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Performance evaluation of cubic boron nitride tool in machining of titanium (grade-II) under minimum quantity lubrication

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The advantages of metal cutting fluids in machining are prominent, yet their utilization is accompanied by health and environment hazards. Besides, stringent environmental policies make the manufacturers to change over to dry turning, which is not viable during the machining of sticky material like titanium alloys. Therefore, the usage of minimum quantity lubrication (MQL) can be considered as a possible solution and a one step towards green manufacturing. The aim of this work is to investigate the machinability of titanium (grade-II) alloy with cubic boron nitride (CBN) tool under MQL conditions. The machining tests was performed under varying conditions of process parameters such as cutting speed (V_c), feed rate (f) and side cutting edge angle (approach angle ϕ). The experiments were planned and executed using response surface methodology (RSM). The tangential force (F_c), tool wear (V_{Bmax}) and power consumption (K) were selected as the response variables. The outcomes demonstrated that the F_c increases with the increase in feed rate and decreases with the increase in cutting speed and approach angle. Whereas the V_{Bmax} and K increases with the increase in feed rate as well as cutting speed. There is very less effect of approach angle on V_{Bmax} and K. Moreover, the results have been presented and optimized process parameters are obtained through multiple response optimizations using desirability function approach. In the end, the optimized parameters under MQL conditions are compared with the wet and dry turning. The MQL conditions have shown better results over wet and dry machining.

Keywords: Green manufacturing, MQL, RSM, Tool wear, Tangential force

Titanium and its alloys have immense modern applications in numerous fields explicitly aerospace, bio-medical, ship building, energy and chemical etc[1]. In spite of the fact that titanium is heavier than aluminium, yet it has surprising mechanical and corrosion resistance properties over aluminium. The machining of titanium is crucial and challenging operation in various manufacturing industries due to its low thermo-mechanical properties, poor thermal conductivity and high chemical reactivity. It prompts vicious temperature rise in the cutting region, particularly at tool-chip interface where temperature may way to deal with 1000°C or even higher[2]. This high cutting temperature accelerates the tool wear, which may result in short tool life. It like-wise tends to weld on cutting tool amid machining, which prompts to chipping and premature failure of tools[3].

In order avoid these issues, the cutting fluids and advanced tool materials such as CBN and PCD are used. They provide better surface finish, longer tool life and noteworthy dimensional accuracy. The PCD tools have revealed more desirable performance when contrasted with high speed steels and carbide tools as reported in literature[4]. Whereas CBN tools have exposed superb mechanical properties such as high temperature strength, high thermal conductivity for dissipating excessive heat produced amid dry cutting, high abrasive wear resistance accompanied with good chemical and thermal stability and hardness next to diamond. The CBN tools also retain high hardness even at high temperatures and subsequently allow use at higher cutting speeds. Dureja *et al*.[5] studied the wear mechanisms of TiN-coated CBN tool during finish hard turning of hot tool die steel. They conclude that the flank wear rate was observed to decrease with increase in cutting speed, depth of cut, and work-piece hardness, but after an initial decrease it increased with increase in feed rate. Dogra *et al*.[6] made an exhaustive study on the work done in the field of CBN tools. A significant pool of CBN turning studies has been surveyed in an attempt to achieve better understanding of tool wear, chip formation, surface finish, white layer formation, micro-hardness variation and residual stress on the basis of varying CBN content, binder, tool edge

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geometry, cooling methods and cutting parameters. Further important modeling techniques based on finite element, soft computing and other mathematical approaches used in CBN turning are reviewed. Dogra *et al*.[7] discussed the performance evaluation of CBN, coated carbide, cryogenically treated uncoated/coated carbide inserts in finish-turning of hardened steel. The results showed that the flank wear of CBN tools was observed to be lower than that of other inserts. Dogra *et al*.[8] performed the finish hard turning experiments of continuous and interrupted surfaces with cubic boron nitride (CBN) and coated carbide tools. The results indicated that the longest tool life was achieved with CBN tools. Dogra and Sharma[9] discussed the machinability and surface quality issues in finish turning of hardened steel with coated carbide and CBN tools. The results demonstrated that the performance of coated carbide tools deteriorated at highest cutting speed tested, and significant chipping/breakage of the cutting edge was observed. The tool wear affected the cutting zone temperature, as well as residual stress generated on the machined surface.

