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Optimal Insert Edge Geometry for Minimum Specific Cutting Energy in Face Milling

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Keywords : face milling, edge geometry, cutting coefficient, Taguchi method, response surface methodology, genetic algorithm

ABSTRACT

This paper investigates the effect of the negative insert geometry on the specific cutting energy and explores the parametric space for optimal design to yield minimum specific energy in face milling. Double-sided negative cutting inserts offer many advantages over traditional face milling cutters, including a greater edge strength, improved stability, a higher feed rate, and a better economy. Accordingly, the present study employs the Taguchi robust design methodology to analyze the relative contribution of each geometry parameter of the cutting edge to the specific cutting energy in a face milling process through finite element simulation. A hybrid method consisting of the response surface methodology with a 2nd-order regression model and a genetic algorithm is then used to determine the optimal values of the insert edge geometry. The simulation results show that the specific cutting energy reduces with a larger rake angle of the cutting edge and a greater primary land width, as well as with a higher feed rate. The validity of the simulation results and analysis is confirmed by means of experimental milling trials using inserts fabricated with the optimal edge geometry.

INTRODUCTION

Double-sided milling inserts are regarded as a promising direction of future research for advanced machining technology. Among the various double-sided milling inserts available, double-sided negative cutting inserts have attracted attention due to their greater edge strength, enhanced stability, higher feed rate and better economy. However, while negative cutting has many benefits, it also induces a larger cutting force and a higher temperature. Consequently, an appropriate design of the edge geometry is essential for prolonging the life of the tool.

The three cutting constants, namely the tangential, radial and axial cutting constants, are important process parameters in predicting forces, process temperature, residual stress and dynamic response of the milling process. The tangential cutting constant, in particular, directly relates to spindle torque, power and process temperature for a combination of tool and work material and is often referred to as the specific cutting energy. This article thus takes the specific cutting energy, or the tangential cutting constant, as the design goal with the geometric design of the insert edge being the essential factor.

Various works were identified projecting the importance of the tool inserts and evaluation of the cutting force coefficients (Budak, 2006; Altintas, 2012; Gonzalo et al., 2010). The cutting forces in all three directions were dependent on the process parameters as well as on the cutting coefficients. To simplify the force model, the cutting coefficients are often treated as constants irrespective of varying chip thickness in a milling process, and thus are often called cutting constants as in this paper. These constants mostly depend on the edge geometries of the cutter and the type of the workpiece material. Fu et al. (1984) developed a new mechanistic force model for the face milling operation over a range of different geometries and cutting conditions. The data arrived in the numerical analysis were compared with the experimental cutting tests. Kim and Ehmann (1993) described a simulated model to evaluate, both the static and dynamic cutting forces in face milling by considering the inserts and eccentricity of the spindle. Simulated forces were compared with the measured forces in both the frequency and time

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domains. Engin and Altintas (2001) presented a simplified mathematical model to predict the cutting forces with cutting inserts along with the effect of chip thickness in the cutting zone. Gomez et al. (2019) analyzed the cutting-edge radius as well as the cutter angular values with the help of a structured light scanning method. Using the reverse engineering method, the behavior of the face mill inserts was presented in the time domain. Borysenko (2019) implemented the inverse ratio approach in the model to suppress the cutting force in face milling. The numerical results arrived with finite element simulations are compared with cutting experiments to validate the force model. Agic et al. (2019) compared the positive cutting edge with the negative cutting edges and further, the influence of cutting loads over the machining process was estimated. Arizmendi and Jimenez (2019) presented a mathematical model for the round cutting edge geometry of face milling operations. Further the effects of axial and radial runout of these inserts were also included in the modeling. Wang and Lin (2016) proposed a model to predict thin plate deformation due to residual stress induced by the bottom cutting edge in surface milling.

