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Application of Nano Cutting Fluid under Minimum Quantity Lubrication (MQL) Technique to Improve Grinding of Ti – 6Al – 4V Alloy

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Abstract**—**Minimum Quantity Lubrication (MQL) technique obtained a significant attention in machining processes to reduce environmental loads caused by usage of conventional cutting fluids. Recently nanofluids are finding an extensive application in the field of mechanical engineering because of their superior lubrication and heat dissipation characteristics. This paper investigates the use of a nanofluid under MQL mode to improve grinding characteristics of Ti-6Al-4V alloy. Taguchi's experimental design technique has been used in the present investigation and a second order model has been established to predict grinding forces and surface roughness. Different concentrations of water based Al_2O_3 nanofluids were applied in the grinding operation through MQL setup developed in house and the results have been compared with those of conventional coolant and pure water. Experimental results showed that grinding forces reduced significantly when nano cutting fluid was used even at low concentration of the nano particles and surface finish has been found to improve with higher concentration of the nano particles.

Keywords**—**MQL, Nanofluid, Taguchi method, Ti-6Al-4V.

I. Introduction

TITANIUM and its alloys are used extensively in aerospace because of their excellent combination of high specific strength which is maintained at elevated temperature. From machining aspect these materials are difficult to machine because of their high chemical affinity, and the chips easily weld onto the grinding wheel due to very high local temperature and pressure. These things will cause faster wheel wear, which affects the wheel life, and ground surface quality.

Abrasive machining processes usually enhance workpiece surface quality, and also produce low surface roughness. But abrasive machining can also lead to surface damage due to the high temperature generation during the grinding[1].

The ill effects due to high temperature can be controlled by increasing the heat transfer rate in the grinding zone using a suitable grinding fluid.

Most grinding operations today employ liquids such as coolants to control the surface quality, temperature and to improve the wheel life. Due to increasingly strict legislation aimed at controlling health hazards and environmental pollution, the real cost of fluids used in machining operations is rising substantially. This provides the economic drive for the ideal, imaginary goal of economical lubrication-free grinding[2]. Transition of the metalworking industry towards sustainable manufacturing is reflected in limiting the use of cutting fluids in machining. This limitation is beneficial for different reasons. First, it reduces operational health and safety (OHS) risks and environmental impact associated with disposal of the cutting fluids. Second, it reduces machining costs. It is known that the costs related to the use of cutting fluids range from 7-17% of the total costs of the manufactured workpiece[3].

Among many of the alternative ways of reducing coolant usage, dry machining techniques and those using compressed cold air and MQL methods have mainly been studied and all the three techniques can be categorized as environment friendly machining[4].

The conventional way to enhance cooling (heat transfer) is to increase the heat transfer surface area (high volume) and the cutting fluid velocity (high pressure). However, this approach is unsustainable due to high power consumption of the pumps and large volume of coolant required. Considering that the velocity of the cutting fluid affects its cooling ability almost as much as its thermal conductivity, it is likely that nanofluids with enhanced heat transfer could meet the cooling challenge at lower cutting fluid velocities. A number of reported experimental work show that the dispersal of nano particles into a base fluid provides extremely desirable thermal properties, such as higher thermal conductivity and high convection heat transfer coefficient. Average heat transfer enhancement for nanofluids is shown to be in the range of 15-40% [5].

MQL has been used as an alternative solution for flood cooling as well as dry machining. However, the benefit of MQL is only realized in mild machining conditions as the heat generation during more aggressive machining conditions can not be effectively eliminated by the small amount of oil mist being applied during MQL process. To extend the applicability of MQL to more aggressive machining conditions, Park[6] developed a potential additive nanographene to MQL lubricant.

Bin Shen[7] investigated the wheel wear and tribological characteristics in wet, dry, and MQL grinding of cast iron. Water-based Al_2O_3 and diamond nanofluids were applied in the MQL grinding process and the grinding results were compared with those of pure water. Their results showed the benefits of reducing grinding forces, improving surface roughness, and preventing workpiece burning.

