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EXPERIMENTAL INVESTIGATION AND OPTIMIZATION OF MINIMUM QUANTITY LUBRICATION FOR MACHINING OF AA6061-T6

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ABSTRACT

This study presents flank wear optimization with minimum quantity lubricant (MQL) for the end milling for the machining of aluminum alloy 6061-T6. Process parameters including the cutting speed, depth of cut, feed rate and MQL flow rate are selected for study to develop an optimization model for flank wear based on the genetic algorithm. The experiments are conducted based on the central composite design method. Three types of tools are used in this experiment, namely, uncoated carbide tools and two coated carbide tools. The study is conducted to perform the experimental investigation of the effects of minimum quantity lubricant (MQL) for the end milling of aluminum alloy 6061-T6, to investigate the relationships of feed rate, axial depth of cut, cutting speed and minimum quantity lubricant flow rate with respect to tool wear for MQL and to perform the optimization of the machining parameters for flank wear. The results of the study show that inserts coated with TiAlN and TiAlN+TiN show higher flank wear on account of the brittleness of the coatings. Uncoated carbide insert shows lower flank wear but the edge integrity is not maintained, so the resultant surface roughness is the worst among the three tools. In order to perform multi-objective optimization, the surface roughness and material removal rate are also measured along with flank wear. Optimization is performed using a genetic algorithm and the optimized designs are obtained in the form of Pareto optimal designs. The best compromised Pareto designs are selected using multi-criteria decision-making.

***Keywords*:** Minimum quantity lubrication; genetic algorithm; multi-objective optimization; aluminum alloy; machining; tool wear.

INTRODUCTION

In machining, cutting fluids are considered an essential and important medium for achieving good surface quality. The large amount of coolant utilization in the industry imparts harmful effects to the health of workers engaged in daily machining processes and also to the environment [1] on account of the tailored properties of these fluids with different additives. These coolants are expensive in terms of both recycling and application. Besides, heavy usage of coolant does not promise good lubrication. Hence there are continuous efforts to find a substitute for these cutting fluids. Minimum quantity lubrication (MQL) is gaining impetus as a suitable candidate for lubrication [2-4]. According to research by Boswell and Islam [5], the challenge of MQL is to dissipate the heat from the tool and workpiece in order to ensure dimensional integrity. Kalpakjian and Schmid [6] studied the relationship of tool wear, surface finish and integrity, dimensional accuracy, temperature rise, force and power. Tool life needs to be longer for economical machinability. Tool wear is generally classified as flank wear, cutter wear, nose wear, notching, plastic deformation of the tool tip, chipping and gross fracture. Flank wear occurs at the relief of the tool due to contact of the tool along the machined surface and high temperatures between the tool and workpieces. In a study by Nouari et al. [7], it was reported that coating in tools helps to reduce the tool wear and thus increase tool life. The heat produced during the machining is critical in tool wear and workpiece surface quality especially in dry machining. Investigations carried out by Arokiadass, Palaniradja [8], results showed that the carbide tool flank wear and the minimum flank wear obtained was 0.1102 mm. The flank wear was measured with a Metzer Tool Maker microscope. The researchers found that at high temperature, the flank wear increases. They used a flat-ended uncoated solid carbide tool.

In another study by Sreejith [9] the effects of different types of coolant environment for tool wear were studied. The adhesion of tool wear increases with increase in spindle speed. The worst rates of tool wear were recorded for dry machining. Boswell and Islam [10] created certain criteria for tool failure, which were part surface, burr formation, flank wear greater than 0.3 mm or maximum notch wear of 1.0 mm, and dramatic change in tool forces and cutting power. They examined the tool wear after machining each test sample by using a Tool Maker microscope. Smith [11] explained that tool wear depends on a number of factors such as physical, mechanical and chemical properties, cutting insert geometry as well as cutting fluid and other machining parameters. Flank wear was described as occurring at the cutting tool edge’s flanks due to the abrasive wear mechanism. Zhang, Li [12] analyzed tool wear based on machine vision in the end milling process.

A great challenge currently being faced is competitive marketing due to the manufacturing environment, low costs, the aim for high rates of productivity and also the high quality required by customers [13-15]. According to a study by Rahman et al. [16], the important characteristics of tool wear are cracking, flank wear, catastrophic, notching, chipping, plastic lowering the cutting edge and so on. Broga, Diniz [17] mentioned that aluminum alloys have the potential to adhere to the tool, thus causing a built-up edge and built-up layer. In a study by Yahya [18] it was emphasized that certain processes are very significant such as the finishing process at given dimensions, surface finish, type of surface generation, tolerance, and other behaviors. The effects of the accuracy of the workpiece dimensions, surface finish, tool wear and tool life on the material removal rate and cutting tool have increased in importance when seeking to enhance the product performance in relation to the impact on the environment [19]. The machinability characteristics can be improved if a proper amount of lubricant is applied during machining [9, 15]. According to Kalita. [1], MQL in high energy machining might not be suitable due to the high temperature and thermal spread over the longer time at the machining surface.

