Assessment of Flank Wear and Tool Life in High Speed Face Milling under Dry and Near Dry Machining

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Abstract

One of the leading environmental pollution sources related to machining industry is the massive amount of cutting fluids used. However, coolant performs many advantages, such as chip removal and reducing the cutting zone temperature. This research aims to analyze the effect of dry machining and near dry machining on flank wear progress in high-speed face milling. Two sets of experiments using Box Behnken Design (BBD) as a part of Response surface methodology (RSM) have been conducted for both dry machining and near dry machining on milling AISI 1050 using five coated carbide inserts (TNGA 160408) for each treatment. The flank wear in both dry and near dry machining was measured using Hisomet II Tool Maker Microscope. The boundaries of the variables in this research are 613-817 (m/min) cutting speed, 100-200 (mm/min) feed rate, and 0.1-0.2 (mm) depth of cut. The results show that at high speed near dry milling, the flank wear and the tool life was better as compared with the dry machining. A new mathematical model for flank wear and tool life has been developed. In conclusion, near dry machining proved to be a better option at high speed.

Keywords: High speed face milling, Flank wear, dry machining, near dry machining

1. Introduction

One of the basic milling processes is the face milling that applied widely in many critical components in different industries, such as gear case, engine block, etc. With the current prominence in shortening time to market and achieving higher productivity levels with higher precision, the face milling process has received considerable interest from many researchers. One of the approaches to take advantage of this process is by increasing the machining speed and then rising in the material removal rate and then to a shorter time to market. This will have some consequences, such as increasing the cutting forces and, later, the temperature. Meena (2011) stated that the growing demands for machining high productivity require high material removal rates, which require high cutting speed and feed rate. These consequences will lead to accelerating the tool wear, especially the flank wear, and as a result, it will shorten the tool life and lead to the need for an effective cooling system. Therefore, the need of coolant become essential. However, the use of cutting fluids is of concern from an environmental perspective, hazard to human contact and increase the overall manufacturing cost. Some researchers have a different point of view, Kumar and Choudhury (2008) claim that using dry machining will lead to reducing the cutting forces. Lin et al. (2008) said that increasing the cutting speed will lead to increases in the cutting temperature, and then the hardness of workpiece material is decreased; accordingly, as a result, both the principal cutting force and feed force will reduce. However, the increasing consciousness of responsibility towards the environment, together with stricter pollution control requirements and maintaining acceptable flank wear rate, demand a balanced machining process. One of the approaches is by going through near dry machining (NDM). NDM is also named as Minimum Quantity Lubricant (MQL). However, NDM is reducing the environmental pollution of cutting coolant and effectively decreasing production costs and, at the same time, having the advantages of coolant such as cleaning the machining area, chip removal, and reducing the cutting zone temperature. Near-dry machining is the approach of using small amounts of lubricant to the tool/workpiece interface that will reduce the threat to the environment and high cost associated with the use of cutting fluids. Filipovic and Stephenson (2006) mentioned that there are two basic types of MQL delivery systems: external spray and through-tool. The external spray system consists of a coolant tank or reservoir related to tubes fitted with one or more nozzles. The system can be assembled near or on the machine and has independently adjustable air and coolant flow for balancing coolant delivery. It is inexpensive, portable, and suited for almost all machining operations. The advantages of such systems are simplicity and low cost; they are suited to be retrofitted to existing machines with high-pressure, through the tool coolant capability. They are accessible to service; no critical parts are located inside the spindle.

Many researchers investigated the use of NDM in the literature (Okafor & Nwoguh, 2020: Kulkarni et al., 2020: Hazza, 2016: Hazza 2020: Chirita et al., 2019: Upadhyay et al., 2013: Yoshimura et al., 2006). Some of them tried to compare the output responses from dry and near dry machining. Yan et al. (2009) investigated the cutting performance of MQL and compared it to dry and near dry cutting using cemented carbide tools in milling high strength steel. The results indicated that MQL reduced tool wear and surface roughness as compared to dry and near dry cutting. Masoud et al. (2019) compares and investigated the effect of machining parameters in MQL, near dry and dry machining on surface characteristic and geometric tolerances in turning of parts made of AISI 1045 steel.