The use of cutting fluid containing nano particles in wet

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grinding and MQL grinding of Ti-6A1-4V was studied by Liao et. al.[8] and they found that the use of cutting fluid containing nano particles results in less loading of the wheel and better ground surface as compared with those with the use of the general purpose water-based cutting fluid because of smaller grinding forces and coefficient of friction originated from "lotus effect" of nano particles.

Rajurkar et al.[9] studied the effect of tribo-chemical lubricant film formation during nanofluid MQL grinding. The performance in terms of force ratio, specific energy, and G-ratio has shown substantial improvement when using nanofluid. Formation of tribo-chemical films on the workpiece surface was identified as the mechanism responsible for these improvements.

Though there have been many research works on the thermal conductivity and lubricity of nano fluids in many fields, the study regarding the usage of cutting fluids with nano particles during grinding of titanium alloy is almost absent.

II. Experimental Setup

The grinding experiments were conducted on Chevalier SMART-H1224 surface grinding machine. The setup of the grinding experiment is shown in Figure 1.

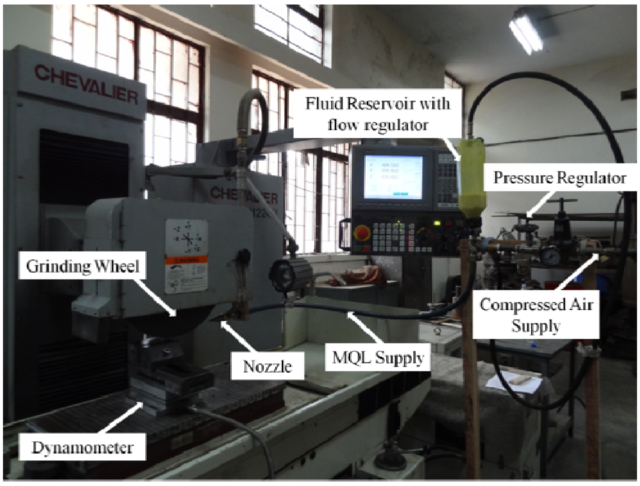

Fig. 1 Experimental Setup

Grinding forces (tangential and normal directions) were measured online using a KISTLER 9257B piezoelectric dynamometer, coupled to KISTLER 5070A multichannel (six component) amplifier and computer data acquisition software (Dyno Ware). The mean value of forces was taken after each pass. A Taylor Hobson Talysurf profilometer was used to measure the surface roughness of the ground surface. The dressing operation was kept constant in all the tests, using a single point diamond dresser. The experimental conditions are given in Table I.

The experiments under MQL mode have been conducted using Taguchi's experimental design (L9) technique, which helps in reducing the number of experiments. The coded values of machining parameters and actual setting values are presented in Table II.

TABLE I
Grinding Conditions

Machine	Chevalier SMART-H1224 surface grinder
Wheel specification	SiC (CGC60-K5-VG)
Environments	MQL
Workpiece material	Ti-6Al-4V
Workpiece dimensions	35mm × 35mm × 5 mm
Dresser	Single point diamond dresser
Dressing depth (mm)	0.010
Dressing Lead(mm/min)	50

TABLE II
Process Parameters and Their Levels

Parameters	Unit	Symbol	Level		
			1	2	3
Wheel Speed	m/sec	V_g	10.89	16.34	21.79
Table speed	m/min	V_w	3	9	15
Depth of cut	μm	d	10	20	30

Four types of cutting fluids were used in grinding tests under MQL mode, water-based Castrol cutting oil at 1:40 concentration, pure water, and water-based Al_2O_3 nanofluids. The Al_2O_3 nanofluids were prepared by dispersing 40nm (avg size) Al_2O_3 nanoparticles (Reinste Nano Ventures, New Delhi, India) to the water. Two volume fractions of Al_2O_3 nanofluids at 1.0% and 4.0% were tested. For MQL grinding, the flow rate and air pressure was set at 18ml/h and 1.5 bar respectively.