Keeping in mind the related constraints and problems, this study considers all the important parameters such as spindle speed, feed rate, tool wear, surface roughness, material removal rate and depth of cut. Besides, a mathematical model is presented to find a combination of independent variables of the CNC end milling process to achieve a good result. The objectives of this study are to investigate the effects of the end milling machining characteristics on the tool wear and to evaluate the progression of tool wear due to the usage of minimum quantity lubricant compared to the flooded coolant.

METHODOLOGY

Machining Parameters and Design of Experiments

The machining variables taken for study in this research are the spindle speed, feed rate, depth of cut and the minimum quantity lubricant flow rate. The central composite design approach of response surface methodology is used for the design of experiments in order to find the effects of individual parameters and combinations of parameters. Five levels of machining variables are selected, as shown in Table 1.

Table 1. Assignment of levels to factors.

Factors	Levels				
	1	2	3	4	5
Cutting speed (rpm)	5252	5300	5400	5500	5548
Axial depth of cut (mm)	0.52	1.0	2.0	3.0	3.5
Feed rate f_z (mm/min)	288	318	379	440	469
MQL flow rate (ml/min/nozzle*)	0.013	0.016	0.022	0.0275	0.030

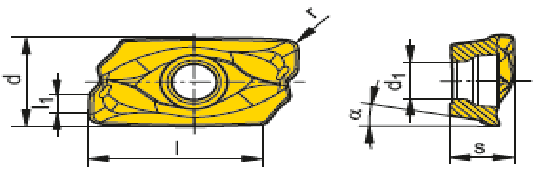
Workpiece and Cutting Tool Material

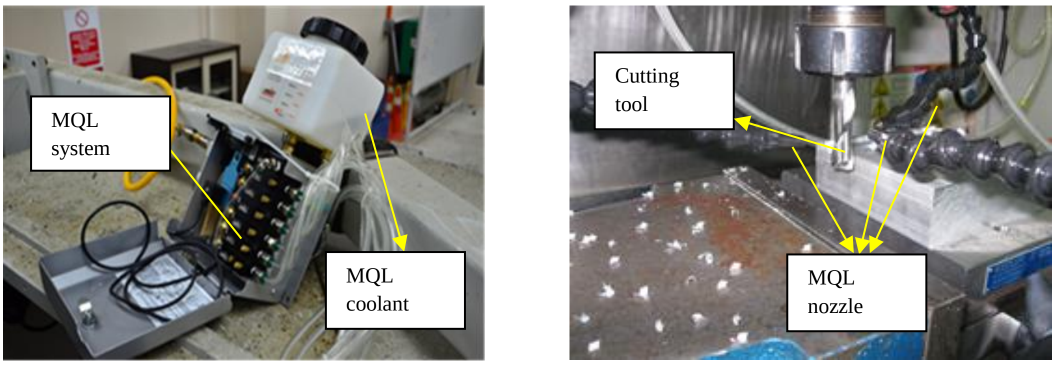
The material used for the study is aluminum alloy AA 6061-T6, selected because it is a commonly available alloy enjoying appreciable applications in the industry because of its good machinability and chip quality. The major alloying elements in the alloy are Si, Cu and Mg. Specifications of the inserts used are listed in Table 2. The inserts are commercially available tools as recommended by the supplier.

Figure 1. CNC end milling machine HAAS VF-6.

Experiments are designed using central composite design methodology and response surface models are applied. Experiments are performed on a vertical machining centre, a HAAS VF-6 (Figure 1). Minimum quantity lubrication is supplied by UNIST self-contained multiple nozzle units provided with metering pumps (Figure 2). Nozzle outputs are controlled by independent adjustments of the air metering screw and metering pump stroke adjustment knob.

Table 2.Composition, properties and dimensions of end mill inserts.

