Effect of chamfer width and chamfer angle on tool wear in slot milling

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Abstract

The tool geometry is generally of great significance in metal cutting performance. The response surface method was used to optimize chamfer geometry to achieve reliable and minimum tool wear in slot milling. Models were developed for edge chipping, rake wear, and flank wear. The adequacy of the models was verified using analysis of variance at a 95% confidence level. Each response was optimized individually, and the multiple responses were optimized simultaneously using the desirability function approach. The Monte Carlo simulation method was applied to tolerance analysis. All milling tests were conducted at dry conditions; the chamfer width and the chamfer angle varied between 0.1 and 0.3 mm, and 10 and 30°, respectively. Optimal chamfer geometry for minimizing chipping and rake wear was small chamfer width and chamfer angle. The flank wear reached the minimum value for the tool with 0.18 mm chamfer width and 10° chamfer angle. The obtained composite model predicted good edge strength and minimum overall wear when the chamfer was 0.1 mm wide at a 10° angle. Thermal cracks were observed on the tools. They were small on the edges with the finest and least negative chamfer but were more significant on the more negative and greater chamfer. A great chamfer width and chamfer angle also resulted in insufficient chip evacuation. The results show how the edge geometry affects the tool's reliability and wear and may help manufacturers minimize tool cost and downtime.

Keywords Chamfered tools · Tool wear · Slot milling · Response surface · Multi-objective optimization · ANOVA · Monte Carlo simulations · Tolerance analysis

1 Introduction

Finding an optimum tool edge geometry to improve tool life reliability during machining is of great importance, especially when manufacturing parts with high accuracy and or high productivity demands. In cutting off or milling deep grooves in steels using carbide cutting tools, one problem is to avoid edge chipping and cracks. Chipping and cracks on the cutting edge can lead to tool breakage and abrupt interruptions in production. Chipping or breakage is the result of an overload of mechanical tensile stresses. These stresses can be due to several reasons, such as re-cutting

chips, improper depth of cut or feed, hard inclusions in the workpiece material, adhesive wear and deposits on rake and clearance of the cutting tool, vibrations, or excessive wear on the cutting insert.

Using a tougher tool material and or inserts with reinforced cutting edge is one solution. The cutting edge can be strengthened in three ways: rounding, chamfering, and designing a negative primary phase [1, 2]. Chamfered edges are often used on cubic boron nitride, polycrystalline cubic boron nitride, and ceramic tools; honed edges on diamond, polycrystalline diamond, and cemented carbide tools [3]. A combination of those three ways is also possible. During the manufacturing of tools, coating applications may develop substrate and coating stress fields in the cutting edge region. In some cases, the maximum stresses can exceed the corresponding yield strength. Bouzakis et al. [4] showed that applying a negative chamfer decreases the developed stresses and thus improves the tool performance. The effect of different chamfer angles or chamfer widths was though not accounted for in the stress distribution in the edge region.

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Although tool performance reliability improves by edge strengthening, the shape of the edge also affects tool life and chip control [1]. Generally, a blunter edge (for example, when a tool edge is protected with a negative chamfer) increases cutting forces and temperatures. There is a lower limit of undeformed chip thickness in metal cutting at which the chip will be formed [5]. Below this minimum chip thickness, rubbing and plowing take place instead of shearing. Greater chamfer increases the minimum chip thickness [6]. Therefore, the effects of the geometry and the chip thickness need to be considered, especially in machining techniques where the critical chip thickness can be on the same order of magnitude as tool edge dimensions, such as in micro-machining. A detailed and thorough investigation of chip formation mechanism in micro-milling is described in ref. [7]. It was shown that the thrust force and the cutting force could be in the same order of magnitude due to the plowing effect. Also, long chips, consisting of many chips from consecutive revolutions, were produced. In ref. [8], the edge chamfer of a micro-mill prevented early tool breakage. However, greater chamfer width caused the tool flank wear width to increase due to the higher stress in the cutting region; the influence of different chamfer angles was not considered.