III. Experimental Methods

A. Taguchi Method

This paper uses Taguchi method for optimization of grinding parameters in nano MQL mode, which is very attractive and effective method to deal with responses influenced by a number of variables. In this method, main parameters are assumed to have influence on process results, which are located at different rows in a designed orthogonal array. With such an arrangement completely randomized experiments can be conducted. This method is useful for studying the interactions between the parameters, and also it is a powerful design of experiments tool, which provides a simple, efficient and systematic approach to determine optimal cutting parameters. Compared to the conventional approach of experimentation, this method reduces drastically the number of experiments that are required to model the response functions[10].

In the case of surface roughness, and cutting forces smaller values are always preferred. The equation for calculating S/N ratio for smaller-the-better characteristic is;

Where Ri is the value of surface roughness for the i^{th} trial in r number of tests.

$$\eta = -10\ \log_{10}\left(\frac{1}{r}\sum_{i=1}^{r} R_i^2\right)\ i = 1,\ 2, \ldots, r$$

In Taguchi method, for reducing the number of experiments and to determine the optimal cutting parameters orthogonal array is introduced. Once the levels of each of the design parameters have been identified, analysis of the influence of grinding parameters on surface roughness and cutting forces has been performed using response table for S/N ratios, which indicates the response at each level of control factors. Response tables are used to simplify the calculations needed to analyze the experimental data. The difference of factor on a response variable is the change in response when the factor goes from its level 1 to level 3. The higher the difference, the more influential the control factor is. The optimum level of cutting parameters can be found from its corresponding S/N ratios

B. Response Surface Method

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that are useful for the modeling and analysis of problems in which a response of interest is influenced by several variables and the objective is to optimize this response.

In most of the RSM problems, the form of relationship between the response and the independent variable is unknown. Thus the first step in RSM is to find a suitable approximation for the true functional relationship between y and a set of independent variables employed. Usually a second order model is utilized in response surface methodology.

$$\widehat{y} = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i} \sum_{j} \beta_{ij} x_i x_j + \varepsilon$$

The β coefficients, used in the above model can be calculated by means of using least square method. The second-order model is normally used when the response function is not known or nonlinear.

IV. Experimental Results

A. Grinding Forces

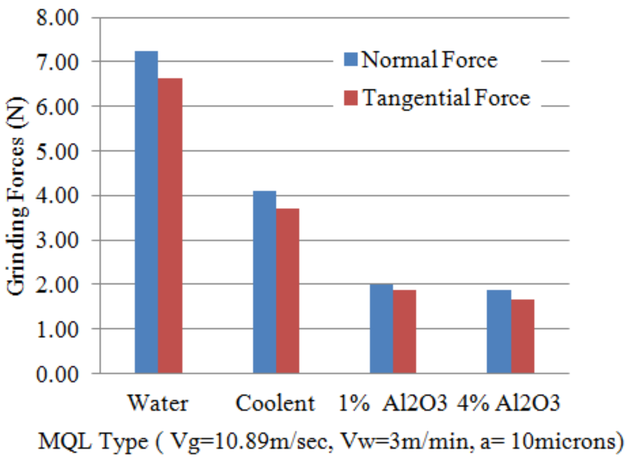

Fig. 2 Grinding Forces results

As can be seen in Figure 2, the grinding forces in the cases of nanofluid MQLs have decreased effectively in both normal and tangential directions. Nano- Al_2O_3 particles have been more effective for reducing grinding forces than the other cutting fluids used under MQL mode. In general, the force reduction in the grinding processes could be attributed to the enhanced lubrication and cooling characteristics shown by the nano cutting fluid. It is also observed that higher concentration of nano particles from 1% to 4% in the fluid has not resulted in reducing the forces. Therefore, it may be assumed that the lubrication effects of nanoparticles may have played more dominant role on the grinding force reduction.

The superior lubrication effects of nanoparticles could be due to the increase of the extreme pressure of the tribo-film and the nanoball bearing effect during the grinding process. Because of an excellent load-carrying capacity of nanoparticles, they could increase the extreme pressure (EP) of the fluid tribo-film and prevent the destruction of the film9. This preservation of the film could result in an appropriate distribution of cutting loads and a low adhesion between the workpiece and tool. As a result, the grinding forces have decreased appreciably.