Type of Inserts	Composition	Hardness / coating thickness	Thermal expansion coefficient (× 10^{-6} K^{-1})	ISO-Grade
Uncoated tungsten carbide milling insert	WC 94%, Co 6.0%	HV 1630	5.0	ISO-HC K15, XDKT 070304FR-F20
PVD TiAlN coated	Co 12.5%; mixed carbides 2.0%; WC-balance	HV 1380 / 4 µm	7.5	ISO-HC, P40M40, XDKT070304SR-M50
PVD TiAlN + TiN coated (outer layer is TiN)	Co 9.0%; mixed carbides 4.0%; WC-balance	HV 1510 / 4 µm	9.4	ISO-HC P35M30, XDKT070304SR-F50
Dimensions of the insert				
				Facet corner radius, r (mm) = 0.80; (uncoated) facet corner radius, r (mm) = 0.40 (coated) d (mm) = 4.90 cutting edge length, l (mm) = 7.80 l_1 (mm) = 1.10 (uncoated), l_1 (mm) = 1.0 (coated) d_1 (mm) = 2.50 clearance angle, α (deg) = 15° insert thickness, s (mm) = 3.18



(a) (b)

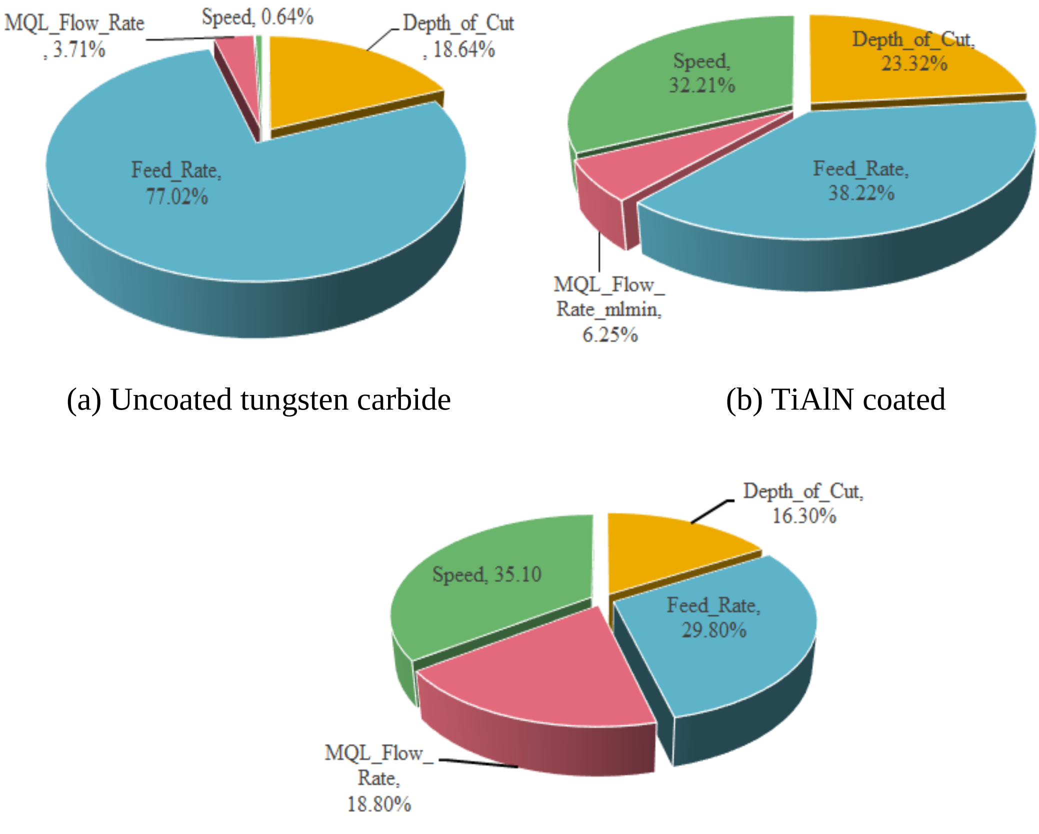
Figure 2. (a) MQL unit with reservoir, (b) MQL metering pumps.

Measurement of Parameters

Three responses are studied in this research, namely: surface roughness, material removal rate and flank wear. Surface roughness and material removal rate are the two opposing responses of the experiments. Surface roughness is measured using a perthometer while the material removal rate is calculated by weighing the workpiece after every single cut. The average surface roughness is determined from the profile data. Surface roughness is measured in µm. The density of the alloy used for calculating the material removal rate is 2712 kg/m^3. Flank wear is investigated using a scanning electron microscope. Flank wear as well as catastrophic tool breakage are also noted.

RESULTS AND DISCUSSION

The experimental results obtained using different tools demonstrate that the influence of the input cutting parameters on the contact properties at the flank–workpiece interface cannot be generalized, as these attributes differ from one tool to another. In this section the effects of cutting parameters on flank wear are studied using the trends derived from the experimental data obtained. The significance and contributions of the input cutting parameters for the output response variables are summarized in the pie-charts shown in Figure 3.