Other researchers tried to investigate the effect of different types of coolants on the outputs of the machining. Sharif et al. (2009) had evaluated the performance of vegetable oil as an alternative cutting lubricant when end milling stainless steel using TiAlN coated carbide tools. The results indicated that vegetable oil using MQL outperformed dry cutting and flood cooling when tool life and surface roughness are the response variables. Others discussed the dry and near dry from the point view of considering this process as one of the green and sustainable manufacturing (Debnath et al., 2019: Fratila, 2010: Goindi & Sarkar, 2017: Andriani et al. 2016: Gajrani et al., 2019: Mohamad, 2016). Debnath et al., 2019 discussed the traditional fluids and their ecological problems compared to the new green lubricants. They overt the latest development in the cutting fluids and their relative advantages and disadvantages toward green manufacturing. Sultana et al., 2019, conducted a comprehensive review on the effects of different cooling strategies on output responses and the effect of different with their positive and negative impacts is also discussed. Singh et al. 2016 have critically reviewed about 90 scholarly articles related to using near dry machining of difficult to machine alloys. Sharma et al. (2016) conducted a comprehensive review. Sharma et al. (2016), in their review paper, discussed the effect of using MQL on the performance parameters of different machining processes. They claimed that the MQL technique is a viable alternative to the near dry machining under similar performance parameters.

2. Experimental Work

The experiments are carried out using CNC Gate Milling Machine type ECMI with ANILAM 5300 MK Control. This experiment was performed using coated carbide inserts (TNGA 160408), which is attached to a 65 mm diameter face milling cutter. Five inserts were attached to mill cutter for each run of the experiment. Minimum Quantity Lubrication (MQL) System were used during near dry machining operation which act as supplier of minimum lubricant. The system is an external spray. Flank wear for each insert was measured. Average flank wear for all five inserts is calculated. The work material used was a carbon steel S50 grade (AISI 1050) of dimension approximately 200x90x50 mm. The Machining operations were carried out under dry and near dry cutting conditions. Flank wear was measured every 100 mm of cutting length. The tests were carried out following ISO 3685 (1993) using tool life criteria of average flank wear: 0.3 mm as maximum value for tool life.

The box-Behnken design (BBD) was used to design and conduct the experiments. 15 runs for each experiment was conducted. BBD are one of the response surface methodology (RSM) collections used to calibrate full quadratic models. BBD is rotatable. However, the advantages of BBD with small number of factors (four or less) with three levels of each factor, require few runs. By avoiding the corners of the design space, they allow experimenters to work around extreme factor combinations. BBD are used to calibrate full quadratic models for a small number of factors (four or less), require few runs. It is suitable for exploration of quadratic response surfaces and construction of a second order polynomial model, thus helping in optimizing a process using a small number of experimental runs. The ranges of cutting speed, feed rate and depth of cut were selected and shown in Table 1.

Table 1 Ranges of parameters for the experiment

Parameters	**Minimum**	**Maximum**
Cutting speed (m/min)	613	817
Feed rate (mm/min)	100	200
Depth of cut (mm)	0.1	0.2

3. Results and Discussion

This section discusses the result and analysis on the effects of dry and near dry machining in high speed milling. The cutting response in terms of flank wear and tool life was studied. Then, comparisons of these cutting responses between dry and near dry machining have been done. The International Standard Organisation (ISO 3685) was used as a benchmark and reference in calculating the tool life. The average flank wear of 0.3 mm with maximum flank wear 0.4 mm was used to calculate the tool life in dry and near dry machining. Simple calculation by using Equations 1 and 2.