Cutting fluids improves machinability by lessening the cutting region temperature and instigating lubrication effect in tool-chip and tool-machined surface interfaces. The improvement of machinability of titanium alloys depends to a vast degree on the viability of the cooling and lubrication methods. The various sorts of cooling strategies are utilized to overcome temperature rise between tool-chip interfaces, i.e., dry machining, cryogenic cooling, high pressure cooling, flood cooling and MQL[10]. Among them, the application of flood cooling is the most famous system. However, the major issue with this method is that it does not reach the real cutting area. They fail to reduce the cutting temperature in cutting zone because they cannot infiltrate legitimately into the tool chip interface[11]. The extensive heat generated at tool chip interface evaporates the coolant before it reaches the real cutting area. Henceforth, heat generated amid machining is not uprooted and is one of the main causes of the reduction in tool life and poor surface finish. Besides it devours high quantity cutting fluid and creates environmental perilous issues. The cost of these fluids is also very high and it affects on operator's health. Out of these, MQL demonstrated noteworthy results as far as reduction in machining cost, quantity of cutting fluid and quality of surface produced. It also known as near to dry lubrication or micro-lubrication in which the quantity of cutting fluid used for the experimentation is very low. The flow rate of the coolant used is very low as contrast with conventional flood cooling method.

A thorough literature survey demonstrated various studies on distinctive materials identified with the cutting forces, surface roughness and tool wear in machining processes under MQL conditions. Varadarajan *et al*.[12] examined the impact of machining parameters on hard turning of AISI 4340 steel using dry, wet and MQL conditions concerning cutting forces, surface finish, tool life and tool chip contact length. They found that MQL gave better results as compared to dry and wet machining. Similarly, Attanasio *et al*.[13] dissected the favorable outcomes of MQL on lessening of tool wear amid turning of 100Cr6 steel. Dhar *et al*.[14] performed the turning tests on AISI-4340 steel under MQL conditions with respect to reduced tool wear and surface roughness. Khan *et al*.[15] exhibited the helpful impact of MQL utilizing vegetable oil-based cutting fluid while turning AISI 9310 alloy steel as compared to dry and wet machining. The outcomes demonstrated that MQL using vegetable oil-cased cutting fluids serves to lessen the chip-tool interface temperature, tool wear, build up edges and surface roughness. According to Liu *et al*.[16] investigations on the wear execution of diverse coated inserts amid high speed turning of titanium alloys with dry and MQL conditions, MQL was figured out to be prevalent. Liu *et al*.[17] also validated the machining parameters optimization in turning of titanium alloy using coupling method of response surfaces (CRSM) under MQL conditions. The results showed that, feed rate was the main factor affecting surface roughness and cutting forces. Ji *et al*.[18] also scrutinized the impact of MQL conditions on cutting forces, residual stresses and cutting temperature while turning AISI 4130 alloy steel. They like-wise contrasted the execution of MQL with dry and flood cooling and they found that coolant plays a most imperative role to reduce the tool-chip interface temperature as well as cutting forces. Saini *et al*.[19] also showed the machining parameters optimization in turning of AISI-4340 steel with carbide inserts using artificial neural network (ANN) under dry and MQL conditions. The given result proved that MQL gives valuable results as compared to dry machining.

Based upon the literature reviewed, it has been observed that much work on the machinability aspects of AISI 4340 steel, AISI 52100 steel, AISI 9310 steel, 100Cr6 steel using MQL has been investigated. Nonetheless, there is hardly very few studies were reported on machining of titanium and its alloys under MQL conditions. It was also found that under MQL conditions the selections of the machining parameters are not the same as the dry and wet machining. Therefore, aim of this present study was to estimate the optimal cutting conditions under MQL through the experimental investigations of titanium (grade-II) work material with CBN insert tool using RSM approach. Moreover, the use of CBN insert tool for turning this titanium (grade-II) alloy at the preferred speed and feed combination is withal unique scenario which will accommodate as a premise to determine the circumscription of utilization for CBN tool. Besides, the endeavors have been made to contrast the execution under MQL conditions with those in wet and dry turning. Hence, the application of MQL for machining of this titanium (grade-II) alloy using CBN tool in the present work is quite challenging.

Experimental Procedure

The work material used in this study was titanium: grade-II (145 HV) as round bars with 50 mm diameter and 150 mm length, so that L/D ratio proportion ought not surpass 10 as per ISO 3685 standards[20]. The chemical composition of titanium (grade-II) is C 0.1 % max, Fe 0.3 % max, H 0.015 % max, O 0.25 % max, N 0.03 % max and Ti 99.2 %.