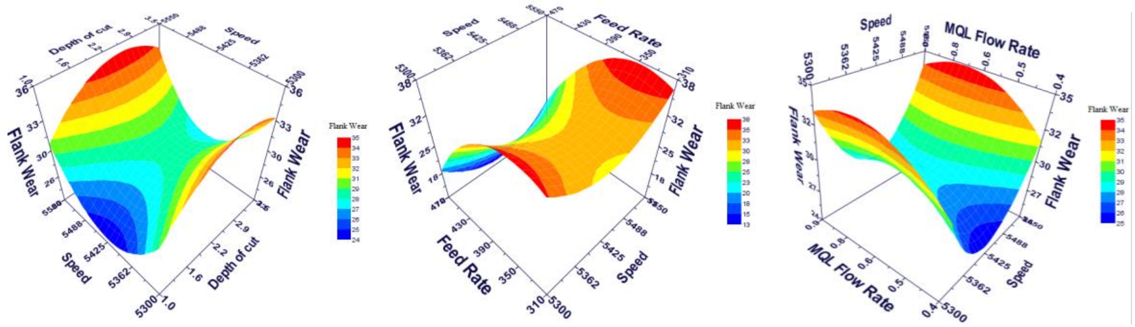


(a) Uncoated tungsten carbide (b) TiAlN coated

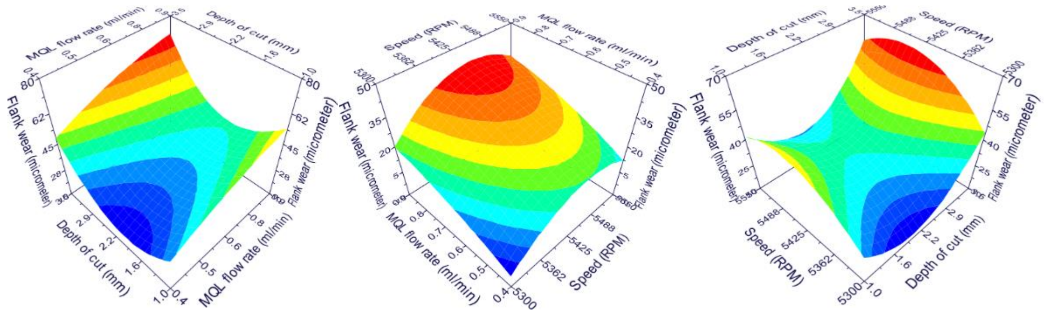
(c) TiAlN+TiN coated

Figure 3. Significance of input parameters for flank wear: (a) uncoated carbide tool, (b) TiAlN coated carbide tool, (c) TiAlN+TiN coated carbide tool.

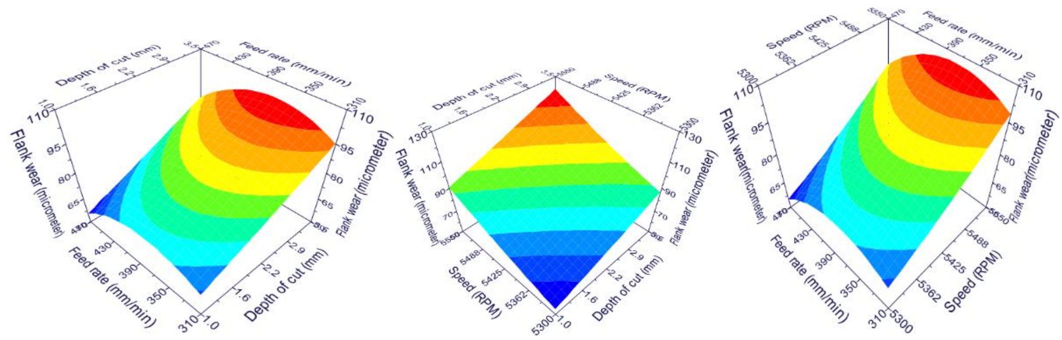
Three-dimensional data showing the functional relationship between a designated dependent variable, i.e. any response variable, and two independent input cutting variables are illustrated by surface plots. 3D surface plots are presented for the most effective interaction terms. Function plots are plotted for all the input parameters in Figure 4.



