Experimental Investigations in Turning of Vacuum Grade Molybdenum using Various Sustainable Cooling Strategies

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Abstract

The refractory nature of molybdenum qualifies the metal to be best used in the microwave tubes and many electronic assemblies. But being manufactured by the powder metallurgical methods makes molybdenum machining difficult. Very little research is attempted to address the issues and leaves large scope for increasing the surface finish by adopting various sustainable cooling strategies. The conventional trichloroethylene is readily used because of the better heat transfer rate and thus better surface finish. The performance of the conventional fluid is compared with bio-degradable oils and nano fluids. Nano fluid is prepared using copper Nano particles of 40nm size and base fluid as Rapeseed oil by Sonication Method. Nano fluid is characterized for thermal stability by conducting three specific tests 1) Thermal conductivity tests by Interferometry method 2) Dispersion test by DLS Method 3) Viscosity Tests by Redwood Viscometer Method. The experiments were carried out separately using Taguchi DOE Technique for three different Cooling Strategies - Copper Nano fluid, Rapeseed oil and Trichloroethylene. Chip morphology study is done for all 3 cooling strategies and conclusions are drawn. Tool tip temperature is captured using thermal infrared camera. Nano fluid had increased thermal conductivity up to 7.5 times in comparison with Base oil. Dispersion test conducted by DLS Method proved the fluid stability with poly dispersity index of 0.05 indicating the fluid to be mono suspension. Viscosity tests proved that the fluid is less viscous when compared to Base oil. Chip morphology studies indicated that working at lower cutting speed with reduced feed rate resulted in improved surface finish for all the three cooling fluids.

Keywords: Nanofluid, Nanofluid characterization, Heat transfer, Sustainable Manufacturing, Chip Morphology, Viscosity, DLS Method, Surface Finish, Powder Metallurgy, Taguchi method.

1. INTRODUCTION

The modern manufacturing industries are aiming to produce the components with reduced cost and maintain high standards in terms of quality, time to market and ease in assembly methodology. Focus is on the estimation of process parameters that will yield the desired quality (meet specific requirements) and subsequently upgrade production frame work towards efficient utilization of the assets. Surface finish is important requirement for all machined components used in electronics considering various requirements like EMI/EMC. Molybdenum also finds applications in Microwave components, Nuclear power plants and Microwave tubes for Radar application. The refractory nature of this metal with creep resistance at high temperature and low coefficient of thermal expansion aids in above applications. The research in molybdenum machining especially turning which is the major machining technique has not been explored. Various researchers have contributed immense literature in machining of material like titanium which caters for many industrial applications. Surface roughness studies have been carried out for this material and sustainable manufacturing techniques were employed. This study focuses mainly on sustainable manufacturing. In Japan very high consumption and disposal costs were recorded [3]. An estimate suggests that almost 16% of the total manufacturing costs are comprised of cutting fluid costs and when it comes to the machining of hard materials, they reach up to 20-30 percent [3].The toxic nature of chlorine and sulphur used as additives in existing cutting oils pose great threats to operator involved in machining process and to the environment during disposal of the same. R.Padmini et.al [1] studied the application of effectiveness of vegetable oil based nano fluids as potential cutting fluids in turning AISI1040 steel. 5% of Molybdenum Di Sulphide is found to reduce cutting forces, cutting temperatures, tool wear and surface roughness compared to all other lubricating conditions. Molybdenum di sulphide as Nano particle and coconut oil as base oil gave best results for reduced surface roughness. E.Abboud. et.al [2] studied effects of residual stresses and surface integrity in Titanium alloys during finish turning. Based on microstructure studies, best Ra value can be achieved with cutting speed of 20m/min, feed rate 0.05m/min, corner radius of tool-1.6 mm, depth of cut-0.1mm. Syed Waqar Raza. et.al [3] studied tool wear patterns in turning of Titanium alloy using sustainable lubrication strategies. They used rapeseed vegetable oil in MQL and MQCL configuration. Inference was made that by using vegetable oil as a lubricant for machining, at high speed, lower feed yielded better surface finish and promoted sustainable manufacturing. G.M.Sayeed Ahmed et.al [4] Optimized feed and radial force in turning process by using Taguchi design approach. He used L9 taguchi orthogonal array to optimize cutting speed, feed and depth of cut to machine mild steel. Paper mainly focused on conduct of Design of Experiments and ANOVA. V.Krishnaraj et.al [5] investigated high speed turning of Titanium alloys concluded that best surface roughness was achieved at temperature of 347° C with 8° rake and reduced feed rate of 0.1mm. Positive rake angle gives better results for tool life enhancement.