The coated CBN inserts (CCGW 09T304-2) were employed through the cutting tests. The working tool geometry of cutting tool is as follows:

Inclination angle = -6°, Orthogonal rake angle = 6°, Orthogonal clearance angle = 80°, Auxiliary cutting edge angle = 15°, Principal cutting edge angle = 60°, 75°, 90°, Nose radius = 0.4 mm and rhombic shape

A fresh tool with 75 mm of cutting length was used for each experiment to maintain a strategic distance from the impact of tool wear on given responses. The turning tests have been partitioned into two main stages. The first stage is exploratory or pilot experimentation stage, in which the experiments were planned and led to locate the suitable MQL parameters. For this situation, three MQL parameters with three levels have been composed as indicated in Table 1.

After analyzing the results from first stage, the MQL parameters (lubricant flow rate of 300 mL/h, input pressure of 4 bar and compressed air flow rate of 60 L/min) that causes lower tangential force, power consumption and tool wear was cautiously elected which will be the main strategy and it is connected for leading the second phase of experiments. The general purpose "Balmerol make Protosole MQ" soluble cutting oil (20:1) was used. The reciprocating compressor with an automatic cut-off and a capacity of generating 1 HP was used to supply compressed air at 4 bars and 60 L/min. The compressed air from air-flow rotameter ("Japsin" acrylic rotameter ranging from 0 to 150 L/min) along with cutting fluid of 300 mL/h was hybrid in the nozzle and delivered mist on to the cutting zone while maintaining a gap of 35 to 40 mm between tool tip and nozzle outlet. The turning was performed on high precision CNC Turning Centre Sprint 16 Tc equipped with a Siemens control system (Batliboi) under MQL condition as shown in Fig. 1. A Telc make DKM 2010 three components tool dynamometer connected with XKM software and PC was used to measure cutting force and power consumption. The Mitutoyo's make tool maker microscope was used to measure the flank wear (measured by the width of wear land on the flank underneath the cutting edge).

Table 1 — MQL Parameters with their levels

Parameters	Level 1	Level 2	Level 3
Lubricant flow rate, mL/h	200	250	300
Input pressure, bar	2	4	6
Compressed air flow rate, L/min	40	60	80

Nozzle diameter = 1 mm, cutting speed = 200 m/min, feed rate = 0.10 mm/rev, dept of cut = 1 mm

Fig. 1 — Experimental setup

Experimental design

In order to examine the effect of machining conditions on tangential force, tool wear and power consumption – primary factors were investigated by varying cutting speed, feed rate whereas depth of cut 1 mm is kept constant. Also one of the important factor known as side cutting edge angle or approach angle is explored and included in this study. It determines the thickness of the uncut chip layer (perpendicular to cutting edge of tool) and improves the heat removal over a larger portion of cutting edge by distributing the cutting forces.

The experiments were planned and executed using RSM design of experiment technique. It is an accumulation of mathematical and statistical strategies that are helpful for modelling and analysis of problems in which a response of interest is affected by a few variables and the purpose is to optimize this response[21-24]. The Box-Behnken design (BBDs) were used for develops the response models. It suggests three level designs for fitting response surfaces which are produced by combination of 2k factorials with incomplete block designs. A total of seventeen experiments were performed under MQL using CBN cutting tool to observe the interaction between machining parameters and given responses. The input parameters range was selected by the extent literature survey and to achieve high material removal rate. In the wake of discovering the enhanced levels for machining parameters: cutting speed, feed rate and approach angle under MQL conditions; experiments were also performed at these optimal cutting conditions under dry and wet (flood cooling) conditions to compare machining performance.

Results and Discussion

The experimental results obtained (Table 2) were used to establish models for tangential force, tool wear and power consumption for titanium (grade-II) through RSM. The satisfactory of generated models were confirmed with the assistance of ANOVA.

ANOVA for F_c

The ANOVA was performed (shown in Table 3) and feed rate, approach angle and interaction of cutting speed and feed rate were significant model terms. The *F*-value from reduced model 31.18 implies that the developed model is significant for tangential force. The "Pred R^2" of 0.7603 is in sensible concurrence with the "Adj R^2" of 0.8830. Furthermore, the correlation coefficient R^2 of 0.91 (close to unity) legitimizes the unwavering quality of proposed model. The Adeq Precision measures signal to noise ratio and greater than 4 (i.e. 20.181) is desirable.