(a) Uncoated WC-Co6.0%



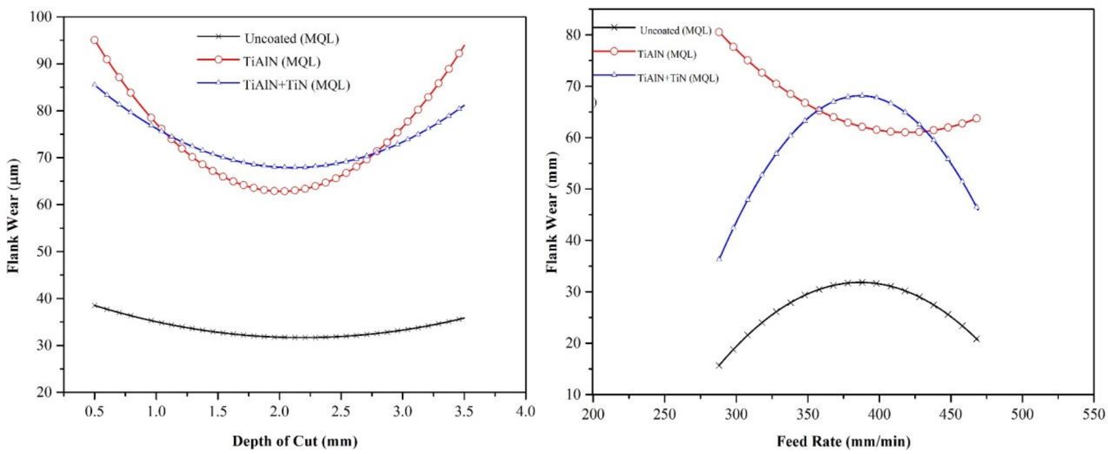
(b) TiAlN coated insert



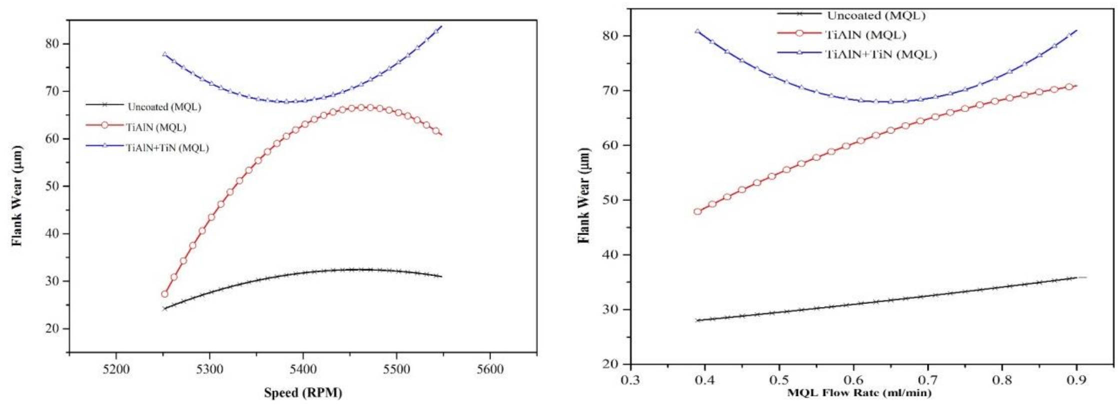
(c) TiAlN+TiN coated carbide insert

Figure 4. 3D surface plots of cutting tool flank wear vs input cutting parameters for different cutting inserts under MQL machining.

The RSM function charts are used to plot the RSM function based on a single selected input parameter, keeping all the other parameters fixed. The function charts show the variation of response variables with individual cutting parameters. The function charts, showing the variation of response variables with input parameters in different cutting conditions, are given in Figures 5.



(a) Depth of cut (b) Feed rate



(c) Speed (d) MQL flow rate

Figure 5. Variation of flank wear with input cutting parameters.
using different cutting inserts under MQL machining:

As far the effect of depth of cut on flank wear is concerned, the three tools show decreasing and increasing behavior as shown in Figure 5(a). For the uncoated WC-Co6.0% insert, the average rate of increase and average rate of decrease in the flank wear are almost same. The data show a rather asymptotic trend. A little variation in the data may be due to the unpredictable nature of the flank wear. The main effect of depth of cut on the flank wear is somewhat increasing. At a lower depth of cut, the amount of workpiece material adhering to the flank is very small. According to [24], as the depth of cut increases, higher temperatures due to the higher material removal rates and material deformation and higher pressures, as well as the cutting forces, result in a larger amount of material adhering to the flank face, thus speeding up the flank wear. Another factor that may contribute towards the higher flank wear at higher values of depth is the inadequate lubrication [25], indicating that the MQL has a reduced cooling capacity at a higher depth of cut. At a higher depth of cut, the area of contact between the surfaces increases [26], thus resulting in higher heat generation and friction. According to [27], increase in the depth of cut results in an increase in the radial force component. This may lead to an increase in the dimension wear rate at the tool nose tip, thus increasing the surface wear rate.