Wang and Zheng (2002) identified the cutting constants for shearing and ploughing mechanisms in ball end milling process, which has a circular edge profile similar to a circular insert with similar chip load. These cutting constants are arrived in terms of average milling forces, tool radius, and axial depth of cut and further verified with milling experiments. Feng and Menq (1994a, 1994b) developed a model for the prediction of cutting forces in a ball end milling with the basis of engaged cutter edge geometry. The model parameters were estimated for the different combinations of cutter and workpiece arrangements. Wang and Wu (2002) presented an advanced method for the identification of the cutting constants with the measured dynamic milling forces in a ball end milling. The numerical simulation models for the cutting constants are confirmed by the experimental trails. Koenigsberger and Sabberwal (1961) simplified the task of analyzing the cutting force in milling processes using the concept of cutting coefficients. In a later study, Tlusty and MacNeil (1975) quantified the relationship between the radial cutting force and the tangential cutting force in end milling using a radial cutting coefficient. Wang et al. (1994, 2002) proposed a milling force model as a convolution of the elementary cutting function, chip width density and tooth sequence function. These a forementioned force models are mostly used to predict milling forces and process variables such as surface error and tool wear. Few are applied for the tool design.

Many researchers (Patel and Joshi, 2006; Fratila and Caizar, 2011; Yoon et al., 2011) have investigated the effects of the cutting conditions on the surface roughness, cutting force, and service life of milling cutters using such techniques as the Taguchi robust design methodology or the Response Surface Methodology (RSM). Furthermore, many studies (Cheng, 2008; Jawaid, 2000; Nalbant, 2003, Thiele, 1999) have shown that the edge geometry design has a critical effect on the cutting force, cutting temperature, chip flow, surface finish, and tool wear. Bjurka (2011) quantified the effects of each edge geometry parameter on the tool life of a milling cutter using an experimental approach. Kuo et al. (2018) performed two-dimensional (2-D) finite element (FE) simulations to investigate the effects of the insert groove geometry on the chip breaking performance. The simulation results were then used to construct a chip breaking performance model using RSM.

Thus far, the literature lacks a detailed investigation into the effects of the edge geometry on the cutting coefficients of a double-sided negative cutting insert. Accordingly, this study sets out to explore the relationships among the edge geometry and cutting constants in the face milling process. The study commences by applying the robust Taguchi design method to establish the relative contributions of the main edge geometry parameters toward the cutting constants obtained from FEM simulation of milling process. A combined RSM and genetic algorithm approach are then used to determine the optimal geometry for a double-sided negative milling insert. Finally, the validity of the simulation results and analysis is confirmed by means of experimental milling trials.

IDENTIFICATION OF CUTTING CONSTANTS FROM MEASURED AVERAGE FORCES

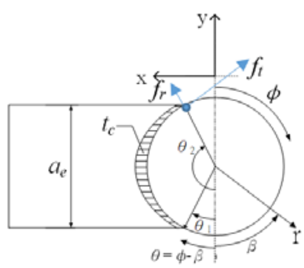

Fig. 1. Schematic diagram of the face milling process

In face milling, as shown in Fig. 1, the thickness of unformed chips varies with the angle of tool rotation. The instantaneous undeformed chip thickness is as follows:

$$t_c(\theta) = f_z \sin\theta \tag{1}$$

For the unit chip width, the equation for the local cutting forces can be expressed as

$$f_t(\theta) = K_t f_z \sin\theta \tag{2}$$

$$f_r = k_r f_t \tag{3}$$

where f_t is the tangential cutting force and f_r is the radial cutting force, K_t is the specific cutting energy or the tangential cutting constant and k_r is the radial cutting constant as the ratio of radial cutting force and the tangential cutting force. These local cutting force components (f_t, f_r) are transformed to the cartesian work coordinate system in x, y, and z directions, integrated over the entire insert and for each engaged insert to obtain the total cutting forces.

Cutting constants can be identified from dynamic force components (Wang and Wu, 2002) or average forces (Wang and Zheng, 2002). An analytical formula from the latter is considered to calculate the cutting constants from the measured average milling forces. The cutting constants (K_t, k_r, k_a) in a three-dimensional space can be obtained as:

$$\begin{bmatrix} k_t \\ k_t k_r \\ k_t k_a \end{bmatrix} = \frac{2\pi}{N f_z a_p} \begin{bmatrix} P_1(0) & P_2(0) & 0 \\ P_2(0) & -P_1(0) & 0 \\ 0 & 0 & P_3(0) \end{bmatrix}^{-1} \begin{bmatrix} A_x \\ A_y \\ A_z \end{bmatrix} \tag{4}$$

where

$$P_1(0) = \frac{1}{4}(\cos 2\theta_1 - \cos 2\theta_2)$$

$$P_2(0) = \frac{1}{2}(\theta_2 - \theta_1) + \frac{1}{4}(\sin 2\theta_1 - \sin 2\theta_2)$$

$$P_3(0) = \cos\theta_1 - \cos\theta_2$$

where θ_1 and θ_2 are the entry and exit angles, N is the number of inserts. (A_x, A_y A_z) are the measured average forces from the simulations or experiments.