Response surface model for F_c

The final equation regarding actual factors for F_c, is shown in Eq. (1):

$$F_c = -202.01471 + 1.28250 * V_c + 3225.00000 * f - 0.74167 * \phi - 9.40000 * V_c * f \quad \ldots (1)$$

Table 2 — Experimental designs and their results

Sr. No.	V_c (m/min)	F (mm/rev)	Φ (°)	F_c (N)	V_{Bmax} (mm)	K (W)
1	200	0.2	75	261	0.42	871
2	250	0.1	60	153	0.28	638
3	250	0.1	90	147	0.26	611
4	250	0.15	75	191	0.41	860
5	250	0.2	90	231	0.51	964
6	250	0.15	75	189	0.4	855
7	250	0.2	60	241	0.55	1006
8	300	0.15	90	185	0.47	926
9	250	0.15	75	193	0.41	863
10	200	0.1	75	125	0.23	419
11	250	0.15	75	192	0.4	859
12	200	0.15	90	197	0.3	655
13	300	0.15	60	225	0.53	1125
14	200	0.15	60	230	0.31	766
15	250	0.15	75	190	0.41	865
16	300	0.2	75	197	0.57	983
17	300	0.1	75	155	0.32	773

Table 3 — ANOVA for response surface reduced model of F_c

Source	Sum of squares	DF	Mean square	F value	Prob > F
Model	18836.75	4	4709.188	31.18136	< 0.0001
V_c	325.125	1	325.125	2.152779	0.1680
f	15312.5	1	15312.5	101.39	< 0.0001
ϕ	990.125	1	990.125	6.556002	0.0250
$V_c * f$	2209	1	2209	14.62665	0.0024
Residual	1812.309	12	151.0257		
Lack of fit	1802.309	8	225.2886	90.11544	0.0003
Pure error	10	4	2.5		
Cor total	20649.06	16			
Std. dev.= 12.28925			R-Squared = 0.912233		
Mean = 194.2353			Adj R-Squared = 0.882977		
C.V. = 6.326993			Pred R-Squared = 0.760302		
Press = 4949.543			Adeq Precision = 20.1807		

The outcome from Fig. 2 indicates that, F_c sharply increases with increase in feed rate, whereas F_c decreases with increase in cutting speed and approach angle. The possible reason behind this phenomenon is that, at higher cutting speed and approach angle, the temperature generation is high because of low heat dissipation resulting in softening of material, which improves the material removal rate. Hence, cutting force decreases as the cutting speed and approach angle increases. Also the increase in feed rate results in a remarkable increase in the contact length which thus increases the F_c. Moreover, Fig. 3 depicts the relation of predicted values versus actual values. From this figure, it has been found that the values are falls on a straight line and do not show any accessible pattern. This implies that the model is adequate and there is no reason to suspect any violation of the independence or constant variance assumption.

ANOVA for V_{Bmax}

In Table 4, cutting speed and feed rate are significant model terms and also the *F*-value 112.12 connotes that the established model is significant at 95% confident interval. This empirical model was well fitted to experimental values, it could be seen that the value of “Pred R-Squared" 0.9242 and “Adj R-Squared" 0.9542 gave a decent defense to the reliability of a regression model to predict tool wear. The adequate precision ratio of developed model is 36.785 (ratio > 4 is desirable), which gives a satisfactory signal to use the proposed model.

Response surface model for V_{Bmax}

The Eq. (2) shows actual factors for tool wear:

$$V_{Bmax} = -0.27368 + 1.57500\text{E-}003 * V_c + 2.40000 * f - 1.08333\text{E-}003 * \phi \quad \ldots (2)$$

Table 4 — ANOVA for response surface linear model for V_{Bmax}

Source	S.S.	DF	M.S.	*F*	Prob > *F*
Model	0.166925	3	0.055642	112.1204	< 0.0001
V_c	0.049613	1	0.049613	99.97139	< 0.0001
f	0.1152	1	0.1152	232.1331	< 0.0001
ϕ	0.002113	1	0.002113	4.256781	0.0597
Residual	0.006451	13	0.000496		
Lack of fit	0.006331	9	0.000703	23.44989	0.0041
Pure error	0.00012	4	0.00003		
Cor total	0.173376	16			

Std. Dev. = 0.022277 R-Squared = 0.962789
Mean = 0.398824 Adj R-Squared = 0.954202
C.V. = 5.585691 Pred R-Squared = 0.924208
Press = 0.013141 Adeq Precision = 36.78527