With the cutting tool coated with 4 μm thick TiAlN coating, the trend from the experimental data is somewhat anomalous. The flank wear initially decreases with increasing depth of cut up to almost 2.4 mm, then it increases with the increasing depth of cut. This anomalous behavior may be attributed to the increased toughness of the TiAlN coating [29] and high oxidation resistance. TiAlN coatings exhibit a variety of interesting properties including higher hot hardness, i.e. high hardness at elevated temperature, together with thermal and chemical stability, as well as low thermal conductivity [30, 31]. The formation of aluminum oxide on the surface of the tool, which increases the operational temperature range of the coating to 800° C compared with 500° C for TiN, makes this coating suitable for a wide range of machining applications [32]. Increasing depth of cut is accompanied by high-temperature and high-pressure conditions, which may also result in variation of flank wear. According to [33], increasing Al content along with anisotropic effects at high temperatures and high pressure conditions may result in reduced flank wear. A similar effect is reported by [34].

The behavior of TiAlN+TiN coating with increasing depth of cut shows a linearly increasing flank wear trend. The SEM images of the TiN coating show rupture of the outer coating, i.e. TiN coating, on the main cutting edge. The spalling effect is also found on the coating for almost every design. The phenomenon arises from the coating's failure to accommodate substrate deformation without failure under load. The failure of the coating may be attributed to the mismatch between the mechanical properties of the coating and substrate and the different types of residual stresses: deposition-induced thermal stresses because of a difference between the thermal expansion of the coating and substrate as a result of temperature change from coating to ambient; sliding-induced thermal stresses because of a difference in the thermal expansion of the coating and substrate from temperature change arising from the friction heating during machining; intrinsic stresses due to deposition-induced defects, and sliding-induced deformation strains. In this study, the dual-layer coatings are TiAlN and TiN, and the thermal expansion coefficient for the inner layer, i.e. the TiAlN coating, is smaller than the thermal expansion coefficient of the outer layer, i.e. the TiN coating, so the TiN coating is in constant residual tension. Therefore the coating tends to rupture or spall during machining. As the ceramic PVD coatings are brittle in nature [35], the constant abrasive contact will rapidly result in significant crack initiation and rapid abrasive wear propagation. [36, 37] made similar observations for tool wear of TiAlN+TiN coating. Another important factor that must be considered is the brittle nature of the coatings, which may lead to accelerated wear. The author's judgment is that the higher values of flank wear in the TiAlN and TiAlN+TiN coated inserts as compared to the uncoated insert may be attributed to their brittleness. Any micro-crack or micro-chipping on these brittle coatings may act as a stress-raiser or "wear-raiser", thus accelerating the abrasive wear.

The response in terms of the flank wear of every tool with regard to feed rate is almost the same as given in Figure 5(b). The main effect of flank wear for all the three inserts decreases with increasing feed rate. The WC-Co6.0% uncoated tool and TiAlN coated tool show a clear decreasing trend with the increasing feed rate. On the other hand, the tool coated with TiAlN+TiN shows an initial increase in the flank wear and after a certain value of feed rate around 370 mm/min, the flank wear decreases with increase in the feed rate. The effect of feed rate on tool wear is governed by many factors: cutting or contact time, the relation between the cutting temperature and the tool-work specific optimal cutting temperature, effects of residual heat from previous cuts, and the dynamic rigidity of the machine tool.

For the uncoated WC-Co6.0%, flank wear decreases with increasing feed rate. The decreasing trend of flank wear for the tool may be attributed to the increasing uncut chip thickness as compared to the depth of cold working, and then the decreasing effect is further accelerated with the decrease in sliding contact [38]. According to Astakhov (2007), during any machining operation, the residual heat from the previous cuts also plays an important role. When the cutting feed is smaller, the tool actually has to cut a transient cold-worked surface with higher hardness compared to the actual hardness of the work material, and thus the tool wear increases. As the feed rate increases, i.e., the uncut chip thickness increases and becomes greater than the depth of cold-worked material, the tool wear decreases. The decrease in the tool wear with increasing feed rate may also be attributed to increased dynamic rigidity of the machine tool system because of an increase in normal feed force [38]. With the increasing feed rate, the sliding contact length of the tool path decreases and therefore the contact time also decreases, resulting in less tool wear [25, 38]. Flank wear for the TiAlN coated tool shows a decreasing trend with increasing feed rate. At the start of cutting, the depth of cold working is higher than the uncut chip thickness. As machining proceeds, the sliding contact length and contact time decreases, while the uncut chip thickness becomes greater than the depth of cold working. The combined effect of these two factors results in a decrease in the flank wear. The former factor may dominate the latter one.The behavior of TiAlN+TiN coated tool wear with feed rate is different from the uncoated one. The initial increasing trend may be attributed to the tool-work material's specific cutting optimal temperature [23, 39]. When the machining takes place at a temperature higher than the optimal cutting temperature, wear increases. In the current study, the flank wear increases with feed rate up to a certain feed rate value of almost 370 mm/min, then decreases. The decrease in tool flank wear may be attributed to the reduced sliding contact length and time.