$$Wear\ rate = \frac{flank\ wear}{machining\ time} \tag{1}$$

$$Tool\ Life = \frac{0.3}{wear\ rate} \tag{2}$$

3.1 Statistical Analysis

The Analysis of variance (ANOVA) and F ratio tests were conducted to confirm the goodness of fit to develop a prediction model. In this research, a 95% confidence interval was used with p-value less than 0.05 is considered significant. R^2, adjusted R^2, and predicted R^2 were calculated and analyzed. Using the adjusted R^2, which increases when removing the insignificant terms from the model, will avoid adding irrelevant terms. In contrast, R^2 is always increasing by adding significant or insignificant terms. Therefore, the best when the values of R^2 and adjusted R^2 are high and close together. Moreover, the higher value of predicted R^2 can give a higher percentage of variability in predicting new observations. Tables 2, 3, 4, and 5 show the ANOVA for the investigated factors.

Table 2: ANOVA for Response Surface Reduced Quadratic Model (Vb (Dry)

	Sum of		Mean	F		
Source	Squares	DF	Square	Value	Prob > F	
Model	0.000309	6	5.15E-05	32.20519	< 0.0001	significant
A	4.44E-05	1	4.44E-05	27.77357	0.0008	
B	5.58E-05	1	5.58E-05	34.86557	0.0004	
C	7.2E-06	1	7.2E-06	4.502902	0.0666	
B2	1.59E-05	1	1.59E-05	9.954875	0.0135	
AC	2.21E-05	1	2.21E-05	13.84262	0.0059	
BC	0.000164	1	0.000164	102.2916	< 0.0001	
Residual	1.28E-05	8	1.6E-06			
Lack of Fit	7.91E-06	6	1.32E-06	0.539351	0.7639	not significant
Pure Error	4.89E-06	2	2.44E-06			
Cor Total	0.000322	14				

Table 3: ANOVA for Response Surface Reduced Quadratic Model TL (Dry)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1194.149	6	199.0248	200.8101	< 0.0001	significant
A	8.423296	1	8.423296	8.498856	0.0194	
B	1086.377	1	1086.377	1096.122	< 0.0001	
C	9.480073	1	9.480073	9.565112	0.0148	
B2	36.91715	1	36.91715	37.24831	0.0003	
AC	4.422357	1	4.422357	4.462027	0.0676	
BC	48.52927	1	48.52927	48.96459	0.0001	
Residual	7.928875	8	0.991109			
Lack of Fit	6.856891	6	1.142815	2.132148	0.3532	not significant
Pure Error	1.071985	2	0.535992			
Cor Total	1202.078	14				

Table 4: ANOVA for Response Surface Reduced Quadratic Model Vb (ND)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	0.000184	7	2.63E-05	21.14733	0.0003	significant
A	0.000123	1	0.000123	98.93067	< 0.0001	
B	1.76E-05	1	1.76E-05	14.16135	0.0070	
C	7.84E-06	1	7.84E-06	6.293931	0.0405	
C2	1.96E-05	1	1.96E-05	15.71554	0.0054	
AB	6.25E-06	1	6.25E-06	5.016972	0.0601	
AC	4.84E-06	1	4.84E-06	3.885143	0.0893	
BC	5.02E-06	1	5.02E-06	4.027705	0.0848	
Residual	8.72E-06	7	1.25E-06			
Lack of Fit	4.16E-06	5	8.32E-07	0.364903	0.8428	not significant
Pure Error	4.56E-06	2	2.28E-06			
Cor Total	0.000193	14				

ANOVA tables evidence that the modified models can be used to navigate the design space for predicting the flank wear and tool life. The R^2, adjusted R^2, and predicted R^2 were calculated and shown in the Table 6. The table is showing that the values of R^2 for the four models are considered high enough and close to the value of the adjusted R^2 which means that the models are reliable for future prediction. Moreover, all the predicted R squared are more than 80% which considered good and acceptable to use the models in predicting the new observations in the boundaries of the experiment design. Moreover, the signal to noise as well was calculated and shown in Table 7.