2. EXPERIMENTATION

2.1 Preparation of Nano-fluid

Copper Nano Fluid is prepared by sonication process both by magnetic stirring and by regular sonication upto 3hours. Copper nano particle weighing 5 gm was purchased from Plasmatech GMBH. Concentration of nanoparticle considered for fluid preparation is 0.5% of volume of base oil. Rapeseed oil about

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900ml is utilised in preparation of fluid [1, 3, 6]. The mixture is prepared by adding oleic acid as surfactant. Percentage of surfactant used was 1gm per 100ml of prepared Nano fluid. Physical properties of solute and solvent are given in table 1 and table 2 respectively.

Table 1. Physical properties of Nano Particle

Sl. No.	Properties of copper nano powder	Specified values
1	Size of Nano particle	40 nm
2	Stabilizing agent	Oleic acid
3	Density @ 20^0C	8.9 gms/cm3

Table 2. Physical properties of Rapeseed oil

Sl. No.	Properties of Rapeseed oil	Specified values
1	Kinematic viscosity (@ 20^0C	78.2 mm2/sec
2	Density @ 20^0C	0.917gms/cm3
3	Thermal conductivity	0.179 – 0.188 W/mK

2.2 Characterisation of Nano fluid

The Nano fluid is characterised for thermal properties such as thermal conductivity which is an important parameter for heat transfer. Physical properties such as viscosity and dispersion are measured for proving the stability of the prepared nano fluid. Thermal conductivity is measured using ultrasonic aided interferometry technique. Fig-1 shows the thermal conductivity measurement set-up used for thermal conductivity measurements of copper nano fluid. Dispersion is measured by dynamic light scattering Method. The equipment used for measuring Poly dispersity index by DLS Method is shown in Fig-2. Viscosity is measured by Redwood viscometer method. Fig-3 represents the redwood Viscometer used for viscosity measurements. Thermal conductivity increased by 7.5 times of base oil. Results of the DLS tests on Nano fluid proved the suspension to be mono dispersed. The thermal conductivity for nano fluid prepared is 1.45 w/m/k and base oil is 0.188 w/m/k, viscosity measured is 73 mm²/s for base oil against 62mm²/s for copper nano fluid. The dispersion value (PDI) is 0.053 which indicate mono suspension as per referred literature.

2.3 Preparation of work-piece

Molybdenum is first rough turned and finished to a size of Ø 37 mm up to a length of about 370mm. Grooves were made between successive sample lengths of 7 mm for conducting 27 experiments. Schaublin125CCN CNC Lathe shown in Fig-4 was used in the experiments for finishing operation. MQL set-up was manually created by hand held pump with a nozzle, flow rate was not measured during experiment. A 370 mm long specimen was cut into 3 parts (123 mm long each) to carry out nine experiments. Each rod was held between centres in the lathe to reduce overhang and the surface was rough turned initially before final finishing. L/d ratio worked out to be around 3.3. Cutting tool used was unground brazed carbide tool of Sandvik make with tool signature of ISO6R1616K20.

Fig-1 Thermal Conductivity Measurement Set-up

Fig-2 Malvern Nano ZS 90 Dispersion Measuring instrument.

Fig-3 Redwood Viscometer

Fig-4 Finishing operation in Schaublin 125CCN CNC lathe

3 DESIGN OF EXPERIMENTS

Taguchi's orthogonal array L27 was chosen for full factorial experiments as it gave better results compared to L9 array. The experiments totally 54 were conducted, 27 experiments each for Nano fluid and Rapeseed oil as cutting fluid. The 27 experiments are the combinations for the 3 parameters and are summarized in table -5

Table 3. Details of Work-Piece

Material.	Molybdenum
Diameter	37 mm
Length	123 mm x 3 Nos (370 mm)
Number of experiments	27
Sample length/experiment	7 mm

Table 4. Details of Cutting tool

Material.	Brazed carbide uncoated turning tool
Front rake angle	3^0 to 3.5^0
Back rake angle	1^0 to 2^0
Nose radius	0.2 mm
Tool make	Sandvik coromant

