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Minimum Quantity Lubrication (MQL) Assisted Machining of Grade-4 Titanium

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Abstract

This paper presents the results of an experimental investigation for turning of Grade-4 titanium with carbide cutting tool inserts with minimum quantity lubrication (MQL). Experiments were designed based on Taguchi's L_9 orthogonal array. The MQL parameters of flow rate (50-70-90 mL/hr); nozzle distance (20-30-40 mm) and air pressure (4-5-6 bar) were varied for three different levels each. Cutting speed, feed and depth of cut were fixed at 125 m/min; 0.2 mm/rev and 1 mm respectively. The grey relational method in conjunction with the Taguchi technique was used for optimizing the MQL parameters. The nozzle distance was recognized as the most significant parameter. The data further indicated that the optimum MQL parameters were a flow rate of 70 mL/hr, nozzle distance of 30 mm and air pressure of 6 bar. When compared to dry and wet cutting conditions MQL was shown to have significant advantages.

Keywords

Minimum quantity lubrication, Green machining, Taguchi robust design, Tool wear

1 INTRODUCTION

Environment awareness is of utmost importance to all socially responsible manufacturers. In order to ensure global competitiveness, manufacturers need to comply with various strict environmental regulations. To maintain economic growth and product quality while adhering to these regulations entails the adoption of sustainable manufacturing techniques. These techniques include; optimizing the machining process parameters; appropriate tool geometry, material and/or coating; employing advanced and hybrid machining processes; and using advanced lubrication/cooling techniques such as minimum quantity lubrication (MQL), cryogenic cooling and dry machining etc [1-3]. The effective utilization of these techniques may assist to achieve resource, energy and cost efficiency while simultaneously addressing environment concerns such as sustainability and pollution.

The 'wonder metal' titanium and its alloys are extensively used for specialized applications in aerospace, medical and general industry because of its superior strength to weight ratio, exceptional corrosion and erosion resistance, bio-compatibility, high fatigue strength and attractive mechanical properties [4, 5]. Commercially pure titanium Grade-4 is a promising material for biomedical applications especially dental implants. Many of its applications require significant machining. It is however generally regarded as a difficult to machine material because of certain inherent properties. These are briefly summarized as: a low thermal conductivity that inhibits heat dissipation within the machining zone and therefore creating high thermal gradients which leads to rapid tool wear and in some cases catastrophic tool failure; a low elastic modulus (effectively 50% of steel) implying large deflections of the workpiece during machining and thereby increases chatter, vibration and rubbing leading to elevated temperatures which in turn may cause poor surface finish; the high chemical reactivity especially at elevated temperatures leads to tool-workpiece interactions such as localized adhesion implying increased wear, chipping and eventually tool failure [5, 6].

The problem of tool failure during machining can be addressed primarily in two ways; careful selection of appropriate tool material, geometry and coating and/or employing a suitable lubrication/cooling technique with appropriate lubricant (cutting fluid).

The use of large amounts of mineral-based harmful cutting fluids during traditional cooling i.e. flood or wet cooling techniques may adversely impact the environment because it may lead to increased ground contamination, implies increased energy consumption, increased wet chip handling and waste disposal, and may increase potential health and safety issues [7, 8]. To address these issues, there has been a steadily increasing interest in performing machining operations dry or near-dry. Minimum quantity lubrication (MQL) is a micro-lubrication technique that facilitates near-dry machining [8, 9]. Micro-lubrication implies the elimination of large quantities of water and mineral oil-based cutting fluids and replacing them with a small quantity of lubricant (10-200 mL/hr flow rate) mixed with and transported by air. Vegetable oils, synthetic esters and fatty alcohols are typically used as lubricant which is mostly environmentally friendly and biodegradable and therefore also less harmful to humans during use. Moreover, supplying a small amount of cutting fluid consumes less power and thus reduces the cost of machining also. The main benefit of MQL is that it primarily focuses on improving the frictional behaviour therefore controlling the heat generation at its source rather than just trying to remove as much heat as possible such as conventional cooling does. This results in improved tool life and good workpiece surface integrity. Metal chips produced during MQL machining are nearly dry and are easy to recycle [8-10].