A nonlinear relationship between the cutting forces, especially the thrust force (feed force), and the undeformed chip thickness has been reported for a chamfered tool, 0.22-mm wide and 17.8° angle, during varying cutting speeds and feed rates in orthogonal turning [3]. Furthermore, Zhou et al. [9] optimized cutting edge geometry for PCBN tools in hard turning based on cutting tests and FEM analysis. It was shown that large chamfer angles produce higher friction and result in more significant rake wear while the flank wear does not follow the same trend; it is at a minimum value simultaneously as the principal stresses on the chamfer area flank face have the smallest value. However, the effect of different chamfer widths was not considered in the investigation. Later, Choudhury et al. [10] investigated cemented carbide chamfered tools' performance. However, regarding tool life, cutting tests were conducted only with chamfered tools of different angles at a constant chamfer width of 0.20 mm. He et al. [11] studied the effect of negative chamfered edges on two hard alloy inserts made for semi-finishing P series steel. It was shown that tool lifetime decreased when the feed increased. The decrease in lifetime was strongly dependent on the cutting speed. At lower cutting speeds, such an increase in feed decreased the tool life slightly, while the tool life decreased significantly at higher cutting speeds. Regarding chamfer geometry, the reduction in tool life at higher feeds was slower for greater chamfer angles. Furthermore, the authors concluded that the tools failed mainly due to flank wear and chipping under small feeds but failed due to brittle fracture at high feeds. However, the analysis did not include the relationship between chamfer angle and chamfer

width; curve fitting parameters, robustness, and other statistics were not reported.

Thus, to obtain several goals, i.e., high edge strength (reliable machining process) and low wear (long tool life), the edge geometry needs to be such that within an acceptable range for each geometry variable, the combined variable settings jointly optimize the set of high edge strength and low wear.

The most common standard chamfer design is a single chamfer, but there are also tools with two or more chamfers [2]. The chamfer angle ranges typically from 20 to 45°, and the chamfer width, 90-degree lead angle in turning, is usually kept below 30% of the feed [1]. For most cutting inserts, the chamfer width ranges from 0.1 to 2.0 mm [3]. Recommendations of chamfer widths and chamfer angles can be found in tooling catalogs. The chamfer can also be of a continuous type, so-called variable chamfer, one angle near the edge, and a gradual change to the chamfer angle near the rake [12]. Tool wear morphology for a uniform 30° chamfered edge and a variable chamfered edge, its chamfer angle gradually increasing from 15° of the tip to 30° of both sides, was observed and compared [12]. The chamfer of both tools was 0.1-mm wide. For the tool with a variable chamfered edge, the rake wear area was larger, and the wear depth was less, and its rake crater wear boundary was relatively farther from the cutting edge. The difference was explained by different chip forms and chip flows. However, different chamfer angles and widths were not investigated, and the relationship between chamfer width and chamfer angle was not considered.

Greater chamfer widths may result in chip jamming. Bad chip formation and evacuation also affect the machined surface finish. By examining the machined groove, if chip jamming has occurred, an uneven surface will be visible. In workshops, the best way to identify such problems is to listen during milling. A consistent sound indicates good chip evacuation. On the other hand, an interrupted sound and or excessive noise generation typically means there is chip jamming and or the tool is worn out. Therefore, chip evacuation can be selected as a response variable and may provide information to evaluate cutting tool micro-geometry.

All cutting tool materials are hard and brittle. The difference between tensile strength and compressive strength for cemented carbide is roughly 100 times. High compression is, in most cases, not a problem, but if tensile stresses occur somewhere in the cutting tool materials, there is a risk for fatigue and chipping. High pressure and high forces are as such not so critical, but with them comes high temperatures, which softens the cutting tool materials.

Negative rake chamfer reduces or eliminates the tensile stress near the edge and in the rest of the cutting tool. The current practice regarding chamfer optimization is iterations with prototypes and machining tests. This way is not

so precise and takes much time. The main problem is a random outcome. The chamfer dimensions, tool life, fatigue, and chipping have all significant random components. A more theoretical approach is needed.

This work aims to increase knowledge about how the combination of chamfer width and chamfer angle affects the tool wear and thereby help steel component manufacturers to minimize tool cost and downtime while maintaining sustainable manufacturing. The objective is to improve the micro-geometry of the cutting edge of a grooving and cut-off tool using design of experiments and multiple response optimization. Quadruple objectives are considered, triple continuous wear responses and one categorical chip evacuation response. The models described in this paper include the relationship between chamfer width and chamfer angle. Single tooth milling is applied for the verification of the theories, see Fig. 1.

2 Materials and methods

The strategy was to examine the factors and determine the approximate best conditions using the multivariate approach. Full factorial design at three levels allowed modeling a second-order response surface and was therefore used as the optimization design [13].

A mathematical regression model was built for each continuous response, fitting a second-order polynomial function. Only second-order interactions were considered since higher-order interactions are very rarely significant in these cases and make the results difficult to interpret. The quadratic model applied to the control factors is:

$$Response_i = b_{i,0} + b_{i,1}w + b_{i,2}\gamma + b_{i,3}w\gamma + b_{i,4}w^2 + b_{i,5}\gamma^2 \quad (1)$$

where $b_{i,j}$ is coefficient estimates for the regression.

Fig. 1 Single tooth milling

The model coefficients were estimated by the method of ordinary least squares [13]. In each model, the significance of the regression terms was evaluated using test statistics from t test (t value) and associated probability value (p value) [13].

