Effect of multi-walled carbon nanotubes based nanofluid on surface roughness and cutting temperature in turning operation using minimum quantity lubrication

Rabesh Kumar Singh[1*], Anuj Kumar Sharma[2], Bishwajeet[1], Vimal Mandal[1], Kumar Gaurav[1], Abhishek Sharma[1], Amit Kumar[1], Amit Rai Dixit[1], Amitava Mandal[1], Alok Kumar Das[1]

[1]Department of Mechanical Engineering, Indian Institute of Technology (ISM), Dhanbad 826004, India
[2]Department of Mechanical Engineering, Faculty of Engineering and Technology, SRM University Kattankulathur, Kancheepuram, Tamil Nadu, 603203, India

*E-mail: rasm.singh@gmail.com

Abstract. Suspension of nano-meter sized metallic and non-metallic particles in a conventional fluid is called as nanofluid (NF). The present work investigates the performance of different concentration of multi-walled carbon nanotubes (MWCNT) mixed nanofluid. The nanofluid samples are prepared by suspension of various concentration of MWCNT in a water-based emulsion (95% water + 5% servo cut S oil). Four different process parameters (feed, speed, depth of cut and nanoparticles concentration) has been selected for experimentation. The experiment is designed, and the L27 orthogonal array is selected using Response Surface Methodology (RSM) technique. Furthermore, all the tests are conducted on AISI 304 stainless steel in turning operation using minimum quantity lubrication(MQL) technique. The analysis of variance (ANOVA) is used to analyse the significant effect of process parameter on response (surface roughness and cutting temperature) parameter during turning operation. The experimental result shows that application of MWCNT nanofluid using MQL significantly reduces the surface roughness and cutting temperature.

1. Introduction

In the manufacturing industry, machining is most commonly used process for removing the extra material and getting the desired shape of the product. There are various types of metal removal processes have been used to remove the material in the form of chips due to shearing action between tool and workpiece. Therefore, it is difficult to machine high strength alloys due to the generation of high heat and machining of these materials limits the cutting velocity. The raises in the cutting temperature results in weakening of sharpness of the edge of the cutting tool, which leads to failure of the tool [1]. Therefore, high speed is desirable to achieve the higher productivity and high heat generated at the tool-workpiece interface must be dissipated throughout the machining process to maintain the geometry of cutting tool. Moreover, it is need of cooling and lubrication at chip-tool-workpiece interface to reduce the power consumption and temperature, tool wear. There are a number of researchers have noticed that application of cutting fluid lowers the cutting temperature, surface roughness, cutting forces and improves the tool life. However, it has been noticed that toxic nature of cutting fluid pollutes the environment [2]. During high-speed machining, the cutting fluid gets diffuse in form of vapour and small particles, this leads to severe health problems, such as respiratory

problems, skin diseases and genetic disorder [3]. Moreover, cutting fluid affects the cost of the production, and it covers the 16-20% of the total cost of the manufacturing of the product.

Therefore, an adequate method for cooling and lubrication is required to reduce the excessive use of conventional cutting fluids and overcome the problems of flood machining. Near-dry machining (NDM) or Minimum quantity lubrication(MQL) is the best-suited technique to deliver the small cutting fluid with compressed air at the machining zone [4]. There are several studies proved that application of cutting fluid with MQL, to be a good alternative over flooded lubrication [5]. The spray technique of MQL system is more effective than a flood in case of high-speed machining over low-speed machining [6]. Application of cutting fluid using minimum quantity lubrication technique reduces the tool wear, cutting temperature, cutting forces and surface roughness compared to dry and flood machining [7]. There are many researchers like Heinemann et al. [8] and Kishawy et al. [9] also noticed the same fact that use of MQL technique significantly reduces the tool wear rate, cutting forces and temperature compared to wet machining. MQL technique is capable enough to send the lubricants and coolants at the tool-workpiece interface. Use of coolant with a minimum quantity of lubrication lowers the frictional force between the tool-chip and tool-workpiece interfaces [10]. Therefore, a new cutting fluid is required which have higher thermo-physical and lubrication properties [11, 12]. Suspension of nano-sized solid metallic and non-metallic particles in base fluid enhanced the heat carrying capacity of conventional fluid [13]. However, use of micro-sized particles can cause some serious problems like clogging and drop in pressure in pipelines of the nozzle. Sharma et al. [14, 15] noticed that addition of molybdenum disulphide (MoS_2) and GnP in water-based emulsion enhanced the thermal conductivity. Marquis and Chibante [16] noticed that addition of 1 vol. % of CNT increases the thermal conductivity by 175% as compared to base fluid. Yang et al. [17] reported that addition of MWCNT in base fluid increases the thermal conductivity up to 200%. Saidur et al. [18] noticed an enhancement in the thermal conductivity of nanoparticle mixed cutting fluid over base fluid. Few researchers like Sharma et al. [19] and Singh et al. [20] concluded that thermal conductivity and density of the base fluid could be improved by adding nanoparticles to base fluid. Krishna et al. [21] noticed that use of nano boric acid (NBA) blended nanofluid reduced the flank wear, cutting temperature and surface roughness. Furthermore, Roy and Ghosh [22] noticed that the application of 3 vol. % of Al_2O_3 and 1 vol. % of MWCNT nanofluid significantly reduce the cutting forces and specific energy during grinding operation. Few researchers, working on the blending of the two or three nanoparticles, to get the combined effect of both properties. Singh et al. [23] noticed that application of alumina and graphene (90:10) water-based hybrid nanofluid performs better as compared to single alumina-based nanofluid during turning operation.