However, the machinability and part quality (in case of titanium also) depends largely on optimizing the MQL process parameters that includes the type and flow rate of the lubricant and nozzle position and pressure [11-14].

This paper reports some preliminary investigations based on the effects and selection of optimum MQL parameters namely flow rate, nozzle distance and air pressure for further detailed research work while turning Grade-4 titanium at different combinations of machining parameters (i.e. cutting speed, feed and depth of cut).

Surface roughness of the workpiece, power consumption during machining, and tool (flank) wear were considered as indicative of machinability.

The main objectives of this research work are:

1. To investigate the effect of MQL process parameters on the machinability of Grade-4 titanium.

2. To identify the levels at which certain MQL process parameters are to be fixed for subsequent experimentation.

3. To find the optimal combination of input process parameters for obtaining improved machinability indicators (multiple responses).

Experiments were designed and conducted based on *Taguchi's robust design* of experiments method and utilizing the L_9 orthogonal array. The statistical *grey relational analysis* technique was employed to perform optimization. In addition, this research is also accompanied by a limited comparative study indicating the advantages of MQL when compared to dry and wet cutting when machining Grade-4 titanium.

2 TAGUCHI METHOD AND GREY RELATIONAL THEORY

The Taguchi method [15-17] is a variance reduction technique which can improve the quality of a system at minimum cost. An orthogonal array (OA) is used to reduce the number of experiments which will have time and cost benefits. In the present case based on the three response parameters each having three levels, L_9 OA was chosen which cut down the number of experiments from 27 (3^3-Full Factorial design) to 9. It is important to ensure that the resultant functionality resembles as closely as possible the ideal function. It is therefore crucial to develop a means for measuring the deviation between the actual and the ideal cases. Hence, Taguchi employs signal to noise (S/N) ratio to measure the performance of the process response. S/N ratio being the ratio of mean to standard deviation that can effectively consider the variation encountered in a set of trials. Again based on the objective of the experiment, S/N ratio characteristics can be categorized into three criteria: lower-is-better (LB), higher-is-better (HB) and nominal-is-best (NB).

As one of the main objectives of the present research work was to determine the machining conditions required to obtain improved machinability in terms of minimum surface roughness of the workpiece, least power consumption and lowest tool wear in the turning of Grade-4 titanium. Therefore, the quality characteristics of lower-is-better was implemented for all the above stated response parameters. The S/N ratio of the lower-is-better characteristic can be expressed as follows:

$$S/_N = -10 \ \log\left(\frac{1}{n}\sum\frac{1}{y_{ij}^2}\right) \qquad (1)$$

Where y_{ij} is the observed data i.e. response of ith trial of jth dependent level and n is the number of observations for a particular experimental combination or simply called experimental replication.

Grey relational analysis based on the grey system is a statistical technique to solve multi response optimization problems. The grey system theory was first proposed by Deng in 1989 [18]. Afterwards, he also proposed grey relational analysis (GRA) in the grey theory that was proved to be an accurate method for multiple attribute decision making problems. The GRA method is based on the minimization of maximum distance from the ideal referential alternative. The aim of GRA is to investigate the factors that affect the system. The method is based on finding the relationships of both independent and interrelating data series. By finding the GRA mathematically, the grey relational grade (GRG) can be used to evaluate the relational level between referential series and each comparative series. This analysis consists of the following steps [18-20]:

Step 1: Transform the responses into the S/N ratio using the appropriate equation depending on the quality characteristics.

Step 2: Normalize the S/N ratio to distribute the data evenly and scale it into an acceptable range for further analysis by applying the appropriate equation:

For lower-is-better (the present case)

$$Z_{ij} = \left(\max\ y_{ij} - \ y_{ij}\right)/\left(\max\ y_{ij} - \min y_{ij}\right) \qquad (2)$$

Where $Z_{ij}$is the normalized value of ith trial for jth dependent response.

