

EFFECTS OF CUTTING PARAMETERS AND TOOL-PATH STRATEGIES ON TOOL ACCELERATION IN BALL-END MILLING

UČINKI REZALNIH PARAMETROV IN STRATEGIJA ZA POSPEŠEK ORODJA PRI MEHANSKI OBDELAVI S KROGLIČNIM FREZALOM

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The determination of the cutting-parameter values that cause increases in vibration values is important to minimize the errors that can occur. Thus, the first aim of this study was to investigate the optimum cutting-parameter values and tool-path strategies in ball-end milling of the EN X40CrMoV5-1 tool steel with three coated cutters using the Taguchi method. The parameters taken into consideration are the cutting speed, feed rate, step over and tool-path strategies. The second aim of the study, a model for the tool acceleration as a function of the cutting parameters, was obtained using the response-surface methodology (RSM). As a result, the most effective parameter within the selected cutting parameters and cutting strategies for both inclined surfaces and different coatings was the step over. In terms of tool coatings, the most deteriorating coating for the tool acceleration on both inclined surfaces was the TiC coating. In addition, the response-surface methodology is employed to predict the tool-vibration values depending on the cutting parameters and tool-path strategy. The model generated gives highly accurate results.

Keywords: inclined surfaces, ball-end milling, tool acceleration, Taguchi method, response-surface methodology, response optimization

Neoptimalni rezalni parametri med mehansko obdelavo lahko povzročijo neželene vibracije in posledično napake. Prvi cilj avtorjev te študije je bil določiti optimalne vrednosti rezalnih parametrov in strategije potovanja orodja med mehansko obdelavo orodnega jekla EN X40CrMoV5-1 s krogličnim frezalom s tremi rezili z različno prevleko (TiC, TiN in TiAlN). Za to so uporabili Taguchi-jevo metodo. Parametri, ki so jih avtorji zajeli v študiji so bili: hitrost rezanja, velikost odvzema, korak odvzema (preskok) in strategija poti orodja. Drugi cilj avtorjev te študije je bil izdelati model pospeševanja orodja v odvisnosti od rezalnih parametrov, z uporabo metodologije odziva površine (angl. RSM). Ugotovili so, da je korak odvzema (angl.: step over) najučinkovitejši parameter med izbranimi rezalnimi parametri in rezalnimi strategijami, tako za oba izbrana nagiba (ukrivljenosti) površine, kot tudi izbrane trde prevleke. Med izbranimi trdimi prevlekami se je v vseh pogojih freziranja kot najslabša izkazala TiC prevleka. RSM metodologija dodatno omogoča napoved vibracij orodja v odvisnosti od rezalnih parametrov in izbrane strategije poti orodja. Izdelani model daje zelo točne rezultate.

Ključne besede: nagib (ukrivljenost) površine, mehanska obdelava s krogličnim frezalom, pospešek orodja, Taguchi metoda, metodologija odgovora površine, optimizacija odgovora

1 INTRODUCTION

Nowadays, machining is one of the most important methods for manufacturing technologies and it remains up-to-date.¹ In the machining of inclined surfaces, tight machining tolerances are generally requested for the processes of finishing and semi-finishing, which are accomplished using indexable insert ball-end mills.^{2,3} The forces that occur at high cutting speeds, especially during hard machining, and at high rates of metal removing, cause excessive, irregular vibrations of cutting tools during the machining. These vibrations cause the cutting tools to break, disrupting the process stability and the quality. Therefore, generating the optimum cutting parameters is crucial to obtain high productivity in the manufacturing process of complex geometries and to reach the desired tolerance values.^{4,5} The studies carried out in the field commonly focus on:

- 1) the effect of cutting parameters and cutting strategies of plain-surface milling,
- 2) analytical tool-acceleration calculations and measurements for end-milling and turning operations.

W. H. Yang and Y. S. Tarn⁶ worked on the optimization of the cutting parameters for turning operations so that both optimum cutting parameters were demonstrated and the basic cutting parameters affecting the cutting performance in turning were defined.