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From the developed model, the graphical illustrations were shown in Figures 1, 2, 3 and Figure 4. The error between the experimental work and the predicted models were calculated to give more reliability to the developed models and shown in Table 9.

Table 5: ANOVA for Response Surface Reduced Quadratic Model TL (ND)

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	1659.311	6	276.5518	234.2381	< 0.0001	significant
A	66.25006	1	66.25006	56.1135	< 0.0001	
B	1477.876	1	1477.876	1251.754	< 0.0001	
C	2.815244	1	2.815244	2.384499	0.1611	
B2	89.75552	1	89.75552	76.02251	< 0.0001	
C2	7.708101	1	7.708101	6.528726	0.0339	
AB	18.18272	1	18.18272	15.40068	0.0044	
Residual	9.445152	8	1.180644			
Lack of Fit	7.88238	6	1.31373	1.681282	0.4188	not significant
Pure Error	1.562772	2	0.781386			
Cor Total	1668.756	14				

Table 6: R squared values

R	Vb (Dry)	TL (Dry)	Vb (ND)	TL (ND)
R-Squared	0.960245	0.993404	0.954848	0.99434
Adj R-Squared	0.930428	0.988457	0.909696	0.990095
Pred R-Squared	0.883631	0.957762	0.819991	0.974656

Table 7: Signal / Noise Analysis

	Vb (Dry)	TL (Dry)	Vb (ND)	TL (ND)
S/N	20.91723	44.51301	15.29233	44.37574

Table 8: prediction models

Prediction factor	Final Model in Terms of Actual values:
Vb (Dry)	$=+0.19812-9.22917e^{-5}*Vc-5.787e^{-4}*f-0.73249DoC+8.26e^{-7}f^{2}+4.61275e^{-4}Vc*DoC+2.558e^{-3}f * DoC$
TL (Dry)	$=+27.54727+0.040986* Vc-0.40143 * f+378.17245 * DoC+1.25784e^{-3} * f^{2}-0.20617 * Vc * DoC-1.39326 * f * DoC$
Vb (ND)	$=+0.051923-4.28922e^{-5}* Vc-7.83451e^{-5}*f+0.47642* DoC-0.916*DoC^{2}+2.45098 e^{-7}*Vc* f-2.15686e^{-4}* Vc * DoC-4.48e^{-4}* f * DoC$

TL (ND)	$=+63.31572+0.090921*Vc-0.56282*f-161.00474*DoC+1.96631^{e-3}*f^{2}+576.23023*DoC^{2}-4.18051e^{-4}*Vc*f$