The terms that were not significant in the models were discarded to simplify the regression models reasonably [14] and the models were compared to the quadratic model from Eq. (1).

Analysis of the models' variance tests (ANOVA) was computed to give a decent prognostic of the model's goodness of fit [13]. The ANOVA table shows the degree of freedom, the sum of squares, mean squares, F values, and p values. If the p value for the regression model was less than the significance level of 0.05, it was assumed that there exists a significant relationship between the response and the predictor variables. Additionally, the ANOVA partitions the residual into the part for the multiple measurements, pure error, and the rest, which is due to the lack of fit of the regression model. If the p value is smaller than the significance level of 0.05, there is sufficient evidence to conclude a lack of fit in the regression model.

Model summary statistics, R squares (percentage of the variations) were used as a decision tool as well. The best models were defined as the simplest models having both adjusted deviance values R^2_{adj} and predicted deviance values R^2_{pred} as high as possible at the same time.

In order to assess whether the errors could be assumed normally distributed, a visual inspection of standardized residuals of the models was performed.

The response surface methodology generated contour maps as a way of visualizing the results. The contour plot consists of constant response curves corresponding to a specific value of the response surface. These contours help to predict response at any zone of the experimental domain.

The responses were optimized individually, and the optimum value for each response was calculated.

Variation of the chamfer geometry is expected for all manufactured components. These uncertainties can be studied via Monte Carlo simulations [15]. The simulations were used to check how the variability in settings is transmitted and affects the predictions [16]. Normally distributed data sets representing model uncertainty and factor tolerances were defined using the Matlab *normrnd* built-in function (www.matlab.com). The factor tolerances of $\pm 10\%$ were used based on engineering experience. The random model noise was based on the standard deviation of the regression model and was added to the simulated predictions. This noise represents the uncontrolled variation in the prediction. The responses were estimated for 10,000 test simulations.

Table 1 Chemical composition of SS 2541–03, (EN 34CrNiMo 6, not Calcium treated) (%)

C	Si	Mn	S	Cr	Mo	Ni	Fe
0.35	0.25	0.70	0.03	1.4	0.20	1.4	Balance

The multi-response surface problem was optimized simultaneously by overlaying the response surfaces [13]. Also, composite desirability function, D , was constructed [17, 18]:

$$D = \left(\prod_{i=1}^n d_i^{k_i} \right)^{1/n} \quad (2)$$

where d is the individual desirability function, n is the number of responses, and k is an importance-factor for each response. The importance factor lie between zero and one and satisfy

$$\sum_i^n k_i = 1 \quad (3)$$

The individual desirability function for minimization problem is:

$$d_i = \begin{cases} 1.0 & \text{if } \hat{Y}_i < T_i \\ \left(\frac{\hat{Y}_i - U_i}{T_i - U_i} \right)^t & \text{if } T_i \leq \hat{Y}_i \leq U_i \\ 0 & \text{if } \hat{Y}_i > U_i \end{cases} \quad (4)$$

where $\hat{Y}$ is predicted or simulated response value, U is the upper bound value of the response, T is the target value of the response (equal to the local minimum), and the exponent t is a weighting function. The weighting determines the shape of the individual desirability function. For $t = 1$, the value of d linearly decreases from one to zero. If $t < 1$, the shape of d is concave, and if $t > 1$, the shape is convex.

2.1 Experimental procedure

SS 2541–03 steel square bars of 250 mm × 250 mm and height of 60 mm was used as workpiece material during the milling tests. Two thousand five hundred forty-one belongs to the Swedish standard high-strength Nickel Chromium Molybdenum alloy structural steel. It is commonly used for large axles, machine components, tools, and high-strength fasteners. The equivalent European standard is EN 34CrNiMo 6 QT. The matrix material is tempered martensite with an average Brinell hardness of 275 HB. The chemical composition of the alloy is given in Table 1.

The cutting tool, a disc milling cutter, D_c 100 mm (Mircona NGOT27 × 100 × 29 × 4) was mounted in a vertical milling machine, DMU 40 DECKEL MAHG. The cutting insert selected for the experiments was a PVD coated cemented carbide, Mircona MT-4, mounted in the cutter: Rake angle $\gamma_o = 10^\circ$, clearance angle $\alpha_o = 5^\circ$, auxiliary clearance angle

$\alpha_o' = 6^\circ$, grade TNP1405. The coating material is TiAlN. The experiments were performed with a single cutting insert mounted in the milling cutter to minimize the potential influence of the runout of the cutting edges among the trials. The experimental setup is shown in Fig. 2.