RESULTS AND DISCUSSIONS

Edge geometry analysis by Taguchi method

In this work, the specific cutting energy, K_t, is taken as the index of quality characteristics in the Taguchi analysis. In performing the Taguchi analyses, the milling process was simulated using AdvantEdge software by Third Wave Systems. A typical simulation plot with pulsing force profiles along with process temperature details are presented in Fig. 2. For each of the considered tool edge geometries, the simulated cutting forces in the tangential, radial and axial directions were used to calculate the corresponding cutting coefficients from Eq. (4).

As illustrated in Fig. 3, the Taguchi analyses considered five geometry parameters of the double-sided milling insert. It is noted that, although the rake angle of the insert is shown as positive, the industrial tool holder for this type of insert is designed with a tilted pocket so that the insert is positioned against the work surface with a negative rake angle, thus the name of a negative rake insert.

The simulations also considered two milling process parameters, namely the feed per tooth, f_z, and the axial depth of cut, a_p, for the analysis. Moreover, each of the geometry and process parameters for the control factors were assigned three different levels (see Table 1).

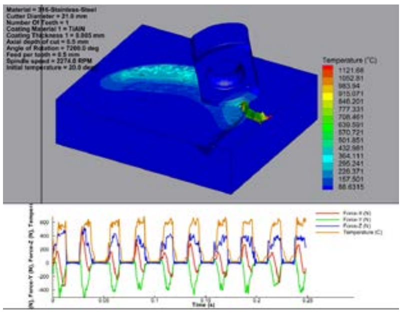

Fig. 2. Outputs of 3D Finite element simulation

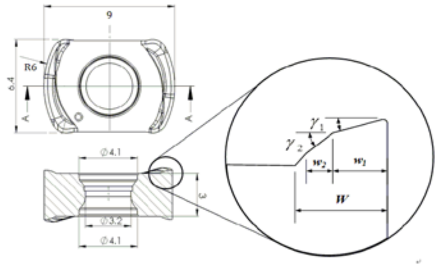

Fig. 3. The edge geometry of a double-sided insert

Table 1. Control factors and level settings for edge geometry and process parameters

Level	w_1 (mm)	w_2 (mm)	W (mm)	γ_1 (deg)	γ_2 (deg)	f_z (mm)	a_p (mm)
1	0.2	0.2	0.8	0	10	0.3	0.3
2	0.3	0.3	0.9	7.5	20	0.5	0.5
3	0.4	0.4	1.1	15	30	0.7	0.7

As shown in Table 2, the Taguchi trials were configured in an L_{18} orthogonal array. In analyzing the simulation results, the quality of the outcome was evaluated using the tangential cutting coefficient, K_t, as the quality characteristic. In practical face milling operations, a lower K_t (i.e., a lower specific cutting energy) is preferred. Hence, in evaluating the quality of the simulation runs, a lower-is-best S/N ratio (η) was adopted with the form shown in Eq. (5).

$$\eta = -10\log\left(\left(\frac{1}{n}\right)\sum_{i=1}^{n} y_i^2\right) \tag{5}$$

The values of K_t and η obtained in each simulation run are listed in the right-most columns of Table 2. The corresponding S/N response graph is presented in Fig. 4. In analyzing the S/N response, edge design parameters along with the process parameters are considered in the present study. Figure 4 shows that the specific cutting energy is reduced when using a higher feed rate and land width. The concept of analysis of variance (ANOVA) is to determine the relative importance of input variables on the response parameters which are orthogonal to each other. Table 3 shows that the contribution (ρ) of each factor to the quality characteristic and indicates that the feed rate followed by the primary land width has a greater contribution than the other factors in affecting the specific cutting energy, K_t.