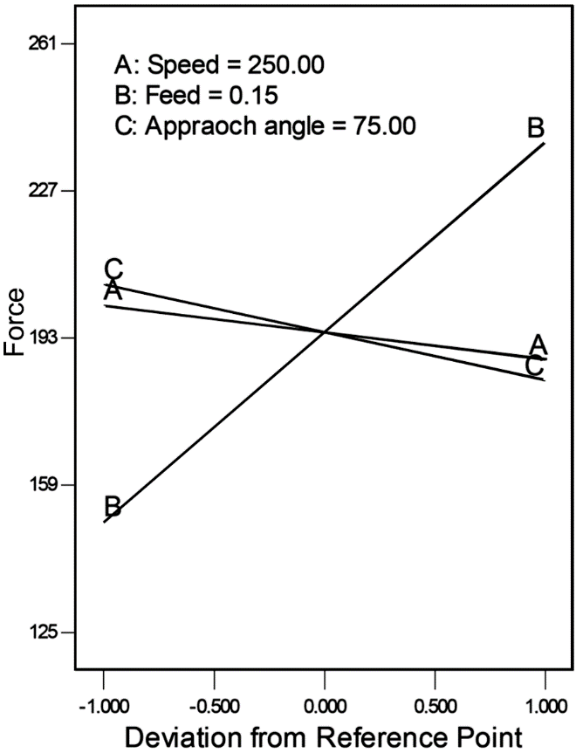


Fig. 2 — Effect of cutting parameters on F_c

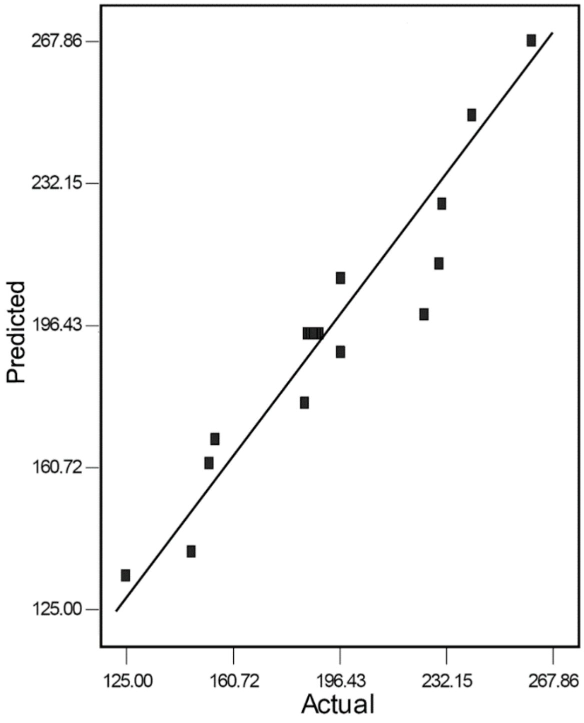


Fig. 3 — Plot of actual value v/s predicted value in the case of F_c

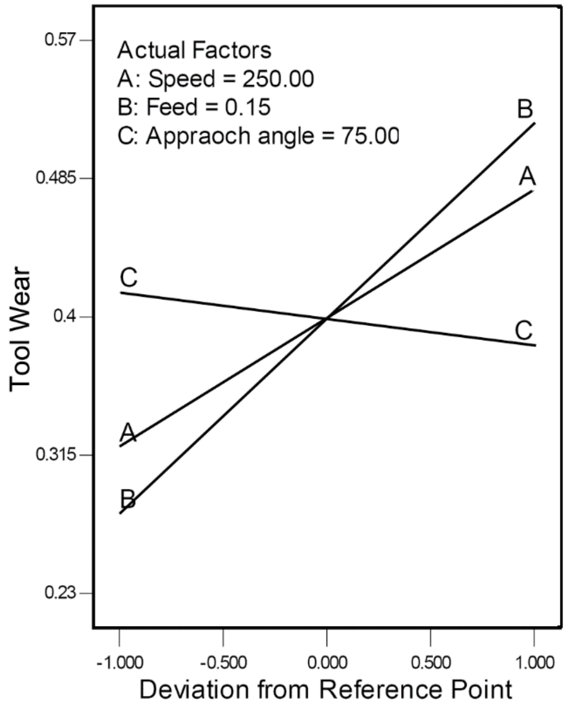


Fig. 4 — Effect of cutting parameters on V_{Bmax}

The effect of all cutting parameters on V_{Bmax} is shown in Fig. 4 and the outcome demonstrates that, as cutting speed as well as feed rate increases the V_{Bmax} piercingly increases and the approach angle has mellow impact on V_{Bmax}. The plot of actual value versus predict value in case of V_{Bmax} is shown in Fig. 5. The images of tool wear are shown in Fig. 6. The fundamental reason is that with expanding cutting speed and feed rate, the area of chip increases and consequently friction increases; this includes an increment in tool-chip interface temperature, resulting in increased tool wear. Additionally, the detachment of the protecting coating or adhered work material from the tool is occurring due to the high speed-feed combination, which further increases the flank wear. Furthermore, Fig. 5 shows the similar pattern of actual versus predicted value (in the case of tool wear), which means that the model is adequate.

ANOVA for *K*