To reduce the risk of tool, chipping down milling (also called climb milling) was used [1]. Both upon cutter entrance and exit, the feed was reduced by 50% [19].

The cutting conditions depend on the workpiece material, tool, machine, and required machined surface quality. In order to select suitable cutting data, preliminary tests were conducted based on tool manufacturer recommendations for the given cutting tool-workpiece system and especially checked so that no built-up edge formation or severe crater wear was observed during 40 min of machining. The preliminary tests led to the following parameters: Mean chip thickness, h_m , and radial depth of cut, a_e , were fixed to 0.04 mm and 6 mm, respectively. This means a feed per tooth, f_z , of 0.18 mm and a radial depth of cut of 6% of the cutting tool diameter, D_c . The cutting speed, v_c , was set to 260 m/min, and the axial depth of cut, a_p , was given by the width of the cutting insert, which was 4 mm. Every 10 min of machining, the inserts were washed in alcohol and examined under an appropriate microscope with a scale.

All cutting tests were conducted dry. The machine's temperature and power output were monitored; no process instability was observed during the milling tests.

A full factorial design [13] with three possible levels was applied. Hence, a total number of 12 experiments was conducted in a random order which includes three repeated experiments at the midpoints of the design. The replicates were performed to estimate the random error of the experiments. The variables were coded as follows: chamfer width

Fig. 2 Photo of the experimental setup

Table 2 Cutting edge chamfer parameters and their levels

Control factor	Quantity	Symbol	Unit	Level		
				Low (−1)	Medium (0)	High (1)
<i>A</i>	Chamfer width	<i>w</i>	[mm]	0.1	0.2	0.3
<i>B</i>	Chamfer angle	γ	[°]	10	20	30

(*A*) and chamfer angle (*B*). Table 2 shows the factors with both their coded and actual levels. The cutting edge and the chamfer parameters are illustrated in Fig. 3. The cutting edge preparations were conducted by the tool manufacturer, Mircona, Sweden.

The measured data were analyzed using statistical software.

2.2 Present and non-present types of wear

Wear in metal cutting is a complex process but can mainly be divided into the following wear mechanisms:

- Adhesive wear [20] and deposits (Build Up Edge).
- Abrasive wear [21].
- Plastic deformation on rake and clearance (small amount together with abrasion).
- Chipping caused by strain stress and hard inclusions in the work material.
- Chipping caused by plastic deformation. The cutting tool gets a disadvantageous geometry while in engagement and breaks by the next entry into the workpiece.
- Thermal (comb) cracks [1].
- Exit failures due to “foot forming.”

Wear mechanisms can, in some cases, operate independently or be a part of a common process. In this work, foot forming is not present due to safe exit angles [22].

Fig. 3 Cutting edge chamfer. Chamfer width w , and chamfer angle γ

Tool wear, referred to as chipping, comb cracks, rake wear, and flank wear, is illustrated in Fig. 4.

3 Results and discussions

Table 3 shows all wear and chip evacuation quality values, together with the full factorial design matrix.

Figure 5 shows scatter plots for the measured wear and chamfer geometry, implying a more or less nonlinear relationship. The medium-level values are mean values calculated from experiment numbers 5, 10, 11, and 12.

3.1 Chipping

Thermal fatigue in interrupted cutting generates cracks, so-called comb cracks, in most cases, perpendicular to the cutting edge [1]. Under stable conditions and without extra disturbing wear mechanisms are these cracks often harmless. Nevertheless, the combination of tensile stress from other sources, vibrations, adhesion, etc., and the thermal cracks can quickly ruin the edge and dramatically shorten the tool life. In the tests, the occurrence of cracks on all samples is observed. They are small and harmless on the edges with the finest and least negative chamfer. However, large cracks are found on the more negative and greater chamfer, often with chipping (see Fig. 6). The cracks look like common comb cracks resulting from cyclic temperature changes in milling. Thus, it is very plausible that the observed cracks are thermal cracks.

Fig. 4 Schematics of chipping and wear

Table 3 Design matrix with responses

Exp. no	Run order	Control factor				Response			
		Coded value		Real-world unit value		Wear after 40 min of machining			Chip control
		A	B	w [mm]	γ [°]	Chipping [mm]	Rake wear [mm]	Flank wear [mm]	Chip evacuation
1	6	−1	−1	0.1	10	0.0629	0.3400	0.1402	Good
2	5	−1	0	0.1	20	0.08699	0.3343	0.1537	Good
3	8	−1	1	0.1	30	0.08173	0.3589	0.1748	Poor
4	3	0	−1	0.2	10	0.0602	0.3949	0.1298	Good
5	12	0	0	0.2	20	0.0812	0.4424	0.1359	Good
6	1	0	1	0.2	30	0.0711	0.5044	0.1566	Poor
7	9	1	−1	0.3	10	0.0687	0.5056	0.1547	Poor
8	10	1	0	0.3	20	0.0739	0.5717	0.1467	Poor
9	4	1	1	0.3	30	0.0658	0.6326	0.1503	Very poor
10	2	0	0	0.2	20	0.0774	0.4508	0.1392	Good
11	11	0	0	0.2	20	0.0749	0.4503	0.1303	Good
12	7	0	0	0.2	20	0.0784	0.4344	0.1407	Good