In the present paper, different samples of nanofluid are prepared by mixing of MWCNT in the base fluid (5% servo cut "S" oil by volume in water). Three concentrations (0.2, 0.6 and 1 wt.%) of nanofluid are considered to conduct the experiments. Experimental design and regression models are developed by response surface methodology(RSM) technique using design expert 10 software. All the experiments are conducted on the AISI 304 stainless steel in turning operation (NH 22 Lathe, HMT, India) using coated carbide tool inserts. Machining performance of MWCNT mixed nanofluid using the minimum quantity of lubrication is analysed in terms of cutting temperature and surface roughness.

2. Experimental Detail

For the experiment, the water-based emulsion was prepared with the addition of 5% servo cut S oil with 95% of deionized water. Three samples of MWCNT mixed nanofluids were prepared by addition of three different concentration (0.2, 0.6, 1 wt.%) in the base fluid. Ultrasonic vibrator and magnetic stirrer are used, to get the uniform dispersion of MWCNT in a water-based emulsion. The frequency of ultrasonic vibrator (Toshiba, India) was in the range of 36 ± 3 kHz. MWCNT are highly hydrophobic, so it is hard to get the uniform dispersion of nanoparticles in base fluid. Therefore, surfactant Cetyltrimethylammonium bromide (CTAB) is added to the base fluid to avoid agglomeration of nanoparticles in base fluid. Ultrasonication is repeated, and mechanical mixing is also performed again and again. Before the experiments, fresh samples of nanofluids were prepared with ultrasonication to conduct the new experiments.

Table1. Illustrates the details of experimental setup, workpiece and tool material used in the experiment.

Workpiece dimension	Ø 70 mm × 300 mm
Machine tool	Lathe (HMT, India)
Cutting tool	Uncoated cemented carbide tool inserts
Cutting fluid	Water based emulsion (95% water + 5% Servo Cut S oil) + MWCNT nanotubes (0.2, 0.6, 1.0 wt.%)
MQL unit	Multi-viscosity single nozzle unit (Unist coolube, USA)
Temperature measurement	NI-USB TC01 device (K-type thermocouple)
Surface analyser	Mitutoyo Surftest SJ-210

In this paper, experiments were performed with Multi-walled carbon nanotubes (MWCNT) mixed nanofluid using MQL technique. The workpiece material AISI 304 stainless steel, hardened (29HRC), hardness (annealed) 82HRB was selected for machining using tungsten carbide tool (CCMT09T304-TN2000), and a tool holder (WIDAX SCLCR1212F09 D 3J). The initial dimension of the workpiece was 70 mm x 300 mm. K-type thermocouple with NI TC01 device was used to record the cutting temperature during experiments. Fig.1 illustrates the complete experimental setup used in turning operation.

(a)   (b)

Figure 1 (a) Different parts of the experimental setup (b) Enlarge view of cutting zone with the nozzle.

In present experimental setup k-type thermocouple was clamped 4 mm below the rake face of tool insert inside the tool holder. USB TC01(manufactured by national instruments) is used to connect the K-type thermocouple to the computer. USB TC01 consists of DAQ, which is used to collect data with a time gap of 1 second during machining. Mitutoyo surftest SJ-210 is used to measure the surface roughness after each turning operation. The function of MQL system was used to supply the nanofluid at cutting zone. The flow rate for nanofluid supplied by MQL was kept constant (50ml/hr) throughout the experiments. The nanofluid was supplied at constant pressure at 4 bar with 50 mm standoff distance from the rake face of the tool insert.