The *F*-value 29.82 from Table 5 construes the model is noteworthy. In this condition, cutting speed and feed rate are significant terms. The "Pred R-Squared" of 0.7469 is in sensible simultaneousness with the "Adj R-Squared" of 0.8438. The “Adeq Precision" measures the sign to noise degree and a proportion more prominent than 4 is desirable. The ratio of 18.938 demonstrates a sufficient sign.

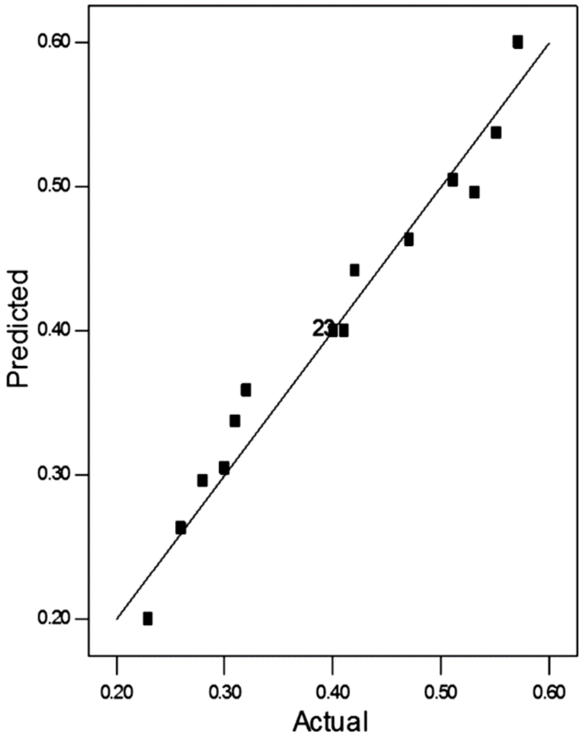


Fig. 5 — Plot of actual value v/s predicted value in the case of V_{Bmax}

Response surface model for *K*

The Eq. (3) shows in terms of actual factors for power consumption:

$$K = -140.92647 + 2.74000 * V_c + 3457.50000 * f - 3.15833 * \phi \quad \dots (3)$$

The effect of all parameters (Fig. 7) demonstrated that the *K* penetratingly increases as the cutting speed and feed rate increases. There is very less effect of approach angle on *K*. The reason is that as cutting speed and feed rate increase, the friction between the newly generated work-piece and tool surface increases. This increment in friction increases the tool wear and cutting forces, which further increases the power consumption in machine, hence *K* increases. In the end, Fig. 8 implies the actual versus predicted value. It indicates that all the points were distributed normally along the line and hence the model is adequate.

Multiple response optimization by desirability approach

In the present study, desirability approach was used for optimization for multi-response characteristics (F_c, V_{Bmax} and K). It is based on the idea that the