Fig. 5 Wear versus chamfer width at various chamfer angles. (a) Chipping, (b) rake wear, and (c) flank wear

Table 4 shows the coded values of b_j together with their corresponding standard error and test statistics for the response chipping. The regression model on chipping is

Fig. 6 Thermal cracks and chipping on an insert with negative and great chamfer, 0.20-mm wide and 30° angle

simplified by the elimination of the chamfer width squared term. The remaining terms are all statically significant because their p values are less than the significance level of 0.05. The chamfer angle has the dominant effect. The linear angle coefficient indicates that a greater chamfer angle generally consequences in developed chipping, while the negative quadratic term shows that the relationship between chamfer angle and chipping is not strictly linear. The negative coefficient for chamfer width reveals that chipping increases with decreased chamfer widths. It must be mentioned that

Table 4 Estimated coded coefficients and statistics for the response chipping

Term	Coefficient	Standard error	t value	p value
Constant	0.07880	0.00134	58.73	0.000
w [mm]	−0.00387	0.00134	−2.88	0.024
γ [°]	0.00447	0.00134	3.33	0.013
w [mm] γ [°]	−0.00543	0.00164	−3.31	0.013
γ [°] γ [°]	−0.01039	0.00190	−5.48	0.001

chipping was in no wise observed in Choudhury et al. [10] turning tests, where the speed, feed, and depth of cut were 120 m/min, 0.12 mm/rev, and 1 mm, respectively. The absence of chipping in that process is probably due to the application of a more negative main rake angle of 5° .

Table 5 shows the analysis of variance, ANOVA, for the regression model on chipping. The p value for the regression model is less than the significance level of 0.05 and indicates that a significant relationship exists between the chipping, and the variables, w , and γ . Since the p value for the lack of fit is larger than the significance level of 0.05, we can conclude that there is not enough evidence that there is a lack of fit in the reduced model. Hence, the regression model is adequate.

The goodness of fit is summarized as follows—the model on chipping displays a satisfactory coefficient of determination. The adjusted R squared (R^2_{adj}) value is high. The regression model explains 83.67% of the variability after considering the significant factors. The predicted R squared (R^2_{pred}) is smaller than the adjusted R squared, having a value of 49.51%, which is entirely expected due to the stochastic behavior of chipping. The standard error of the regression, which estimates the standard deviation of the random part of the data, Root Mean Squared Error, RMSE, is 0.0033. A visual inspection of standardized residuals of the model shows that the error terms are approximately normally distributed (see Fig. 7). All data points fall between the absolute value of two, hence, no suspicious outliers. There are some minor deviations toward the center, but generally, the data points follow the dashed line.

The model equation on chipping in real-world units is given by:

$$\text{Chipping} = 0.0143 + 0.0699w + 0.005691\gamma - 0.00543w\gamma - 0.000104\gamma^2 \quad (5)$$

Figure 8 shows the contours on chipping generated by Eq. (5). The model calculates the most extensive wear at a chamfer of 0.1-mm wide and 25 degrees. Optimal settings for minimizing chipping are low chamfer width and chamfer angle. The model predicts chipping of 0.0624 mm when the chamfer width and chamfer angle are $w = 0.1$ mm

Table 5 Analysis of variance for the regression model on chipping

Source	Degree of freedom	Adjusted sum of squares	Adjusted mean squares	F value	p value
Model	4	0.000652	0.000163	15.09	0.001
Error	7	0.000076	0.000011		
Lack-of-fit	4	0.000055	0.000014	2.03	0.293
Pure error	3	0.000020	0.000007		
Total	11

Fig. 7 Normal probability plot of standardized residuals of the model on chipping

and $\gamma = 10^\circ$, respectively. The 95% prediction intervals at optimum are 0.0521 and 0.0727 mm.

For the Monte Carlo simulations, random model noise is generated from a normal distribution with a mean of zero and the standard deviation of RMSE = 0.0033. Figure 9 shows a summary of the Monte Carlo simulation at optimal factor settings with tolerance ranges of $\pm 10\%$. The summary shows that the distribution of the chipping is normal, the mean chipping is 0.0623 mm, very close to the initial model prediction (0.0624 mm), and the standard deviation is 0.0037 mm, which means that 95% of the generated values lie between 0.0550 and 0.0697 mm. Hence, the model is robust, and the output is kept within the 95% prediction intervals if the assumed manufacturing variability is correct.