The trends obtained for tool flank wear with cutting speed are different for the three tools as shown in Figure 5(c). The flank wear for the uncoated tool initially decreases with cutting speed and then increases. For the tool with TiAlN coating, the flank wear initially increases with increasing speed and then decreases with increasing speed. The TiAlN+TiN coating shows a linearly increasing trend of flank wear with the increasing speed. The uncoated WC-Co6.0% shows a typical flank wear behavior. Owing to a high hardness and toughness because of the cobalt binder, as the plastic deformation zone reduces with increasing cutting speed, the flank wear decreases as the cutting speed increases. The reduction in the flank wear with increasing speed may also be attributed to the reduction in the cold-working depth of the work material, which decreases with increase in the cutting speed [40, 41]. At a certain optimum cutting speed the flank wear is at the minimum. From there on, the elastic deformation zone begins to form, stabilizes at a certain CCR, then the plastic deformation zone again starts to develop as a result of elastic deformation [42]. With the development of the plastic deformation zone, the tool wear starts to increase after the optimum cutting speed. With the increase of speed, the plastic deformation of cobalt phase is rapid, resulting in the separation of carbide grains from the deforming cobalt layer. The deforming cobalt layer rubs against the hard particles or constituent of the work material, resulting in higher flank wear. Another factor which may also contribute to the improved performance of the tool at low cutting speeds is the built-up edge (BUE) formed at lower cutting speeds. The presence of a BUE is not always damaging, as for rough cuts the presence of a stable BUE can be advantageous by providing an intermediate layer between the tool surface and the workpiece. The cutting edge of the tool is protected from progressive wear due to the formation of a relatively stable BUE that develops at the edge, performing the task of a protective shield on the cutting edge. The cutting force acts on the built-up edge and the cutting edge is protected [26]. The increase in cutting speed results in a decrease in the cutting time and contact between the flank face and cutting layer, so the friction at the interface also decreases and hence the flank wear decreases [43].

The flank wear of the TiAlN coated insert shows an initial increasing trend with increasing cutting speed. After a certain speed of almost 5440 rpm, the trend for flank wear shows a decreasing rate with increasing spindle speed. On account of a low thermal conductivity, the coating ensures that a large portion of heat is generated via the deformed chips. Hence friction becomes the main wear mechanism. The coating shows very little built-up edge on all cutting conditions, and very little spalling or chipping effect. The abrasive wear may have accelerated from the worn edges. In the event of coating removal from the flank at the chipped edges, the tribological contact takes place between the substrate and workpiece. These chipped or worn edges act as wear-raisers and the flank wear accelerates at higher rate because of the high coefficient of friction and brittleness of the coating [44]. The poor performance of the coating at lower speed may also be attributed to the high friction coefficient and brittleness. The advantage of the coating is achieved by operating it at higher temperatures as it shows high temperature stability by forming a dense, highly adhesive and protective oxide layer of Al_2O_3, which makes it tougher and more stable at higher cutting temperatures associated with high cutting speed coatings [45]. The flank wear obtained with the two-layered TiAlN+TiN coating is comparatively higher for the same cutting conditions. The coating shows rupture on the main cutting edge in all cutting conditions. The thermal conductivity is low and heat dissipation is mostly through the chips. Hence the major contributor towards the abrasive wear may be the friction between the flank face of the tool and the machined surface of the work material. Removal of the coating fragments of the full coating thickness from the main cutting edge will result in free edges of the coating [46], which act as wear propagators in the case of abrasion between the coating fragments and the workpiece. Hard inclusions in the work materials and coating fragments contribute to higher flank wear [47].

End milling is an intermittent cutting process and the tool undergoes many cycles of cooling and heating during a cutting process; hence, the tool embrittlement may be caused by the cooling. This tool embrittlement may be accelerated when the tool coating is damaged and there are coating-free edges on the tool surface. These free edges and the micro-cracks on the surface of the tool may trap the mist particles and cause an embrittlement effect. This effect was discussed by the Russian researcher Epifanov in 1977 [29]. The wear rapidly progresses from these micro-cracks. The flank wear behavior against the MQL flow rate for the three tools in the current study is consistent with the above findings. The effects of MQL flow rate on flank wear are shown in Figure 5(d). For the uncoated WC-Co tool, the MQL flow has almost no effect on the flank wear. This may be due to the built-up edge covering the cutting edge of the tool, making the fluid unable to reach the flank face. This also shows that the amount and velocity of the coolant are not enough to remove relatively stable built-up material. The high rotating speed of the tool also hinders the cooling effect because of the high centrifugal force. The tool coated with TiAlN also shows very little effect on the flank wear. In the case of the tool coated with the dual coating of TiAlN+TiN, the tool wear rapidly increases with the increasing flow rate. Wear of the ruptured top layer, i.e. TiN, provides free edges which serve as stress concentrators, while trapping of bigger mist particles will result in the rapid progression of flank wear.