Table III shows the S/N ratios obtained for different parameter levels. As shown in Table III, the depth of cut is a dominant parameter on the forces followed by table speed. The wheel speed had a lower effect on the forces. Lower normal force is always preferred. The quality characteristic considered in the investigation is lower-the better characteristic. Based on the above discussions and also as evident from Table III, the optimum conditions for the minimum normal force can be established at: Wheel speed (V_g): 21.79 m/sec, Table speed (V_w): 3 m/min, Depth of cut (a): 10µm

TABLE III
S/N Ratio for Normal Force in 4% Al_2O_3 MQL Mode

Level	Vg	Vw	a
1	-18.087	-12.781	-7.583
2	-16.174	-16.100	-19.903
3	-17.251	-22.631	-24.027
Delta	1.912	9.851	16.444
Rank	3	2	1

The second order response surface representing the normal force can be expressed as a function of grinding parameters as follows:

F_n = -31.8300 + (V_g × 0.8773) + (V_w × 6.7456) + (a × 1.3754) – (V_g × V_g × 0.0351) – (V_w × V_w × 0.2779) – (a × a × 0.0379) – (V_g × V_w × 0.1090) + (V_g × a × 0.0395)

B. Surface Roughness

The surface roughness (R_a) of the ground workpiece is presented in Figure 3.In general, MQL grinding using nanofluid has better surface finish than pure water and coolant. The fact that the nanofluid outperforms the pure water can be partly due to the reduction in grinding forces and friction. The nanoparticles could also play a role in dressing the grinding tool during the grinding process. Nanoparticles could tear off the bond material from the wheel and it results in exposure of fresh active grits into the grinding zone.

Similar to the grinding forces, here also based on the S/N ratio table obtained at different parameter level the optimum parameters for minimum surface roughness may be obtained.

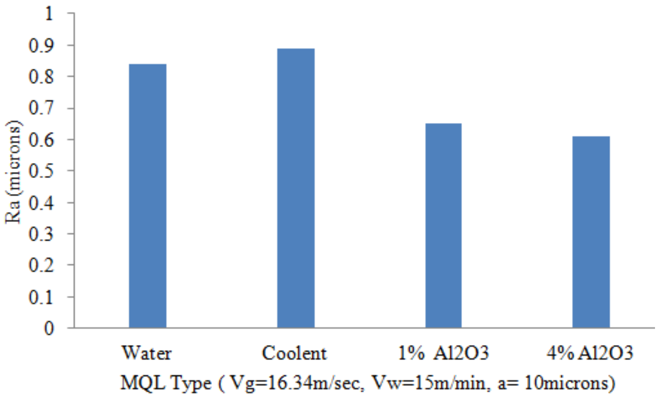

Fig. 3 Surface roughness results

Table IV shows the S/N ratios obtained for different parameter levels.

Here wheel speed and table speed are the dominating parameters. Because in grinding operation the roughness mainly depends on the speed ratios between the wheel and workpiece, the depth of cut had a lower effect on the surface roughness. The optimum conditions for the surface roughness can be established at: Wheel speed (V_g): 21.79 m/sec, Table speed (V_w): 15 m/min, Depth of cut (a): 30µm

TABLE IV
S/N RATIO FOR SURFACE ROUGHNESS IN 4% AL2O3 MQL MODE

Level	Vg	Vw	a
1	8.306	5.470	6.810
2	4.971	7.943	6.217
3	5.592	5.402	5.788
Delta	3.389	2.541	1.022
Rank	1	2	3

The second order response surface representing the surface roughness can be expressed as a function of grinding parameters as follows:

$$Ra = -0.4250 + (V_g \times 0.1219) - (V_w \times 0.0383) - (a \times 0.0030) - (V_g \times V_g \times 0.0036) + (V_w \times V_w \times 0.0031) - (a \times a \times 0.0003) - (V_g \times V_w \times 0.0008) + (V_g \times a \times 0.0009)$$

V. VALIDATION OF DEVELOPED MODELS

To validate the developed model, additional runs of experiments were conducted within the region of exploration with 4% Vol. fraction of Al_2O_3 nano fluid under MQL mode. Table V shows the levels of cutting parameters selected for the validating trials.