It is also confirmed from the Table 3, the parameters such as wedge width (W) and secondary rake angle (γ_2), have the least contribution to affect the specific cutting energy. In further analysis, to obtain the optimal design of the edge parameters,

Table 2. Simulation results in Taguchi trials

No.	w_1 (mm)	w_2 (mm)	W (mm)	γ_1 (deg)	γ_2 (deg)	f_z (mm)	a_p (mm)	K_t (MPa)	η (+80)
1	0.2	0.2	0.2	0	10	0.3	0.3	4715.91	6.53
2	0.2	0.3	0.3	7.5	20	0.5	0.5	2182.16	13.22
3	0.2	0.4	0.4	15	30	0.7	0.7	2717.98	11.32
4	0.3	0.2	0.2	7.5	20	0.7	0.7	2135.78	13.41
5	0.3	0.3	0.3	15	30	0.3	0.3	4232.49	7.47
6	0.3	0.4	0.4	0	10	0.5	0.5	3078.37	10.23
7	0.4	0.2	0.3	0	30	0.5	0.7	2888.64	10.79
8	0.4	0.3	0.4	7.5	10	0.7	0.3	1661.73	15.59
9	0.4	0.4	0.2	15	20	0.3	0.5	3844.13	8.30
10	0.2	0.2	0.4	15	20	0.5	0.3	3069.39	10.26
11	0.2	0.3	0.2	0	30	0.7	0.5	2788.21	11.09
12	0.2	0.4	0.3	7.5	10	0.3	0.7	4056.63	7.84
13	0.3	0.2	0.3	15	10	0.7	0.5	2596.93	11.71
14	0.3	0.3	0.4	0	20	0.3	0.7	4141.26	7.66
15	0.3	0.4	0.2	7.5	30	0.5	0.3	2093.41	13.58
16	0.4	0.2	0.4	7.5	30	0.3	0.5	4642.19	6.67
17	0.4	0.3	0.2	15	10	0.5	0.7	1992.70	14.01
18	0.4	0.4	0.3	0	20	0.7	0.3	1568.25	16.09

Table 3. ANOVA results for the geometrical and process parameters

	DoF	*SS*	*Var*	ρ (%)
w_1	2	10.795	5.397	6.98%
w_2	2	8.924	4.462	5.77%
W	2	3.128	1.564	2.02%
γ_1	2	6.415	3.207	4.15%
γ_2	2	5.483	2.742	3.54%
f_z	2	112.318	56.159	72.61%
a_p	2	5.740	2.870	3.71%
error	7	1.879	0.626	1.21%
total	17	154.6824	---	100.00%

only five factors with the major contribution are considered.

Fig. 4. Taguchi S/N response graph.

Cutting coefficient fitness model

To obtain suitable cutting-edge geometric parameters under the specific machining conditions, Box-Behnken design (BBD) is considered for the mathematical analysis. The experiments were designed with five major factors as input variables to obtain the response K_t, and the five-factor Box-Behnken design with a total of 41 experiments are used as the configuration framework. The configuration and their coded levels are shown in Table 4 &5, respectively.

Table 4 Box-Behnken design parameters

No.	w_1	w_2	γ_1	f_z	a_p
1	±1	±1	0	0	0
2	±1	0	±1	0	0
3	±1	0	0	±1	0
4	±1	0	0	0	±1
5	0	±1	±1	0	0
6	0	±1	0	±1	0
7	0	±1	0	0	±1
8	0	0	±1	±1	0
9	0	0	±1	0	±1
10	0	0	0	±1	±1
11	0	0	0	0	0

Table 5 Coded values for BBD parameters

Coded levels	w_1 (mm)	w_2 (mm)	γ_1 (deg)	f_z (mm)	a_p (mm)
-1	0.2	0.2	0	0.3	0.3
0	0.3	0.3	7.5	0.5	0.5
1	0.4	0.4	15	0.7	0.7

This paper has established a three polynomial regression models. Table 6 is a comparison of the three polynomial regression models. Among them, the second-order regression model has the largest R^2adj, which means that the model has the best explanatory ability and the smallest estimated standard error. Therefore, this article considered the second-order model as the fitness function for the response surface model.