Table 2. Illustrates the controlled parameters and their levels during experiment

S.NO	Input Parameters	Notation	Level1	Level2	Level3
1	Cutting speed(mm/min)	Vc	40	90	140
2	Feed rate (mm/rev)	f	0.08	0.12	0.16
3	Depth of cut(mm)	d	0.6	1.0	1.4
4	Conc. Of nanoparticles (wt.%)	C	0.2	0.6	1.0

3. Results and discussion

The experiments were performed three times, and the average of values of response outputs are recorded for analysis. In the present experiment, cutting temperature and surface roughness is taken as response outputs. Response surface methodology is performed to investigate the influence of the concentration of MWCNT as well as cutting velocity, feed rates and depth of cut on the output

parameters. Regression models were developed to analyse the interrelation between variable parameter on surface roughness and cutting temperature.

3.1 Surface Roughness

A variance of analysis (ANOVA) of the surface roughness (Ra) was used to analyse the contribution of cutting speed, feed rate, and depth of cut and wt.% of MWCNT. Table 3 shows the results of ANOVA for surface roughness a confidence level of 95% (significance level is 5%). After analysing it suggests that cutting force is highly influenced by V_c, f, d and wt.% of MWCNT nanoparticles.

Table 3. Results of ANOVA for surface roughness

Source	Sum of Squares	DF	Mean sum of Square	F-Value	P-Value	
Model	2.86	14	0.20	8.61	0.0003	
A-V_c	0.22	1	0.22	9.29	0.0101	Significant
B-f	0.13	1	0.13	5.48	0.0374	Significant
C-d	1.15	1	1.15	48.43	< 0.0001	Significant
D-C	0.49	1	0.49	20.63	0.0007	Significant
AB	0.011	1	0.011	0.46	0.5097	not significant
AC	0.18	1	0.18	7.77	0.0164	Significant
AD	1.537E-003	1	1.537E-003	0.065	0.8034	not significant
BC	0.24	1	0.24	10.09	0.0080	Significant
BD	0.019	1	0.019	0.80	0.3888	not significant
CD	0.067	1	0.067	2.81	0.1197	not significant
A²	2.326E-004	1	2.326E-004	9.806E-003	0.9228	not significant
B²	0.30	1	0.30	12.70	0.0039	Significant
C²	0.059	1	0.059	2.48	0.1416	not significant
D²	0.012	1	0.012	0.52	0.4843	not significant
Residual	0.28	12	0.024			
Lack of Fit	0.21	10	0.021	0.56	0.7809	not significant
Pure Error	0.075	2	0.037			
Cor. Total	3.14	26				

Final equation for regression model of surface roughness with respect to process parameters is given in Eq.1.

$$R_a = 0.35095 + 0.010415 * V_c - 17.53570 * f + 1.77833 * d - 0.057959 * C + 0.026166 * V_c * f - 0.010732 * V_c * d - 0.000980250 * V_c * C - 15.28906 * f * d - 4.30391 * f * C + 0.80650 * d * C + 0.00000264183 * V_c^2 + 148.55599 * f^2 + 0.65594 * d^2 + 0.30085 * C^2 \qquad \text{Eq. (1)}$$
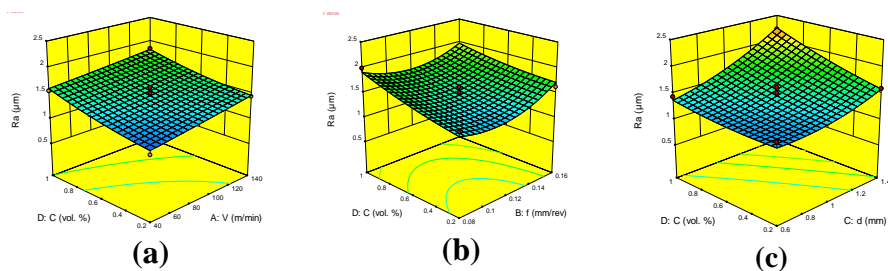

(a)   **(b)**   **(c)**

Figure 2 (a-c) shows the 3D surface plots for surface roughness with respect to feed, speed, depth of cut and concentration of nanoparticles.

In Fig 2(a) shows the surface and contour plots of surface roughness with a concentration of MWCNT and cutting velocity. As the concentration of nanoparticles increases the surface roughness also increases. Furthermore, Fig 2 (b) show less variation in the surface roughness with respect to feed rate and concentration of nanoparticles. Similarly, depth of cut did not have any impact, but a lower concentration of nanoparticles improves the surface finish. Less change in the surface roughness was observed for lower values of cutting velocity and feed. Furthermore, a higher concentration of

MWCNT nanoparticles reduces the surface roughness, due to a reduction in the coefficient of friction between the tool-workpiece interface.