M. Kurt et al.⁷ worked on the optimization of the cutting parameters for the finish surface and the accuracy of the hole diameter during dry drilling. In this way, optimum cutting conditions were obtained with the process optimization.

C. Gologlu and N. Sakarya⁸ investigated the effects of tool-path strategies on the surface roughness for pocket-milling operations using cutting parameters with

different values. It was found that the most influential parameter for one-way and spiral tool-path strategies was the feed rate, and the depth of cut was the most important parameter for back-and-forth tool-path strategies. S. Neseli et al.⁹ worked on the optimization of the tool-geometry parameters for turning operations based on the response-surface methodology. In parallel to this study, Asilturk and Neseli¹⁰ worked on the multi-response optimization of CNC turning parameters via a Taguchi-method-based response-surface analysis. M. M. De Aguiar et al.¹¹ investigated the correlating surface roughness, tool wear and tool vibration in the milling process of hardened steel using long slender tools. In this study, a good workpiece-surface roughness together with a long tool life of long tools with small diameters was achieved. H. Wang et al.¹² worked on an investigation of the influence of the tool-tip vibration on the surface roughness and its representative measurement in ultra-precision diamond turning. This paper is dedicated to a study of the influence of the tool-tip vibration on the surface roughness. A. O. Abouelatta and J. Madl¹³ worked on the surface-roughness prediction based on the cutting parameters and tool vibrations in turning operations. S. Orhan et al.¹⁴ worked on the relationship between the vibration and the tool wear during end milling.

The studies given above were concentrated on the determination of the most appropriate parameters for the machining processes involving flat and inclined surfaces. However, the studies confirm that an aggregated effect of the cutting parameters and tool-path styles on the tool acceleration in inclined geometries (convex and concave) were not widely investigated. This study examines the

effects of the cutting parameters and tool-path styles on the tool acceleration in the machining of convex and concave surfaces using ball-end mills. By doing so, it aims to keep the tool-acceleration values at a minimum, and to control the unwanted machining results such as poor surface quality and machining errors.

1.1 Tool-path strategies and cutting parameters

In the experimental studies, contouring and ramping tool-path styles are used to produce inclined surfaces. These tool-path styles can be established based on up-milling and down-milling strategies by making the movements of ramping and contouring. Ramping and contouring are inevitable choices of the tool-path styles for the implementation of the up-milling and down-milling strategies.⁵ In the ramping tool-path styles, the cutter scans an inclined surface following the lines in parallel to the surface radius. On the other hand, in the contouring tool-path styles, the cutter scans an inclined surface following the lines perpendicular to the surface radius.^{15–17} In this study, the step-over values are kept constant in both tool-path styles. After each step of the machining, the cutter moves one step sideways to the position, in which it returns back to the starting level of that step and then makes the next step.¹⁵ In the study under these conditions, four tool-path styles were generated: contouring up milling (CUM), contouring down milling (CDM), ramping up milling (RUM) and ramping down milling (RDM). The form radius of workpiece, milling position angle, nominal depth of cut, step over and spindle speed are indicated by R , θ , a_p , f_p , and S , respectively (Figure 1).

In addition to the cutter path styles defined, three different variable parameters were used for semi-finishing operations. These were the cutting velocity (V_c), feed rate (V_f) and cutting step over (f_p). The cutting-velocity and feed-rate values were taken from the reference catalogues of the tool manufacturer (Sandvik Company). In order to determine the right cutting-tool values (Table 1), a number of experiments for each tool coating was conducted based on the reference values.⁵ The cutting-