Fig. 8 Contour plot of chipping versus chamfer width w and chamfer angle γ

Fig. 9 Monte Carlo simulation of chipping. Summary statistics: mean μ , and standard deviation σ . Normal distribution is fitted to the data

3.2 Rake wear

Abrasive wear [21] and adhesive wear [20] are the two primary mechanisms involved in the deterioration of the rake. Figure 10 shows abrasive wear patterns on the rake, close to the edge, and degenerated edge line due to the adhesive wear. Greater chamfer width and angle result in higher cutting forces and thus higher temperatures. High cutting temperatures soften the tool material and, combined with high cutting forces on the ceramic inclusions in the workpiece material, such as aluminum oxide, which has a Micro Vickers hardness value of about 2000, cause the abrasive particles to cut deeper marks and accelerate the abrasive wear. On the other hand, the adhesive wear probably decreases

Fig. 10 The abrasive and adhesive wear pattern after about 10 min of machining. Insert with negative chamfer, 0.20-mm wide and 20° angle

Table 6 Estimated coded coefficients and statistics for the response rake wear

Term	Coefficient	Standard error	<i>t</i> value	<i>p</i> value
Constant	0.45169	0.00351	128.83	0.000
<i>w</i> [mm]	0.11278	0.00496	22.75	0.000
γ [°]	0.04257	0.00496	8.58	0.000
<i>w</i> [mm] γ [°]	0.02703	0.00607	4.45	0.002

slightly at the same time as the temperature increase since the material is not adhered to the tool as easily. Higher cutting forces generate more forced vibrations which fatigue the cutting edge and in the end cause chipping.

Table 6 shows the coefficients table for the response rake wear (crater wear). Both squared terms are removed from the regression model; the remaining terms are all statically significant since their *p* values are less than the significance level. The model for the rake wear is thus linear, including the interaction term. All the coefficients have the same sign, and thus the direction of the relationship between the terms and the response is the same. The chamfer width has the dominant effect—an extended chamfer width causes greater rake wear. The standard errors are small, indicating precise estimates.

Table 7 shows the ANOVA for the regression model on rake wear. The figures indicate that the relationship is significant and that the model is adequate.

The regression model explains 98.22% of the variability and predicts 94.68% of new out-of-sample observations. The R^2_{pred} is thus in excellent agreement with R^2_{adj} . The standard error of the regression is RMSE = 0.0121. The standardized residuals of the model shown in Fig. 11 are linear,

Table 7 Analysis of variance for the regression model on rake wear

Source	Degree of freedom	Adjusted sum of squares	Adjusted mean of squares	F value	p value
Model	3	0.090113	0.030038	203.62	0.000
Error	8	0.001180	0.000148		
Lack-of-fit	5	0.001000	0.000200	3.34	0.175
Pure error	3	0.000180	0.000060		
Total	11				

supporting the condition that the error terms are normally distributed. One observation has a residual greater than 2, but is still smaller than 3, so no suspicious outlier.

The model equation on rake wear in real-world units is given by:

$$\text{Rake wear} = 0.2491 + 0.587w - 0.00115\gamma + 0.02703w\gamma \quad (6)$$

Figure 12 shows the contours on rake wear generated by Eq. (6). When both factors are at a high level, the largest wear is found by the model. This can be explained by the fact that the cutting force increases with the increased chamfer width and chamfer angle [10]. Also, the cutting temperatures are supposed to be higher compared to sharp tools [11]. Although temperature differences due to different angles may be small [23], the results show that optimal settings for minimizing rake wear are low chamfer width and angle. Rake wear is less sensitive to chamfer angle. The model predicts rake wear of 0.3234 mm when the chamfer width and angle are $w=0.1$ mm and $\gamma=10^\circ$, respectively. The 95% prediction intervals at optimum are 0.2872 and 0.3595 mm.

For the Monte Carlo simulations, random model noise is generated from a normal distribution with a mean of zero and the standard deviation of RMSE=0.0033. The summary of the Monte Carlo simulation at optimal factor settings with

Fig. 12 Contour plot of rake wear versus chamfer width w and chamfer angle γ

tolerance ranges of $\pm 10\%$ is shown in Fig. 13. The mean rake wear is 0.3235 mm, very close to the initial model prediction (0.3234), with a standard deviation of 0.0129 mm, meaning that 95% of the generated values lie between 0.2977 and 0.3493 mm. Hence, the model is robust, and the output is kept within the 95% prediction intervals if the assumed manufacturing variability is correct.