3.2 Cutting Temperature

The variance of analysis of cutting temperature was made to analyse the influence of cutting speed, feed rate, and depth of cut and wt. % of MWCNT nanoparticles. Table 4 shows the results of ANOVA for cutting temperature at a confidence level of 95% (significance level is 5%). The analysis shows that cutting temperature is highly influenced by V_c, f, d and wt. % of MWCNT nanoparticles.

Table 4. Results of ANOVA for cutting temperature

Source	Sum of Squares	DF	Mean sum of Square	F-Value	P-value	
Model	1193.74	14	85.27	29.60	< 0.0001	
A-V_c	34.61	1	34.61	12.02	0.0047	significant
B-f	233.20	1	233.20	80.95	< 0.0001	significant
C-d	759.07	1	759.07	263.51	< 0.0001	significant
D-C	16.38	1	16.38	5.69	0.0345	significant
AB	0.053	1	0.053	0.018	0.8945	not significant
AC	46.92	1	46.92	16.29	0.0017	significant
AD	7.02	1	7.02	2.44	0.1444	not significant
BC	13.62	1	13.62	4.73	0.0504	not significant
BD	15.60	1	15.60	5.42	0.0383	significant
CD	15.92	1	15.92	5.53	0.0367	significant
A²	13.77	1	13.77	4.78	0.0493	significant
B²	3.42	1	3.42	1.19	0.2973	not significant
C²	17.39	1	17.39	6.04	0.0302	significant
D²	0.22	1	0.22	0.075	0.7884	not significant
Residual	34.57	12	2.88			
Lack of Fit	33.36	10	3.34	5.53	0.1628	not significant
Pure Error	1.21	2	0.60			
Cor. Total	1228.31	26				

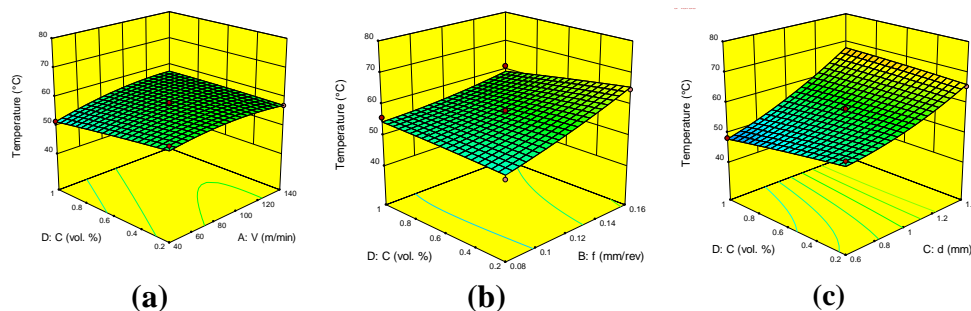**(a)**   **(b)**   **(c)**

Figure 3 (a-c) shows the 3D surface plots for cutting temperature with respect to feed, speed, depth of cut and concentration of nanoparticle.

Final equation for regression model of cutting temperature with respect to the cutting parameter is given in Eq. 2.

$$T = 8.18869 + 0.28805 * V_c + 184.63333 * f + 19.07917 * d - 5.02708 * C) - 0.057500 * V_c * f - 0.17125 * V_c * C - 115.31250 * f * d - 123.43750 * f * C + 12.46875 * d * C - 0.000642667 * V_c{}^2 + 500.52083 * f^2) + 11.28646 * d^2 - 1.26042 * C^2$$ Eq. (2)

Results of the analysis show the lower values of temperature was obtained at low cutting speed, feed rate and depth of cut. Fig 3 (a) indicates that increase in the concentration of nanoparticles reduces the cutting temperature. Similar, trend was obtained with combinations of depth of cut and feed with a concentration of nanoparticles. Furthermore, from all plots, the same pattern of decrease in the cutting temperature was observed at the increase in the nanoparticles concentration.

4. Conclusion

In present work, three different concentration (wt.%) of MWCNT mixed nanofluid was prepared. The effect of nanofluid on turning operation was analysed. Response surface methodology (RSM) was used to develop the regression model effects, and effect of concentration (wt.%) of MWCNT nanoparticles mixed in a base fluid with other parameters like cutting speed, feed and depth of cut was analysed on surface roughness and cutting temperature.

1. Application of MWCNT-based nanofluid MQL influenced the cutting conditions on different response outputs under MQL, and it can be noticed that higher concentration of MWCNT nanofluid reduces the cutting temperature at lower values of cutting speed, depth of cut and feed rate.
2. Similarly, the lower surface roughness of the work material was recorded at lower values of concentration of MWCNT nanofluid, cutting speed, feed rate and depth of cut.
3. It is observed that concentration of MWCNT nanoparticles along with other machining parameters is affecting the surface finish and cutting temperature.

Acknowledgements

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