Step 3: Compute the grey relational coefficient (GRC) for the normalized S/N ratio values as per the following equations:

$$\mathrm{GRC_{ij}} = (\Delta_{\min} + \mathrm{r}\,\Delta_{\max})/(\Delta_{0\mathrm{j}} + \mathrm{r}\,\Delta_{\max}) \quad (3)$$

Where Δ_{min} and Δ_{max} are the minimum and maximum normalized values of S/N ratio among all experimental combinations for a particular response, $\Delta_{0J} = \|1 - Z_{ij}\|$, and r is the distinguishing coefficient which is used to adjust the difference of the relational coefficient and usually lies between 0 and 1. The distinguishing coefficient reduces the effect of Δ_{max} when it gets too big, enlarging the different significance of the relational coefficient. The suggested value of r is 0.5 due to the moderate distinguishing effects and good stability of the outcomes.

Step 4: Compute the grey relational grade by using:

$$G_n = \frac{1}{n}\sum GRC_{ij} \quad (4)$$

Where n is the number of performance characteristics (4 in the present case). The grey relational grade is simply calculated by averaging the grey relational coefficients. The grey relational grade is treated as the overall response of the process instead of the multiple responses individually. The higher the grey relational grade, the closer is the experimental value to the ideal nominal value. Thus, a higher grade indicates that the corresponding parameter combination is closer to the optimal.

Step 5: To compute the significant parameter based on the largest difference of maximum and minimum grades among all the levels of that parameter.

Step 6: Selecting the optimal levels of process parameters corresponding to the level of a parameter having highest grade.

Step 7: to conduct a confirmation experiment, verify the optimal process parameter settings and optimization by comparing the results with that of the experimental combination corresponding to the highest grey relational grade.

3 EXPERIMENTAL DETAILS

In the present study, Grade-4 titanium is used as the workpiece material. Experiments were performed on a manual lathe using a rhomboid shaped carbide tool insert. An MQL device (*Producut APL 005/03)* was mounted on the machine tool to supply environmentally friendly lubricant which is a blend of natural, synthetic and sulphurized esters with anti-wear additives and anti-oxidants with flow rate ranging from 10 mL/hr to 540 mL/hr through a micro nozzle at pressure ranges between 1 and 6 bars. Figure 1 illustrates the experimental setup whereas Table 1 presents the details of machining parameters used in the present research work.

Figure 1 - Experimental setup.

Variable parameters	Symbol	Unit	Level		
			-1	**0**	**1**
Flow rate	F_L	mL/hr	50	70	90
Nozzle distance	N_D	mm	20	30	40
Air pressure	N_P	bar	4	5	6
Fixed parameters: Cutting speed-125 m/min; Feed rate-0.2 mm/rev; Depth of cut-1 mm **Properties of Lubricant:** Pour point- 8^0C; flash point- >290^0C; kinematic viscosity- 39.11 mm^2/s at 40^0C; density- 0.9199 g/cm^3 at 20^0 C					

Table 1 - Details of parameters used in the experimentation.

The effect of the three most important MQL parameters i.e. flow rate, nozzle distance and air pressure were evaluated at three levels each. These levels were selected based on conducting some preliminary experiments, machining constraints and recommendations of the MQL device manufacturer. Cutting speed, feed and depth of cut were fixed at the values considered as the median levels for a subsequent next phase of experimentation. A cutting speed of 125 m/min implies a speed in the transition zone (in between the ranges of conventional and high speed machining) for machining of titanium [21]. Workpiece surface roughness (average and maximum roughness), power consumption and tool wear were the main output/response parameters. The run time for each of nine experiments was fixed at 5 min in order to get a significant amount of tool wear.

The total power consumption during each experimental run is the sum of total power consumption of the lathe during actual machining, power consumption by the MQL device set to deliver lubricant at the particular flow rate value and the power consumption of the air compressor associated with the MQL device at the particular pressure. The power consumption of the lathe was measured in time whereas the power consumption of the MQL device and compressor was calculated using the MQL operation parameters based on actual calibration power assessment tests. Two important surface roughness parameters average roughness 'R_a' and maximum roughness 'R_{max}' (distance between highest peak to deepest valley) were considered to describe the work piece surface quality. Roughness measurements were done by a handheld roughness tester (*Hommel* T500) set at 0.8 mm cut-off length and 4 mm evaluation length, and by tracing the work surface along the tool feed direction. Three measurements were taken for each experimental run and the average value was considered for further analysis.