3.3 Flank wear

The wear pattern on the flank is similar to the pattern on the rake (see Fig. 10) but is much smaller in magnitude. The difference is due to the fact that chips form and flow over

Fig. 11 Normal probability plot of standardized residuals of the model on rake wear **Fig. 13** Monte Carlo simulation of rake wear. Summary statistics: mean μ , and standard deviation σ . Normal distribution is fitted to the data

Table 8 Estimated coded coefficients and statistics for the response flank wear

Term	Coefficient	Standard error	<i>t</i> value	<i>p</i> value
Constant	0.13684	0.00198	69.07	0.000
<i>w</i> [mm]	−0.00283	0.00177	−1.60	0.161
γ [°]	0.00950	0.00177	5.36	0.002
<i>w</i> [mm] γ [°]	−0.00975	0.00217	−4.49	0.004
<i>w</i> [mm] <i>w</i> [mm]	0.01274	0.00266	4.79	0.003
γ [°] γ [°]	0.00574	0.00266	2.16	0.074

the rake, so this surface almost always remains in physical contact (neglecting vibrations), while the flank is inclined toward the finished surface, designed to be free from contact. The physical contact is at the vicinity of the edge due to the edge radius.

More wear is often found near the corners. This is because the chips grow in width and become larger than the machined slot. The cutting geometry is made to handle this problem but is never perfect. Consequently, the chips are pressed against the machined shoulders. Hence, the corners of the edge become more stressed, which leads to slightly more significant wear near the corners of the flank.

Table 8 shows the coefficients table for the response flank wear. All of the terms of the full quadratic model are included in the model on flank wear. Note that the *p* values for both *w* and γ^2 terms are greater than the usual significance level of 0.05. Inspection has shown that elimination of γ^2 term produces non-random pattern in residuals versus predictors plot, exhibiting a distinct curvature. Furthermore, the term *w* is included since it is part of both the interaction term, *w* γ , and the higher-order term, w^2 . In this way, a hierarchical model is obtained, which is commonly desirable. The linear coefficients inform that a greater chamfer angle results in more flank wear, which is consistent with results from previous studies [10], while an increase in chamfer width reduces the response.

The figures from the ANOVA for the regression model on flank wear shown in Table 9 indicate that the relationship is significant and that the model is adequate.

Table 9 Analysis of variance for the regression model on flank wear

Source	Degree of freedom	Adjusted sum of squares	Adjusted mean squares	<i>F</i> value	<i>p</i> value
Model	5	0.001702	0.000340	18.06	0.001
Error	6	0.000113	0.000019		
Lack-of-fit	3	0.000049	0.000016	0.77	0.581
Pure error	3	0.000064	0.000021		
Total	11

Fig. 14 Normal probability plot of standardized residuals of the model on flank wear

The regression model explains 88.58% of the variability and predicts 66.74% of new out-of-sample observations. The R^2_{pred} is thus in reasonable agreement with R^2_{adj} . The standard error of the regression is RMSE = 0.0043. The probability plot in Fig. 14 shows the distribution of the standardized residuals compared to a normal distribution. All the data points are between the residuals of ± 2 , far below the absolute value of 3, hence, no large suspicious residuals. The data points are fairly close to the straight dashed line; there is some slight deviation toward the ends, but generally, the residuals are linear, suggesting that the data fit the model reasonably.

The model equation on flank wear in real-world units is given by:

Fig. 15 Contour plot of flank wear versus chamfer width *w* and chamfer angle γ

Fig. 16 Settings and sensitivity for the optimal solution of the flank wear model

$$\begin{aligned} \text{Flank wear} = & 0.1584 - 0.343w + 0.00061\gamma - 0.00975w\gamma \\ & + 1.274w^2 + 0.000057\gamma^2 \end{aligned} \quad (7)$$

Figure 15 displays the contours on flank wear generated by Eq. (7). A maximum value of wear is expected for the tool having chamfer width and chamfer angle of 0.1 mm and 30°, respectively. The best factor settings, minimizing flank wear, are chamfer width and chamfer angle of 0.1728 mm and 10°, respectively. The model predicts a flank wear of 0.1321 mm within an interval of 0.1191 and 0.1451 mm, with 95% probability. Settings and sensitivity for the optimal solution of the model are shown in Fig. 16.