TABLE V
LEVELS OF CUTTING PARAMETERS SELECTED FOR VALIDATING TRIALS

Run	V_g	V_w	a
1	10.89	3	10
2	10.89	9	20
3	10.89	15	30
4	16.34	3	20
5	16.34	9	30
6	16.34	15	10
7	21.79	3	30
8	21.79	9	10
9	21.79	15	20

At all these selected combinations of parameters, grinding operation was performed under MQL mode. The obtained cutting forces and surface roughness values in comparison with the predicted values are plotted in Figure 4 and Figure 5. The proposed models show an acceptance level of adequacy since the measured values were in reasonable agreement with the predicted values.

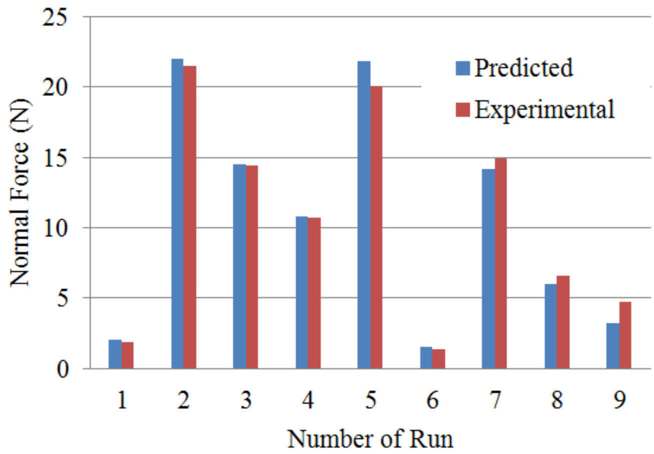

Fig. 4 Predicted and observed force values

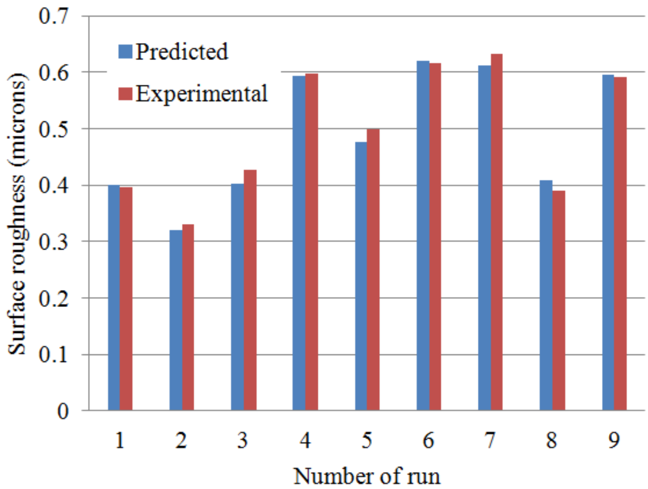

Fig. 5 Predicted and observed surface roughness values

VI. Conclusion

This paper addressed grinding of Ti alloy by nanofluid under MQL mode through a number of experiments. For the nanofluid additives, nano- Al_2O_3 particles were selected after considering their superior tribological properties. In the grinding experiments, the grinding forces and surface roughness were measured in the cases of nanofluid MQL with varying nanoparticles volumetric concentrations. Those results were then compared with those under the conditions of pure MQL with water and coolant. The experimental results showed that nanofluid MQL could significantly reduce grinding forces and enhance surface quality. Regarding grinding forces, nanoparticles in the case of nanofluid MQL were effective for significantly reducing grinding force magnitudes due to their superior lubrication effects rather than their cooling effect. In addition, it was also observed that higher volumetric concentration of nanoparticles were not that effective in reducing grinding forces. Regarding surface roughness, it was also found that nanofluid MQL was effective for reducing surface roughness values of ground work pieces. Nano- Al_2O_3 particles with 4% Vol. concentration seemed to be more effective than others. Finally, the developed models can be used for predicting the cutting forces and surface roughness in MQL grinding of Ti-6Al-4V with nano Al_2O_3 particles based on Taguchi and response surface analysis.

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