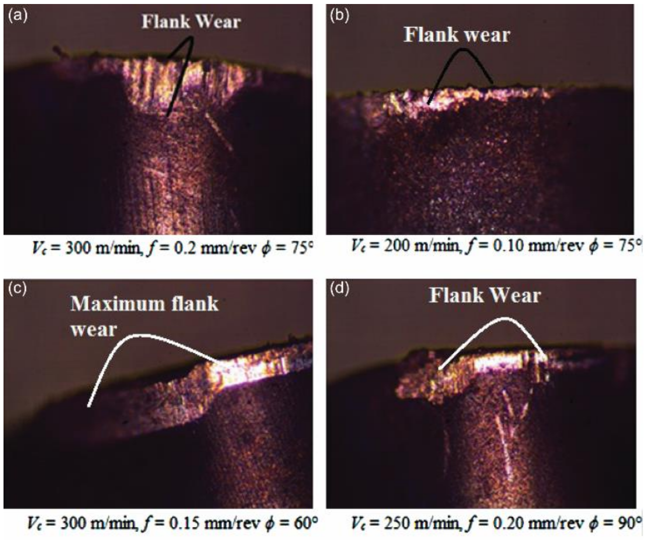


Fig. 6 — Tool Wear, V_{Bmax} at different machining conditions

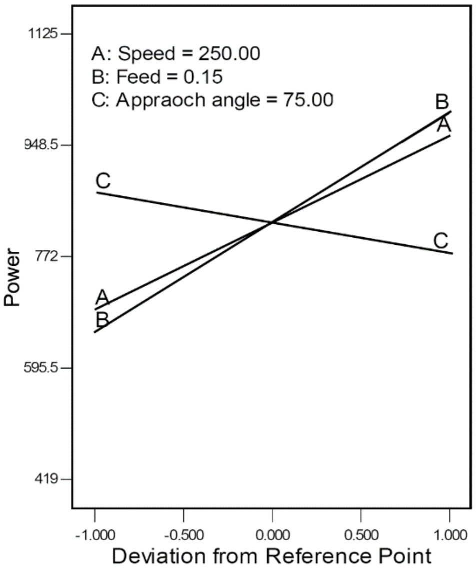


Fig. 7 — Effect of cutting parameters on K

Table 5 — ANOVA for response surface model for K

Source	S.S.	DF	M.S.	F	Prob > F
Model	407193.3	3	135731.1	29.82132	< 0.0001
V_c	150152	1	150152	32.98972	< 0.0001
f	239086.1	1	239086.1	52.52933	< 0.0001
ϕ	17955.13	1	17955.13	3.944899	0.0685
Residual	59169.22	13	4551.479		
Lack of fit	59110.02	9	6567.78	443.7689	< 0.0001
Pure error	59.2	4	14.8		
Cor total	466362.5	16			

Std. Dev. = 67.46465 R-Squared = 0.873126
Mean = 825.8235 Adj R-Squared = 0.843848
C.V. = 8.169378 Pred R-Squared = 0.746904
Press = 118034.6 Adeq Precision = 18.93803

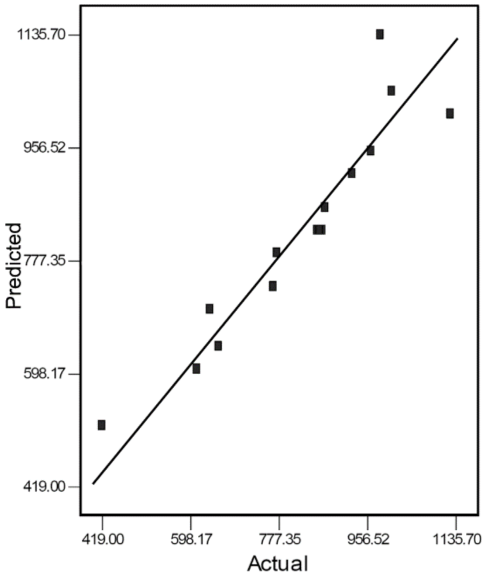
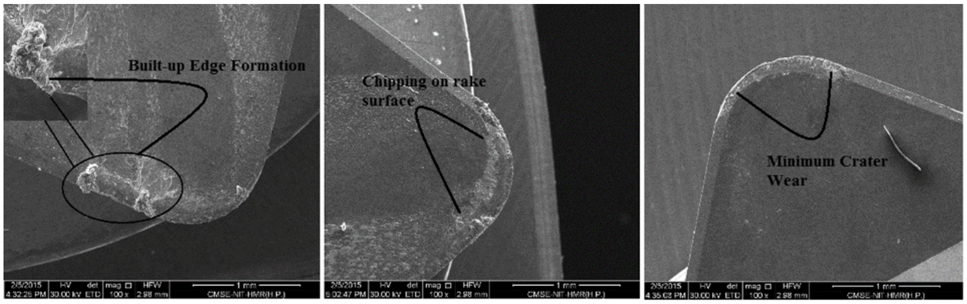


Fig. 8 — Plot of actual value v/s predicted value in the case of K

"quality" of a product or process that has multiple quality characteristics, with one of them outside of some "desired" limits, is completely unacceptable. The optimization module searches a combination of factor levels that simultaneously satisfies the requirements placed on each of the responses and factors in an attempt to establish the appropriate model. During the optimization process the aim was to find the optimal values of cutting parameters in order to minimize the values of tangential force, tool wear and power consumption while turning titanium (grade-II) under MQL condition. The desired target for each process parameter were selected, i.e., cutting speed, feed rate and approach angle were selected “within range”. The optimal solutions are reported in Table 6 in order of decreasing desirability level.