Table 5. Design of experiments vs chip profile

Experiments	Cutting speed	Feed	Depth of cut	Remarks (chip formation)	
	m/min	mm/rev	mm	Nano fluid	Rapeseed oil
1	45	0.03	0.3	powder form	powder form
2	45	0.03	0.4	powder form	powder form
3	45	0.03	0.5	powder form	powder form
4	45	0.04	0.3	powder form	powder form
5	45	0.04	0.4	powder form	powder form
6	45	0.04	0.5	powder form	powder form
7	45	0.05	0.3	powder form	powder form
8	45	0.05	0.4	powder form	powder form
9	45	0.05	0.5	powder form	powder form
10	104	0.03	0.3	powder form	powder form
11	104	0.03	0.4	powder form	curly striped chip
12	104	0.03	0.5	powder form	curly striped chip
13	104	0.04	0.3	powder form	curly striped chip
14	104	0.04	0.4	powder form	curly striped chip
15	104	0.04	0.5	powder form	Curly striped chip
16	104	0.05	0.3	curly striped chip	curly striped chip
17	104	0.05	0.4	curly striped chip	curly striped chip
18	104	0.05	0.5	curly striped chip	curly striped chip
19	159	0.03	0.3	curly striped chip	curly striped chip
20	159	0.03	0.4	curly striped chip	curly striped chip
21	159	0.03	0.5	curly striped chip	curly striped chip
22	159	0.04	0.3	Curly striped chip	Curly striped chip
23	159	0.04	0.4	curly striped chip	curly striped chip
24	159	0.04	0.5	curly striped chip	curly striped chip
25	159	0.05	0.3	curly striped chip	curly striped chip
26	159	0.05	0.4	curly striped chip	curly striped chip
27	159	0.05	0.5	curly striped chip	curly striped chip

4 RESULTS AND DISCUSSION

Minitab 17 statistical software was used for conducting DOE. Table-6 represents the factors considered for experiments at 3 levels. Response parameter which is surface roughness is measured using SURFCOM Roughness tester which is stylus based measuring equipment. Roughness value (Ra) is measured for all the experiments. Taguchi's design is analyzed for Response Parameter with interactions between factors. S/N plot for smaller the better option is selected, since the response should be minimum for the two cutting fluids. S/N ratio Plots are depicted in Fig-5 and Fig-6. Surface finish is better for both Nano fluid and base oil at lower cutting speed of 45m/min from the main effect plot. But lower surface finish of Ra 0.95 was achieved with copper nano fluid against Ra 1.059 achieved with base oil for a given cutting speed.

Table 6. Factors and Levels in Experiments

Factors	Process parameters	Level 1	Level2	Level3
V	Cutting speed (m/min)	45	104	159
F	feed rate(mm/rev)	0.03	0.04	0.05
D	Depth of cut (mm)	0.3	0.4	0.5

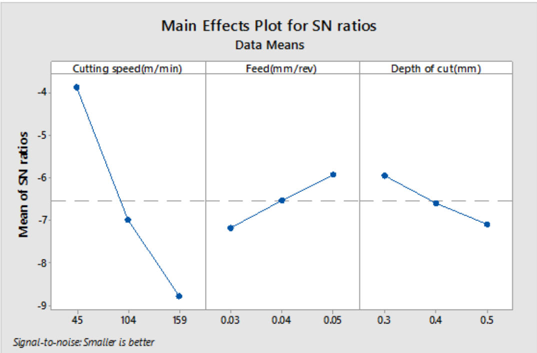

Fig-5 S/N Ratio Plot of Factors for Copper Nano Fluid

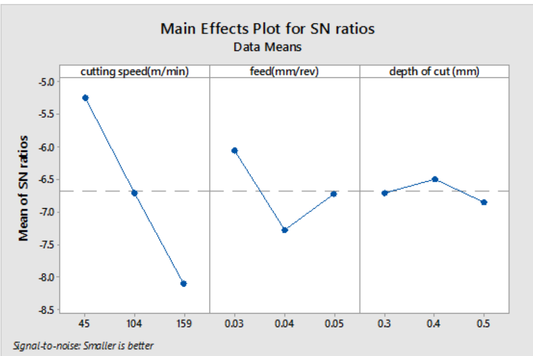

Fig-6 S/N Ratio Plot of Factors for Rapeseed oil

4.1 Analysis of variance (ANOVA)

Analysis of Variance is conducted to identify the key parameter /factor affecting the response. The optimised machining process parameters for copper nanofluid are cutting speed of 45 m/min and feed 0.05mm/rev, depth of cut 0.3mm. Similarly, optimised machining process parameters for Rapeseed oil are cutting speed of 45 m/min and feed 0.03mm/rev, depth of cut 0.4mm. The most dominant factor affecting surface roughness for copper nano fluid is cutting speed followed by depth of cut and subsequently feed. The most dominant factor affecting surface roughness for Rape seed oil is cutting speed followed by feed and subsequently depth of cut.