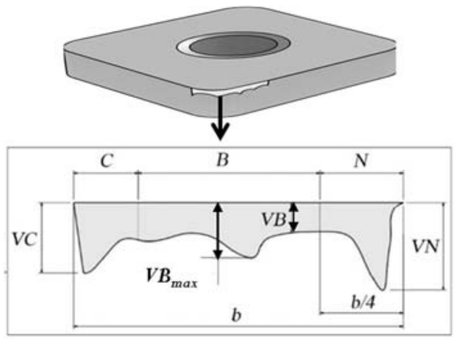

Figure 2- Flank wear in carbide tools: VB-average width of flank wear; VB_{max}- maximum width of flank wear in zone B; Notch wear VN in zone N and Nose wear VC in zone C.

Flank wear was selected as the criterion of tool wear and measured with a tool maker's microscope. The tool was deemed failed when the maximum flank wear 'VB_{max}' (see Figure 2) reached 0.6 mm as recommended by the ISO-standard [22].

4 RESULTS AND DISCUSSION

The experimental results for the machinability descriptors (response parameters) evaluated are presented in Table 2 for each experimental run as designed based on the Taguchi technique for different combinations of input parameters. Table 3 presents the values of S/N ratios calculated using Eq. 1 along with corresponding grey relational coefficients and grades for each experimental run.

4.1 Effect of flow rate

During MQL assisted machining, the number of droplets, droplet size and distribution are the main parameters that determine mist quality [23]. Efficient MQL implies the maximum number of droplets to fully cover the surface area between the tool-chip interface. This is usually ensured by high flow rates. Therefore, improved workpiece surface roughness and lower tool wear were obtained with high flow rate (see Fig. 3).

The high tool wear at the lowest flow rate is due to insufficient lubricant (oil droplets) to reduce the friction and thereby heat generated between tool-chip and tool-workpiece interfaces. The lower power consumption at the lowest flow rate is due to the lower consumption of the MQL system at lower flow rates. The difference between the power consumption for the lowest and highest value flow rates is not significant.

Expt. No.	F_L (mL/hr)	N_D (mm)	N_P (bar)	Surface roughness (μm)		Power consumption (kW)	Flank wear (mm)
				R_a	R_{max}		
1	50	20	4	0.617	4.6	2.0	.557
2	50	30	5	0.798	5.41	2.083	.302
3	50	40	6	0.66	4.51	2.059	1.700
4	70	20	6	0.733	4.94	2.143	1.015
5	70	30	4	1.24	8.56	2.115	.800
6	70	40	5	0.877	6.4	2.279	.907
7	90	20	5	0.463	3.5	2.188	.612
8	90	30	6	0.997	8.64	2.293	.400
9	90	40	4	0.613	6.72	2.226	1.175

Table 2 - Experimental design matrix and results.

Expt. No.	Surface roughness				Power Consumption		Flank Wear		GRADE
	R_a		R_{max}						
	S/N ratio	GRC	S/N ratio	GRC	S/N ratio	GRC	S/N ratio	GRC	
1	4.194	0.4135	-13.255	0.4175	-6.0205	0.3333	5.0828	0.4363	0.4002
2	1.959	0.5274	-14.663	0.4906	-6.3737	0.4157	10.399	0.3333	0.4417
3	3.609	0.4382	-13.083	0.4098	-6.2731	0.3884	-4.6	1	0.5591
4	2.697	0.4835	-13.874	0.5595	-6.6204	0.5025	-0.129	0.6257	0.5428
5	-1.868	1	-18.649	0.9784	-6.5062	0.4582	1.938	0.5341	0.7426
6	1.140	0.5868	-16.123	0.6002	-7.1548	0.9177	0.847	0.5787	0.6708
7	6.688	0.3333	-10.881	0.3333	-6.8009	0.5931	4.264	0.4906	0.4375
8	0.026	0.6925	-18.730	1	-7.2080	1	7.958	0.3736	0.7665
9	4.250	0.4111	-16.547	0.6418	-6.9505	0.6974	-1.4	0.7002	0.6126

Table 3 - Signal to noise ratio and grey relational coefficient for various response parameters and grey relational grade