A second-order regression model is developed for the specific cutting energy based on the BBD

Table 6 Comparison of three polynomial regression models

	First-order model	First-order model with interaction	Second-order model
R^2	0.667	0.886	0.926
R^2_{adj}	0.658	0.873	0.902
σ	666.868	406.542	356.815

experimental trials. An empirical equation was developed to frame the quadratic equation at a 95% confidence level. Based on the BBD results presented above, the geometry and processing parameters having the greatest effect on the specific cutting energy were determined in no particular order to be as follows: (1) first land width, w_1, (2) secondary land width, w_2, (3) first rake angle, γ_1, (4) feed rate, f_z, and (5) axial depth of cut, a_p, The five parameters were thus processed by RSM to construct an appropriate fitness model for the tangential cutting coefficient (see Eq. (6)). The ideal edge geometry is determined for specific cutting conditions and at a constant feed rate of 0.5 mm and a cutting depth of 0.5 mm.

$$\begin{aligned} K_t\left(\mathrm{MPa}\right) &= 18603.877 - 10682.162 w_2 - 43204.079 f_z - 7854.682 a_p \\ &+ 6.671\gamma_2^2 + 27988.026 f_z^2 + 19896.337 w_1 w_2 - 12173.303 w_1 f_z \\ &- 178.869 w_2 \gamma_1 + 13069.871 w_2 f_z + 15418.600 f_z a_p \end{aligned} \qquad (6)$$

The optimal values of the geometry parameters which minimized the value of K_t for given values of the feed rate and depth of cut were then determined using a genetic algorithm. An objective function (i.e. fitness function) as obtained in Eq (6) is framed to minimize the value of K_t. The variables of lower and upper bound in the objective function are taken as follows: 0.2 mm $\leq w_1 \leq$ 0.4 mm, 0.2 mm$\leq w2 \leq$ 0.4 mm, and $0 \leq \gamma_1 \leq 15$ degrees. The fitting model is optimized with the setting values as: population size 20, mating probability as 0.8, mutation rate as 0.001, and termination generation number is set to be 200. The ideal groove geometry is determined, and the corresponding values are tabulated in Table 7.

Table 7. Optimal edge geometry at f_z = 0.5 mm, a_p = 0.5 mm

w_1 (mm)	w_2 (mm)	γ_1 (deg)	K_t (MPa) (Fitness value)
0.4	0.2	14	2226.44

Experimental verification

In the present work, the cutting experiments were carried out in a three-axis CNC vertical milling machine (Type: LEADWELL-MCV-610AP) with an insert holder of 20 mm in diameter (CMTec CXBNE6-03020150), and only one insert is installed to avoid the tool runout effect. The spindle speed is fixed at 2388 rpm (Vc=150 m/min) in a slot milling configuration. The cutting forces were measured during the machining of AISI 316 stainless steel by the Kistler dynamometer (type: KISTLER Type 9272). The experimental set up is presented in Fig. 5.

Comparison of the simulated and experimental cutting forces

The directional cutting forces were experimentally measured with a three-axis dynamometer during the machining of AISI 316 stainless steel using the commercial face mill insert

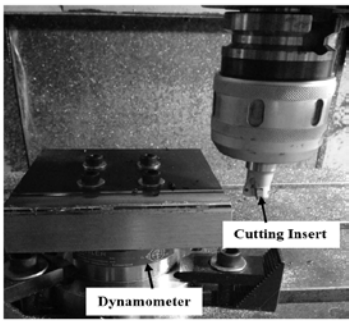

Fig. 5. Experimental set up

(Winstar BNMX0603-RG). The feed per tooth and axial depth of cut are both taken as 0.5 mm. Figure 6represents the comparison of the experimental forces measured with the dynamometer and numerical simulations. Here, Sim.1 are the cutting forces obtained by the finite element simulation software whereas Sim. 2 are the forces with the experimentally determined cutting constants substituted in the milling force model to obtain the time domain forces. It is observed that Sim. 1 and Sim. 2, the time-domain forces, are in close agreement with the experimentally measured forces in all the three cutting directions.