For the Monte Carlo simulations, random model noise is generated from a normal distribution with a mean of zero and a standard deviation of 0.0043. Figure 17 summarizes the Monte Carlo simulation at optimal factor

Fig. 17 Monte Carlo simulation of flank wear. Summary statistics: mean μ , and standard deviation σ . Normal distribution is fitted to the data

Fig. 18 Chip evacuation for three different chamfer geometries

settings with tolerance ranges of $\pm 10\%$. The mean flank wear is 0.1322 mm, very close to the initial model prediction (0.1321 mm), with a standard deviation of 0.0043 mm, meaning that 95% of the generated values lie between 0.1236 and 0.1409 mm. Hence, the model is robust, and the output is kept within the 95% prediction intervals if the assumed manufacturing variability is correct.

3.4 Chip evacuation

All factor combinations where any factors have a high level result in insufficient chip evacuation (see the last column in Table 3). The vertex of the design square where both factors are at high level results in almost non-existing chip evacuation. Chip evacuation for three different chamfer geometries is shown in Fig. 18. For each geometry, five slots have been machined, corresponding to about 10 min of machining. The picture is a representative zoomed part of the machined slots. The categorical response variable, chip evacuation, agrees with the model on flank wear. Chip jamming and poor chip evacuation cause rapid and or excessive flank wear.

3.5 Multi-response optimization

Since the optimal values for each response are localized in similar regions, the best geometry is roughly estimated by overlaying the contour plots of each individual wear response. Low chamfer width and angle is the best condition when the models are optimized graphically. For a more detailed analysis, the triple responses are transformed into

Table 10 Optimization input parameters

Response	Target	Upper bound	Weight	Importance
Chipping [mm]	0.0624	0.0690	1	0.7
Rake wear [mm]	0.3234	0.4100	1	0.2
Flank wear [mm]	0.1321	0.1500	1	0.1

Fig. 19 Desirability values as a function of chamfer widths and angles. Note the different axis limits

a single response. Also, trade-offs are needed. Chipping is the most critical wear characteristic, rake wear is the next important one, and flank wear is the least important. The individual desirability values, d_i , are calculated using Eqs. (2) and (3), and predicted responses Eqs. (5)–(7). The composite desirability values, D , are calculated using Eq. (4). The input parameters are shown in Table 10.

Figure 19 shows a summary of the desirability outputs. Based on the composite desirability values, the optimal settings are identified as $w = 0.1$ mm, and $\gamma = 10^\circ$. The optimal composite settings coincide with the individual optimal settings of chipping and rake wear. Thus, the optimal solution, prediction intervals, and tolerance analysis for chipping and rake wear have already been presented. The model on flank wear, Eq. (7), predicts wear of 0.1389 mm within an interval of 0.1247 and 0.1531 mm, with 95% probability. As shown in Fig. 20, Monte Carlo

Fig. 20 Monte Carlo simulation of flank wear, at composite optimum. Summary statistics: mean μ , and standard deviation σ . Normal distribution is fitted to the data

simulations produce mean flank wear of 0.139 mm (same value as the initial model prediction) with a standard deviation of 0.0044 mm, meaning that 95% of the generated values lie between 0.1302 and 0.1478 mm. Hence, the simulation output is kept within the 95% prediction intervals of the model.

4 Conclusions

A study on the optimization of chamfer geometry to achieve reliable and minimum tool wear in slot milling is presented. The study applies statistical methods to handle stochastic problem statements. A total of 12 experiments are conducted on high-strength Nickel Chromium Molybdenum alloy structural steel using milling inserts with various chamfer widths and chamfer angles. Despite all investigations, much is lacking for a complete fundamental understanding of the physics of wear in metal cutting. Nevertheless, the proposed methodology has been shown to work satisfactorily for our cutting tool and working material. Wear models, including the relationship between chamfer width and chamfer angle, are presented. The results add understanding of how to decrease the wear speed, i.e., minimize abrasive and adhesive wear, which cause the measurable flank and rake wear, and at the same time prevent chipping. In practice minimize the forces on the edge, making the edge as light cutting as possible. The following conclusions can be drawn from the investigation:

- The chamfer geometry affects the capability and durability of the cutting edge. To find the overall, compromised, optimal geometry, trade-offs are needed since the developed wear models on chipping, rake wear, and flank wear, have different desirable regions.

- A tool with a chamfer of 0.1 mm wide and 10° angle have the best edge strength and wear performance, and sufficient chip evacuation.
- Based on ANOVA, the models developed fit and are statistically significant.
- Monte Carlo simulations have shown that the transmitted variation of chamfer width and chamfer angle are in an acceptable order of magnitude, the models generated from the design of experiments produce results within their required specification and are robust.
- The proposed methodology helps to improve tool reliability and tool life for a large range of cutting tools and operations.
- One always has to pay attention to what is possible to manufacture in the tool shop or elsewhere. For example, if the chamfer's optimal width is less than 10 µm, which is difficult or expensive to produce with tolerances and then another solution is necessary.

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Declarations

Competing interests The authors declare no competing interests.

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