Comparison of machining performance under dry, wet and MQL conditions

After determine the optimum levels of input parameters under MQL turning; experiments under dry and wet conditions were performed to compare machining performance with respect to F_c, V_{Bmax} and K. The results from Table 7 revealed that MQL is a better alternative to dry and wet machining for sticky materials like titanium (grade-II). Because the mist of lubricant along with the compressed air properly penetrated into the tool-chip interface with the impingement effect that apparently caused the cooling of the cutting zone along with proper lubrication. This lowered temperature at the cutting zone evidently



Dry Machining Wet Machining MQL Machining

Fig. 9 — Tool wear at V_c = 300 m/min, f = 0.13 mm/rev, ϕ = 90°

Table 6 — Optimization results

Number	Speed	Feed	Approach angle	Force	Power	Tool wear	Desirability	
1	200.00	0.10	90.00	122.238	468.584	0.18383	0.976019	Selected
2	200.00	0.10	90.00	122.942	470.39	0.185031	0.975123	
3	200.00	0.10	89.25	122.79	470.935	0.184883	0.974852	
4	200.00	0.10	90.00	124.504	474.412	0.187707	0.973122	
5	200.00	0.10	90.00	125.032	475.762	0.188606	0.972372	

Table 7 — Comparison of dry, wet and MQL techniques

Dry			Wet			MQL		
F_c	V_{Bmax}	K	F_c	V_{Bmax}	K	F_c	V_{Bmax}	K
148	0.37	550	136	0.25	515	122	0.18	468
Optimized parameters, V_c = 200 m/min, f = 0.10 mm/rev, ϕ = 90°								

abridged the stickiness of the work material. Also, the lowered temperature maintained the strength and hardness of the tool material. This led to lesser adhesion of the work material to the tool surface, in turn increasing the tool life significantly as compare to dry and wet machining (shown in Fig. 9). Furthermore, in dry and wet conditions, the large proportion (about 80%) of the heat generated when machining titanium-II alloy is conducted into the tool because it cannot be removed with the fast flowing chip or bed into the work-piece due to the low thermal conductivity of aerospace materials. Hence, the high tool wear are obtained under dry and wet conditions. Apart from this, the high cutting temperature, high mechanical pressure and high dynamic loads in the machining of aerospace materials, which result in plastic deformation, thereby resulted the rapid tool wear[25,26].

Confirmation experiments

In order to certify the established models, the confirmation experiments have been performed. In total, a set of three confirmation experiments, including the best optimal solution, have been performed to validate the adequacy of the established mathematical models. The values of responses obtained by confirmation tests and predicted through model are within the 95% prediction interval, which plainly exhibits the accuracy of model established in this study.

Conclusions

In this work, RSM was used to establish the mathematical models of tangential force, power consumption and tool wear in order to investigate the influence of machining parameters amid turning of titanium (grade-II) with a CBN tool under MQL conditions. The multiple response optimization in RSM and the desirability function approach were used to obtain optimum values for machining parameters. The experimental study has led to the following conclusions.

(i) The minimum quantity lubrication could be employed as an effective and economic option to dry and flood cooling system in turning of titanium (grade-II) with CBN tool, inferable from sensibly great execution inside of the scope of parameters chosen in this study.

(ii) In MQL machining the tangential force increases with the increase in feed rate and decreases with the increase in cutting speed and approach angle. Whereas the tool wear and power consumption shows quite distinct behavior and increases with the increase in feed rate and cutting speed. There is very less effect of approach angle on tool wear and power consumption.

(iii) The results of ANOVA and the conducting confirmation tests have proved that the models of the responses are fit and predicted values which are close to those readings recorded experimentally with a 95% prediction interval.

(iv) The optimized machining conditions for minimizing tangential force, tool wear and power consumption were: cutting speed 200 m/min, feed rate 0.10 mm/rev, approach angle 90°.

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