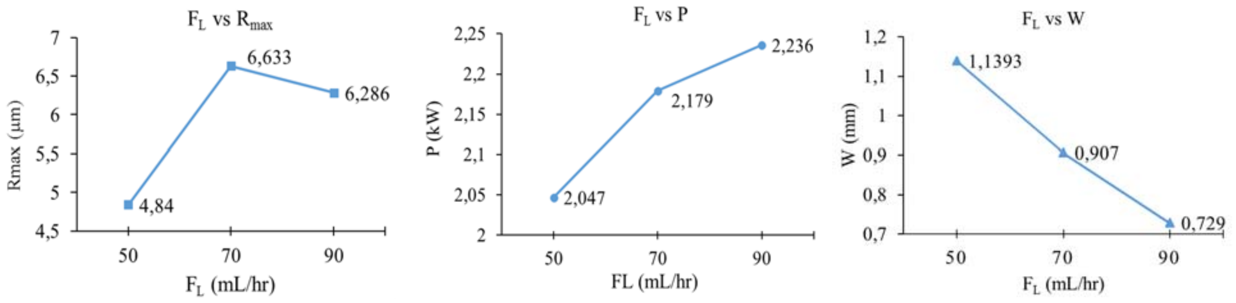

Figure 3- Effect of flow rate on (a) surface roughness; (b) power consumption; and (c) tool wear.

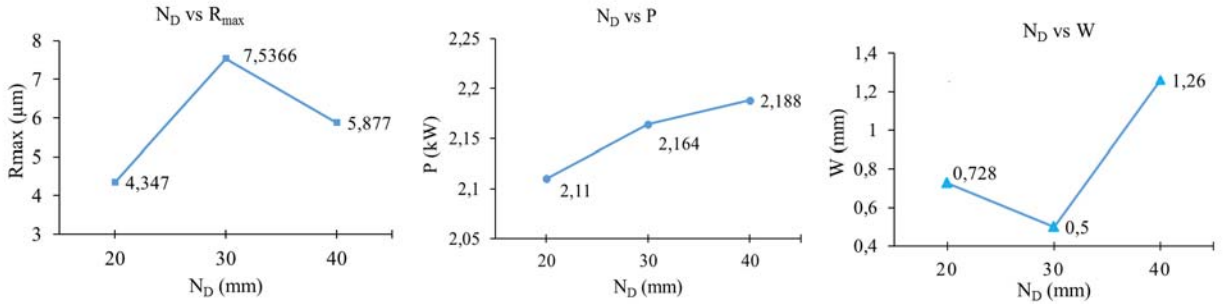

Figure 4- Effect of nozzle distance on (a) surface roughness; (b) power consumption; and (c) tool wear.

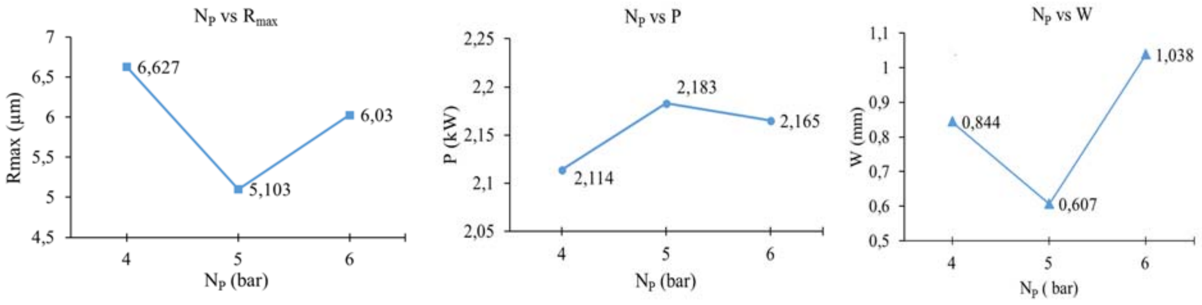

Figure 5- Effect of air pressure on (a) surface roughness; (b) power consumption; and (c) tool wear.

4.2 Effect of nozzle distance

The effect of the nozzle distance on the machinability parameters investigated is presented in Figure 4. The nozzle distance has an effect on the diffusive nature of the spray over the travel distance, the chip breakage and droplet penetration into the interface. A shorter nozzle distance is preferable as it ensures high mist velocity [24]. In the present case the shorter nozzle distance ensured the presence of a fully enveloped mist to the target surface and consequently resulted in minimum roughness and low tool wear.