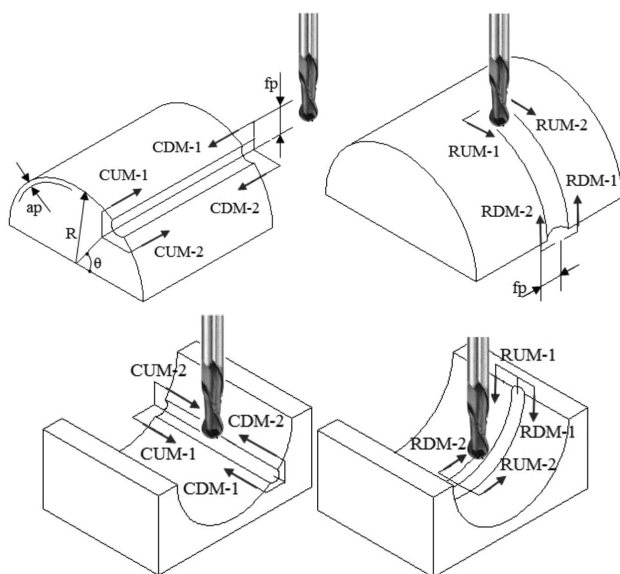


Figure 1: Inclined surfaces and related cutter path styles: CUM-1 (upward step over), CDM-1 (upward step over), CUM-2 (downward step over), CDM-2 (downward step over), RUM-1 (left step over), RDM-1 (left step over), RUM-2 (right step over), RDM-2 (right step over)

Table 1: Assignment of the levels to factors

Factors		Level 1	Level 2	Level 3	Level 4
Cutting velocity, V_c (m/min) – A	TiC	70	80	90	100
	TiN	100	110	120	130
	TiAlN	110	120	130	140
Feed rate, V_f (mm/rev) – B	TiC	223	255	286	318
	TiN	318	350	382	414
	TiAlN	350	382	414	445
Step over, f_p (mm) – C		0.8	1	1.5	2
Cutting path styles – D		Contouring up milling (CUM)	Contouring down milling (CDM)	Ramping up milling (RUM)	Ramping down milling (RDM)

tool step-over values directly affect the tracks on the surface made by the cutter, the load on the cutter and processing time.⁸ The step-over value was chosen to be 5 % of the tool diameter and this value was set as the lower level of *fp*. The depth of cut was taken as 0.3 mm and fixed as a constant. An orthogonal array of *L*16 was chosen for the experimental design and four different levels were defined for each cutting parameter (**Table 1**).

2 EXPERIMENTAL PART

The EN X40CrMoV5-1 hot-work tool steel was selected for the study. The material is commonly used in tool-making processes due to the quality characteristics including high durability, high thermal conductivity, high machinability and high cracking resistance.⁵ First, experimental samples of (40 × 30) mm islands on a (220 × 135 × 50) mm block were machined. In the experiments, an indexable cutter body of an Ø16 mm cylindrical shank (CoroMill, R216-16A20-045) with a two-fluted 30°-helix-angle end mill was used. The ball-end inserts of TiC, TiN and TiAlN coated with 3-µm R216-16 03 M-M H13A were used. Semi-finishing operations were employed and no coolant was used in the machining. The experiments were carried out on a vertical machining center of a John Ford VMC 550, with 12000 min⁻¹ and a 12-kW engine. The experimental set-up is shown in **Figure 2**. The acceleration of the vibration signals generated during the cutting was measured using a piezoelectric accelerometer (VibroTest 60) based on the ISO 2954 standard. The accelerometer was mounted on the workpiece via a magnetization feature.

2.1 Tool acceleration

Tool acceleration occurs in machining operations due to the interaction between the tool and workpiece structure. Each tooth pass leaves a modulated surface on the workpiece due to the vibrations of the tool and workpiece, causing a variation in the expected chip thickness. Under certain cutting conditions (i.e., feed rate, depth of cut and cutting velocity), significant chip-thickness variations, and hence force and displacement variations, occur and a vibration is present.¹⁸ Vibrations result in a poor surface finish, excessive tool wear, reduced dimensional accuracy and tool damage. For a milling process, conservative cutting conditions are usually selected to avoid vibrations that decrease productivity.¹⁹

The values of the tool acceleration were experimentally measured during the machining of inclined surfaces (**Table 2**).