Table 9: Models accuracy

Model	Vb (Dry)	TL (Dry)	Vb (ND)	TL (ND)
Error %	1.23232	2.280929	1.12925	2.04181

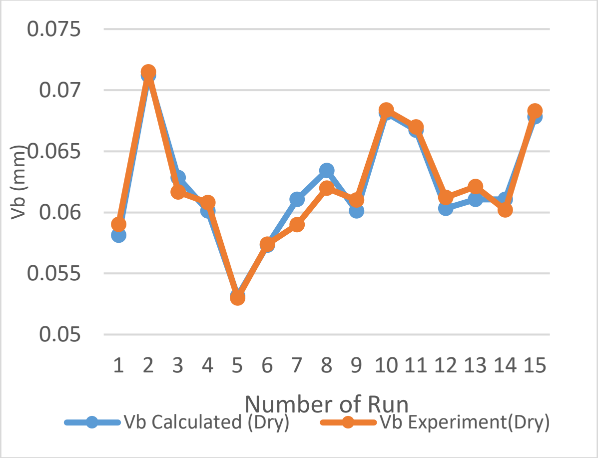

Figure 1: Measured and calculated flank wear in dry machining

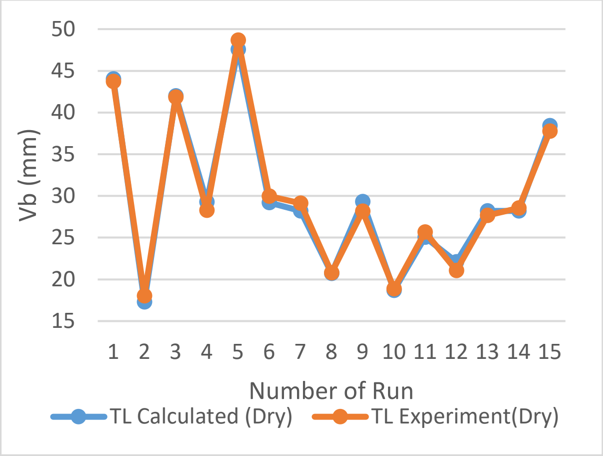

Figure 2: Measured and calculated tool life in dry machining

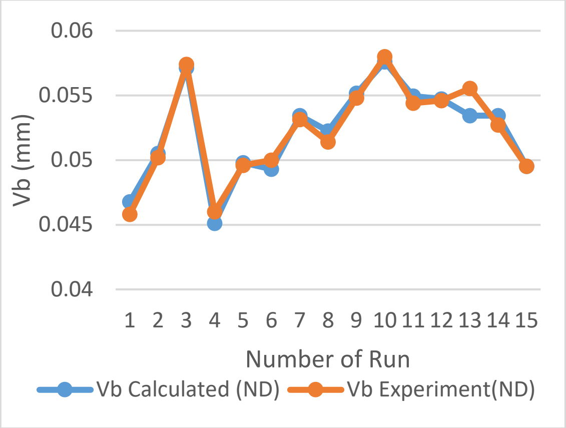

Figure 3: Measured and calculated flank wear in near dry machining

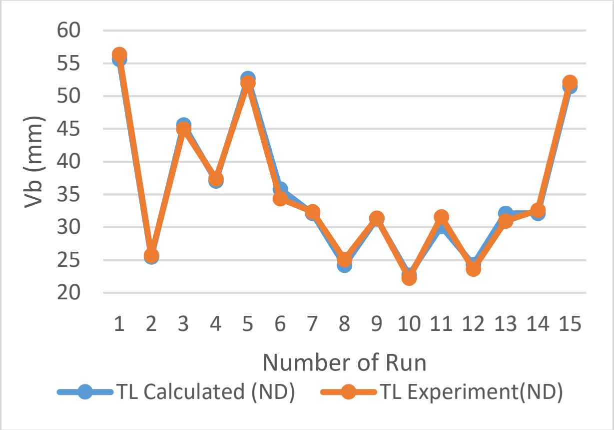

Figure 4: Measured and calculated tool life in near dry machining

As shown table 9, the four models have an error of less than 3%. This low value of error can give high reliability for future prediction in the boundaries of the design. The flank wear progress and tool life in dry and near dry machining were compared graphically for the same treatments and shown in Figure 5 and Figure 6.

Based on the graphs in Figure 5, it can be concluded that flank wear of cutting tool insert for near dry milling tends to be lower than those in dry milling and as results the tool life as shown in figure 6 of cutting tool insert for near dry milling tends to be higher than those in dry milling as expected from lower flank wear result.

