluid MQL machining is a feasible option. To obtain better surface finish with reduced surface roughness of the work piece (Al7075-T6), nanofluid MQL technique is best. Hence, use of MQL systems for surface milling of aerospace Al7075-T6 material will significantly reduce the coolant consumption thereby promoting eco-friendly machining. Further studies can be performed by varying the other parameters.

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