Longer spray distances implies lower pressure intensity of the jet and therefore lower lubrication efficiency causing an increase in cutting force and consequently power consumption.

4.3 Effect of air pressure

High air pressure helps the oil mist to penetrate into the cutting zone. Therefore the lowest air pressure resulted in increased roughness and tool wear for the present case.

The highest air pressure is also not optimal. High air pressure may lead to droplets bouncing off the work and tool surfaces because of conservation of momentum effects [12] thereby not being available for effective lubrication and consequently resulting in higher roughness and tool wear.

Medium air pressure probably results in a fully uniform fluid film that provides sufficient cooling and lubrication, which resulted in best surface finish and lowest tool wear (see Fig. 5). The lowest pressure probably implies a non uniform film and consequently higher roughness and wear.

Higher grey relational grades, as presented in Table 3, imply that the corresponding experimental result is closer to the ideal normalized value. Consequently experiment no. 8 displays the best performance characteristics amongst all the experiments.

5 OPTIMIZATION AND COMPARATIVE STUDY

The average grey relational grade for each level of a parameter was calculated by using the values of the grades presented in Table 3. A high relational grade results in good performance of the parameter at said level. Therefore, the optimal level of the parameter is the level with the highest average grey relational grade value. The highest average grey relational grade for the flow rate is at 70 mL/hr, for nozzle distance it is at 30 mm and for pressure it is at 6 bar. A validation (confirmation) experiment was conducted at the optimum parameter combination to verify the optimization. Table 4 presents the results of the optimization i.e. the values of output parameters at optimal combination of input parameters. When comparing these values with those obtained corresponding to experiment no. 8, having the highest grey relational grade, it is found that the optimum values are much improved implying that the results were optimized indeed.

Optimal parameters	**Optimal responses**			
Machining condition	**R_a (μm)**	**R_{max} (μm)**	**P (kW)**	**W (mm)**
F_L-N_D-N_P 70-30-6	0.76	7.07	2.065	0.395

Table 4 - Results of the validation test

After validating the results of the optimization for MQL turning; additional experiments were performed under dry and wet conditions at the same cutting speed, feed and depth of cut to compare machinability in terms of tool flank wear, machined surface roughness and power consumption. An emulsion of water and mineral oil was used as the cutting fluid in wet cutting at a flow rate of 2 L/min. The results have revealed significantly lower values of tool flank wear and total power consumption for MQL compared to dry and wet conditions. The surface finish measured for MQL was much better than those of the dry condition, but a little less than that of the wet condition.

Table 5 presents the results of this comparative study which comprehensively confirms the advantages of MQL when compared to dry and wet cutting conditions during turning of Grade-4 titanium.

Machining condition	**R_a (μm)**	**R_{max} (μm)**	**P (kW)**	**W (mm)**
MQL	0.76	7.07	2.065	0.395
Dry	1.15	8.77	3.433	0.820
Wet	0.61	4.07	2.553	0.708

Table 5 - Comparison of MQL, dry and wet machining

6 CONCLUSIONS

The results of the present work contribute to overall sustainability by achieving improved energy, resource and economic efficiency when machining Grade-4 titanium with the assistance of MQL. The following conclusions can be drawn from the present research work:

- Machining with the lowest MQL flow rate results in minimum roughness and power consumption, but for low tool wear machining with highest flow rate is best.
- Minimum roughness and power consumption are achieved at the lowest nozzle distance, whereas the low to midlevel distances provide lower tool wear.
- Machining with optimum parameters i.e. medium flow rate (70 mL/hr) and nozzle distance (30 mm), and high air pressure (6 bar)

resulted in optimized work surface roughness, power consumption and tool wear.

- The comparative study comprehensively demonstrated the advantages of MQL over dry and wet cutting conditions when machining Grade-4 titanium.
- The difficulties usually associated with machining of titanium and its alloys can be significantly reduced by using MQL techniques.
- The future scope of this work will include efforts towards optimization of work piece surface roughness, investigation on the effect of cutting speed, feed rate and depth of cut on the machinability of Grade-4 titanium especially as related to cutting forces and on the geometry (form features) of the machined part.

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