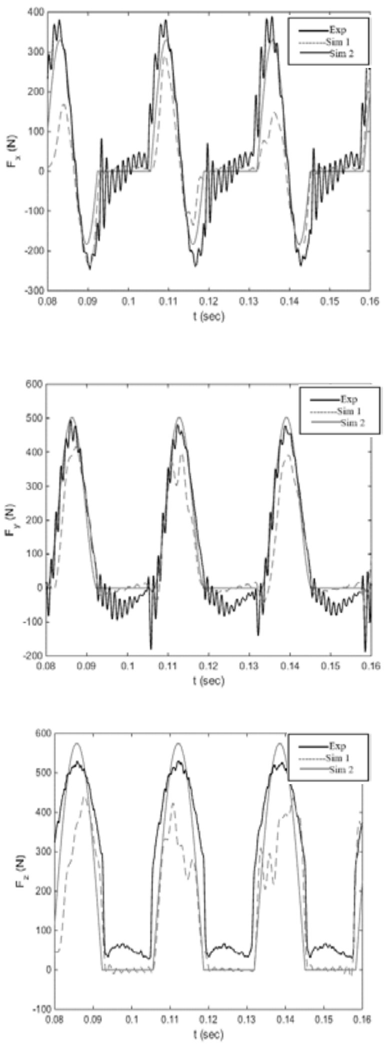

Fig. 6. Comparison of FEM simulation, model simulation and experimental cutting forces

Validation of optimal edge geometry

The validity of the optimal edge geometry design was confirmed by comparing the simulated values of the cutting constants and average chip thickness with the experimental results obtained using two round inserts, namely (1) a commercial round insert (Winstar BNMX0603-RG) and (2) an insert fabricated with the ideal edge geometry determined above. The geometry details of the two inserts are listed in Table 8 for comparison purposes.

Table 8. Geometrical parameters of commercial and optimized inserts

Insert	w_1 (mm)	w_2 (mm)	W (mm)	γ_1 (deg)	γ_2 (deg)
No.1	0.25	0.29	0.82	0	16
No.2	0.40	0.20	0.9	14	20

Furthermore, the milling trials were performed using AISI 316 stainless steel with the same tool holder and cutting speed with the axial feed rate and axial depth of cut set in the ranges of f_z = 0.3 ~ 1.0 mm and a_p = 0.3 ~ 0.7 mm, respectively.

Figures 7~9 present the results obtained for the three cutting constants using the insert No.2 with respect to the average chip thickness. The average chip thickness is proportional to f_z and a_p by Lee (2015). The results show that the simulation and experimental results are in general in good agreement. The simulated values of K_t are slightly higher than the experimental values, while those of k_r and k_a are slightly lower. Moreover, the experimental results show that the value of k_a is around 1, which indicates that the negative rake milling insert generates a large

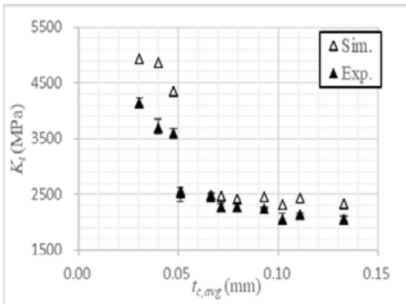

Fig.7. Comparison of FEM simulation and experimental results for specific cutting energy, K_t

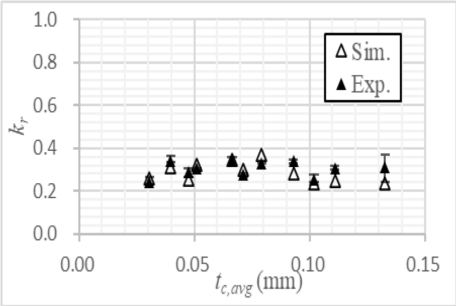

Fig. 8. Comparison of FEM simulation and experimental results for k_r

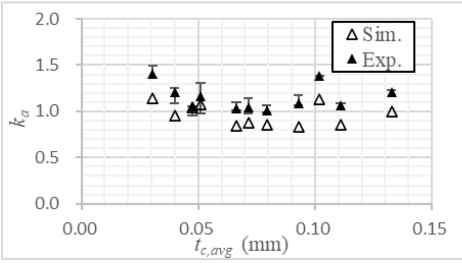

Fig. 9. Comparison of simulation and experimental results for k_a

axial force with a magnitude almost equal to or greater than the tangential force. The results confirm that in face milling with a negative rake insert, an appropriate spindle design with the ability to withstand a large axial force is essential.