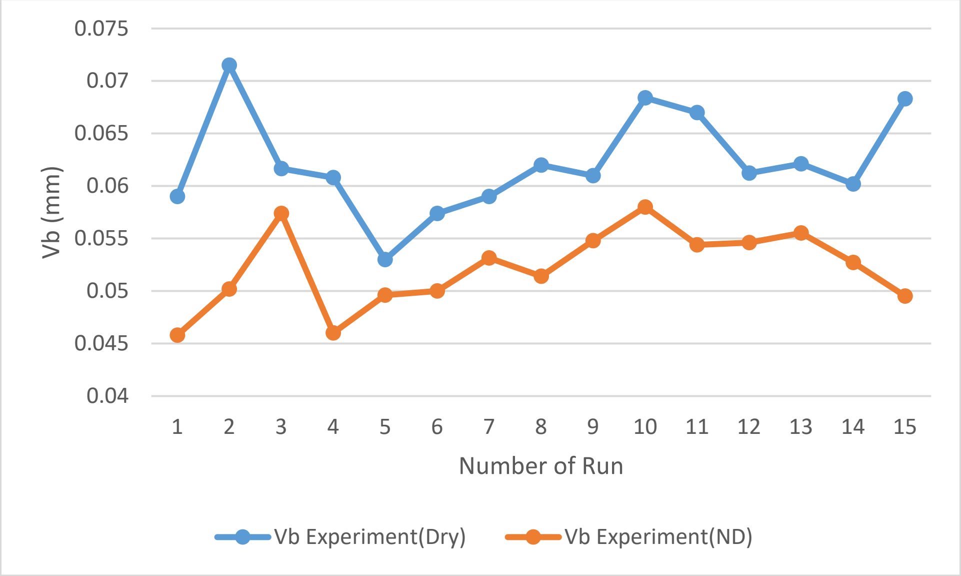

Figure 5: Flank wear in dry and near dry machining

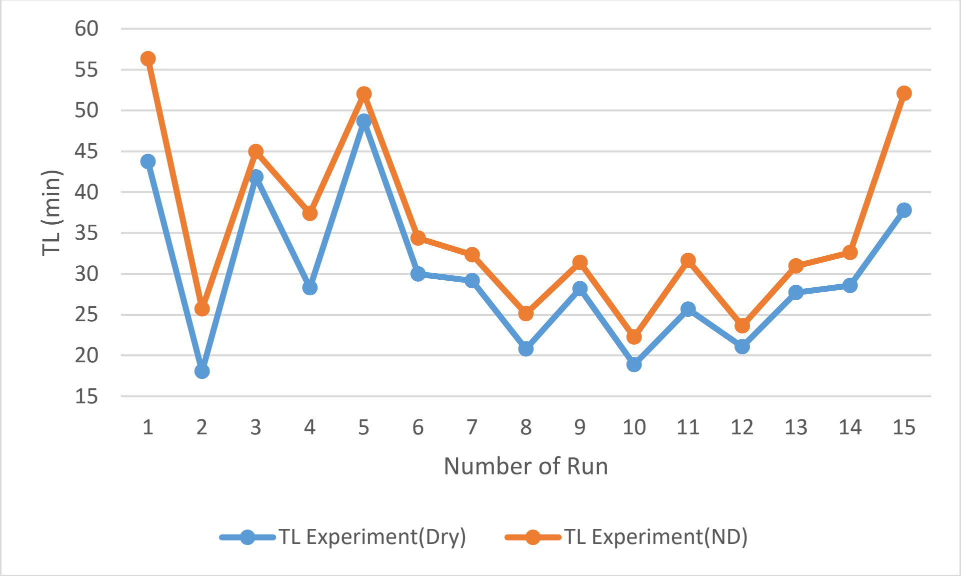

Figure 6: Tool life in dry and near dry machining

Conclusions

The flank wear and then the tool life in both dry and near dry machining was measured and compared. The results can be concluded in the followings:

1. At high speeds, the near-dry milling shows better effectiveness in terms of flank wear progress and, as a result, the tool life for the same level of treatment.
2. The four mathematical model for flank wear and tool life for both: dry and near dry milling: Vb (Dry), TL (Dry), Vb (ND), and TL (ND) show a high level of accuracy with low rate percentage of error of 1.23%, 2.28%, 1.13%, and 2.04% respectively.
3. With this small percentage error, the developed mathematical model can be accepted and applicable for any values within the boundary design.

4. Both dry machining and near dry machining are best practices in reducing the environmental pollution coming from cutting coolant and effectively decreasing the production cost while practicing the safety and health of the human being.
5. The need for cost justification is considered one of the most recommended research areas that supported the green technology implementation

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Biography

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