4.2 Regression Analysis

Regression equation is plotted for the response parameter and variation of theoretically calculated surface roughness to experimental value is between 3 to 6 %.

4.3 Chip Morphology Studies

The temperature of the tool tip is measured using fluke make infrared thermal camera. The temperatures for each trial and chips generated during trials are collected. Chips generated during machining are studied using optical microscope with magnification of 100x. The images captured by video camera unit fitted along with microscope are given in Fig-7.

4.3.1 Observations

Chips in powder form is obtained for nano fluid and rape seed oil for cutting speed of 45 m/min, depth of cut 0.3mm, 0.4mm, 0.5mm and feed of 0.03 mm/rev, 0.04 mm/rev, 0.05 mm/rev (first fifteen experiments for Nano fluid and first ten for rapeseed oil). The temperature measured is between 49°C to 74°C for nano fluid as coolant and temperature between 42°C to 54°C for Rapeseed oil. Though the thermal conductivity of the nano fluid is higher than the rapeseed oil the temperatures measured are higher in case of nano fluid due to the fact that the infrared camera could be focused only of the flowing cutting fluid rather than the tool or the specimen as the fluid covers the entire cutting zone. Thus only the temperatures of the fluid are measured and the higher thermal conductivity fluid has indicated higher temperatures due to better heat transfer from the cutting zone. The small curly chips obtained for both nano fluid and rape seed oil for cutting speed of 104m/min, depth of cut 0.3, 0.4, 0.5 and feed of 0.03, 0.04, 0.05 (16th to 20th experiments for nano fluid and 10th to 18th for Rapeseed oil). The temperature measured is between 57°C to 62°C for Nano fluid and temperature between 50°C to 56°C for rapeseed oil. The nature of the chip is predominantly governed by the molybdenum material properties and manufacturing (powder metallurgy). The surface finish is better at lower cutting speed (45m/min) for both Nano fluid and rapeseed oil. However, powdery chips were formed for both copper nano fluid and base oil at lower cutting speed of 45 m/min. This indicates that both the fluids are effective only at lower cutting speeds and rough surface was observed at 104 m/min and 159 m/min with a striped curled chips depicted in Fig-7.

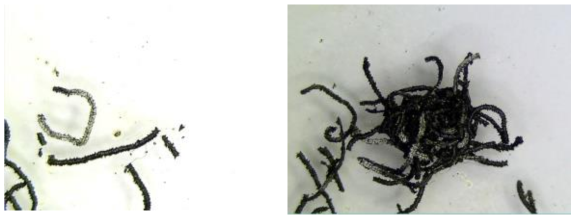

Fig-7 Curly striped chip formation

Table 7. Summary of Ra obtained from various fluids vs requirement

Cooling strategy	Best Ra achieved	Requirement for microwave component
Nanofluid	0.95	< 1.5μm
Rapeseed oil	1.059	
Tri-chloro ethylene	0.73	

5 CONCLUSIONS

Experimental studies of Molybdenum turning with three cooling strategies suggest that Copper Nano fluid and Rapeseed oil can be used as an alternate to Tri Chloro Ethylene, as the Surface Finish requirement in Microwave Component Manufacturing of Ra less than 1.5μm is met (table – 7). Nano fluid prepared had increased thermal conductivity up to 7.5 times when compared to base oil. Dispersion test conducted by DLS method proved the fluid stability with poly dispersity index of 0.053 proving the fluid to be Mono suspension. Viscosity tests prove that fluid is less viscous compared to base oil. The process parameters for turning molybdenum are optimized. Analysis of variance (ANOVA) results indicate that feed is significant factor affecting surface finish with a contribution of 54.69% in case of Copper Nano fluid. Cutting speed is significant factor respectively for both Rapeseed oil and Tri chloro ethylene with percentage contribution of 58.85% and 49.56%. Regression Analysis shows that the variation from experimental results to the theoretical results to be 9% for Copper Nano fluid, 5.5% for Rapeseed oil and 2.55% for Tri chloro ethylene. Chip morphology studies indicate that working in lowest cutting speed with decreased feed rate resulted in improved Surface finish for all the three cooling strategies. Sustainable cooling with MQL technique has served the dual purpose firstly the surface finish requirement and secondly an alternative solution to replace existing hazardous chemical Tri Chloro Ethylene. The main motive for the work was to replace ecologically unfriendly cutting fluid of Tri-chloro ethylene without compromising the criterion of surface finish with Ra of less than 1.5 microns for microwave components.

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