Figure 10 compares the simulation and experimental results obtained for the specific cutting energy using both the commercial and optimally designed inserts. It is seen that, even though the second optimized insert is designed based on a fixed feed rate of 0.5 mm and a_p of 0.5 mm with an average chip thickness of 0.066 mm, the optimal design by RSM is demonstrated to reduce the specific energy compared to RSM value for the commercial one within a wide range of average chip thickness. The experimental results for the optimal insert 2 are shown to have a slightly higher specific energy than the RSM prediction. However, they are lower or

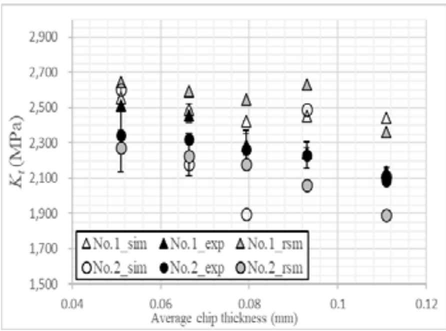

Fig. 10. Comparison of simulation and experimental results for K_t given two different edge geometries.

slightly lower than that of the commercial insert for all average chip thickness values with various combination of feed rate and axial depth of cut. The optimal insert geometry design for minimum specific cutting energy thus can be validated.

CONCLUSIONS

This study has utilized a hybrid approach consisting of the robust Taguchi design method, RSM, and a genetic algorithm to clarify the effects of the edge geometry and processing conditions on the cutting constants produced in face milling process. Using ANOVA analysis, it is confirmed that, the specific cutting energy is affected mainly by the feed rate, rake angle and primary land width of the cutting edge. High axial cutting constants in face milling with a negative rake insert confirm that an appropriate spindle design with the ability to withstand a large axial force is essential. Further, with the BBD method of design, a second-order fitness model is developed to obtain the optimal edge geometry. It is observed from the simulation and experimental results, there is a decrease in the value of the specific cutting energy for optimized insert edge design. These results have confirmed that an optimal design of the edge geometry with a lower specific cutting energy has been achieved.

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NOMENCLATURE

A_x, A_y, A_z	average cutting forces of x, y, z-direction
a_e	radial depth of cut
a_p	axial depth of cut
f_z	feed per tooth
K_t	tangential cutting coefficient
k_r	radial cutting coefficient
k_a	axial cutting coefficient
	number of teeth
t_c	chip thickness
f_t	tangential cutting force
f_r	radial cutting force
f_a	axial cutting force
W	wedge width
w_1	primary land width
w_2	secondary land width
ϕ	tool rotation angle
θ	cutter position
θ_1	entry angle
θ_2	exit angle
γ_1	primary rake angle
γ_2	secondary rake angle

最小比切削能之面銑刀片刃口幾何最佳化設計

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摘要

本論文針對面銑加工用雙面負角銑刀片，探討最佳刃口幾何設計以求得最小比切削能。先使用有限元素分析軟體模擬面銑加工，利用田口方法探討刃口幾何對比切削係數的影響。並運用反應曲面法及實驗設計，建立以進給、軸向切深與刃口幾何參數對切削係數的二階迴歸模型，再以基因演算法求取特定切削條件下的理想幾何參數，最後進行模擬與實際切削的差異比較，並驗證田口方法所分析的趨勢與迴歸模型之可靠度。模擬分析與驗證實驗的結果顯示，進給量對比切削係數有顯著的影響，進給量愈大比切削係數愈小。而在刃口幾何設計參數中，選擇較大的刃寬有助於比切削係數的減少，前傾角對比切削係數的貢獻度較大，角度增加也有助於比切削係數之減小，但有一範圍限制。最後以實驗證實最佳刀片刃口幾何設計之正確性。