Table 3. Comparison of input and optimum solutions for uncoated WC-Co6.0% insert under MQL machining.

Initial variables	Initial values		Optimum cutting variables
	Minimum	Maximum	
Cutting speed, rpm	5252	5548	5548
Feed rate, mm/min	288	469	463.1
Depth of cut, mm	0.52	3.48	1.610
MQL flow rate, ml/min	0.39	0.90	0.430
Objectives	Initial values		Optimum solution
	Minimum	Maximum	
Minimize surface roughness, µm	0.279	2.102	0.430
Minimize flank wear, µm	20.71	43.20	14.23
Maximize material removal rate, mm^3/min	2116.5	15443.1	8602.5
Constraints			
0.27 < Surface roughness, µm < 2.103			
14.1<Flank wear, µm < 43.3			
2116.6 < Material removal rate, µm < 15444.0			

Table 4. Comparison of input and optimum solutions for TiAlN coated insert under MQL machining.

Initial variables	Initial values		Optimum cutting variables
	Minimum	Maximum	
Cutting speed, rpm	5252	5548	525.2
Feed rate, mm/min	288	469	38
Depth of cut, mm	0.52	3.48	3.48
MQL flow rate, ml/min	0.39	0.90	0.657
Objectives	Initial values		Optimum solution
	Minimum	Maximum	
Minimize surface roughness, µm	0.212	1.505	0.375
Minimize flank wear, µm	59.90	97.44	27.35
Maximize material removal rate, mm^3/min	2069.2	15642	15536
Constraints			
0.211 < Surface roughness, µm < 1.506			
21.6 < Flank wear, µm < 98.4			
2069.1 < Material removal rate, µm < 15462.2			

The results of optimization from MOGA-II are sets of non-dominated optimal feasible solutions depicting a trade-off among the three objectives for all the machining conditions. These sets are called Pareto design sets. Pareto designs are selected from among the feasible designs and thus the feasibility of these designs is ensured. The Pareto approach to optimization is aimed at identifying the set of parameters that characterize a design and beyond which no aspect of performance can be improved without compromising another. In order to decide which design is the most optimal or most compromised among all the solutions from a list of optimal Pareto designs, the multi-criteria decision-making (MCDM) approach is used. Alternative Pareto designs are ranked according to their fitness to the applied evaluation criteria or according to the decision-maker's preference. In this study, the ranking of Pareto designs is based on equal weights assigned to each response variable. In order to select a single best compromised solution among the solutions located on the Pareto frontiers, the MCDM tool provided in modeFRONTIER is employed. Depending on the non-preference based relation among the response variables, all the solutions are classified with rank values. The results of the optimization are listed in Tables 3-5 for three different cutting inserts such as uncoated WC-Co6.0%, TiAlN single carbide coated and TiAlN+TiN dual carbide coated insert respectively.

Table 5. Comparison of input and optimum solutions for TiAlN+TiN coated insert under MQL machining.

Input variables	Initial values		Optimum cutting variables
	Minimum	Maximum	
Cutting speed, rpm	5252	5548	5271
Feed rate, mm/min	288	469	468.9
Depth of cut, mm	0.52	3.48	2.03
MQL flow rate, ml/min	0.39	0.90	0.41
Objectives	Initial values		Optimum cutting variables
	Minimum	Maximum	
Minimize surface roughness, µm	0.202	1.047	0.204
Minimize flank wear, µm	41.0	82.64	39.7
Maximize material removal rate, mm^3/min	2104.7	15305.8	10758.0
Constraints			
0.201 < Surface roughness, µm < 1.048			
26.1 < Flank wear, µm < 97.0			
2104.6 < Material removal rate, µm < 15306			

CONCLUSIONS

End milling machining with minimum quantity lubrication for aluminum alloy 6061-T6 is investigated in order to assess the effects of minimum quantity lubrication on flank wear of the uncoated and coated tools. Multi-objective optimization of the end milling process is performed. The performance of the uncoated carbide insert, TiAlN coated insert, and TiAlN+TiN coated inserts is compared. The performance of the TiAlN coated inserts is the best of the three inserts used on account of its high toughness and hot hardness. For multi-objective optimization, the surface roughness and material removal rate are also modeled. The best feasible design is selected from among the feasible Pareto optimal designs. The optimal design selected provides the optimum operating parameters for the experimental domain.

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