Table 2: Measured values of tool acceleration

Exp. No.	Convex inclined surface			Concave inclined surface		
	(m/s ² peak) (TiC)	(m/s ² peak) (TiN)	(m/s ² peak) (TiAlN)	(m/s ² peak) (TiC)	(m/s ² peak) (TiN)	(m/s ² peak) (TiAlN)
1	0.125	0.117	0.103	0.287	0.254	0.241
2	0.197	0.189	0.214	0.428	0.277	0.358
3	0.205	0.216	0.235	0.501	0.411	0.383
4	0.292	0.239	0.286	0.637	0.471	0.465
5	0.137	0.154	0.149	0.356	0.346	0.326
6	0.145	0.167	0.195	0.311	0.265	0.275
7	0.261	0.217	0.277	0.556	0.456	0.411
8	0.253	0.206	0.218	0.477	0.461	0.437
9	0.210	0.196	0.174	0.389	0.379	0.325
10	0.249	0.247	0.219	0.461	0.381	0.375
11	0.174	0.162	0.189	0.292	0.260	0.317
12	0.181	0.187	0.228	0.481	0.398	0.263
13	0.191	0.175	0.182	0.447	0.417	0.445
14	0.131	0.186	0.197	0.345	0.357	0.281
15	0.138	0.135	0.130	0.308	0.293	0.279
16	0.129	0.127	0.128	0.297	0.259	0.254

The orthogonal array chosen was *L*16 (4⁴), with 16 rows corresponding to the number of experiments (4 factors with 4 levels each). To obtain the optimum cutting performance, the smaller-the-better quality characteristic for the tool acceleration was adopted. The *S/N* ratio was defined as follows in Equation (1):

$$\frac{S}{N} = -10 \lg \frac{1}{N} \sum_{i=1}^n Y_i^2 \tag{1}$$

where *Y_i* is the observed data at the *i*th experiment and *n* is the number of experiments.

2.2 Response-surface methodology

The response surface methodology (RSM) is a well-known up-to-date approach to the optimization of input-parameter models based on either physical or simulation experiments and experimental observations.

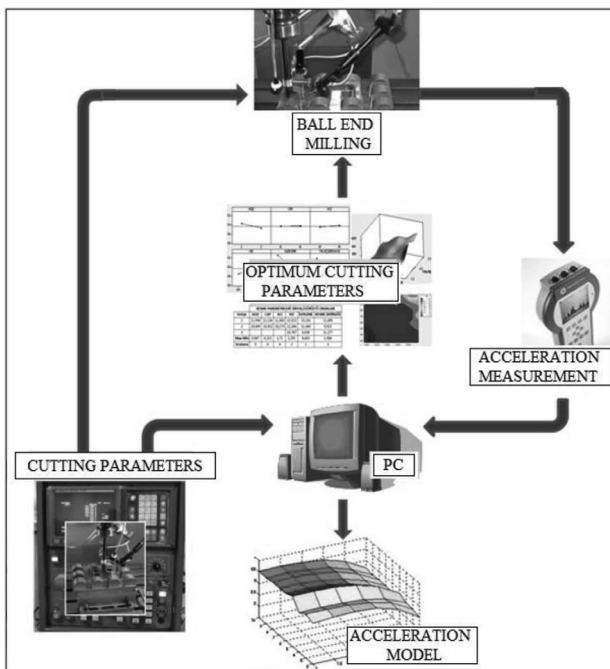


Figure 2: Experimental set-up

These approximated models need to be assessed statistically for their adequacy, and then they can be utilized for an optimization of the initial model.¹⁰ Response-surface-methodology problems follow a functional relation between responses and independent variables, and this relation can be explained using the second-order polynomial model in Equation (2):²⁰

$$\eta = \beta_0 + \sum_{i=1}^k \beta_i X_i + \sum_{i=1}^k \beta_{ii} X_i^2 + \sum_i \sum_j \beta_{ij} X_i X_j + \varepsilon \quad (2)$$

where η is the estimated response (the tool acceleration); β_0 is the constant; β_i , β_{ii} and β_{ij} represent the coefficients of linear, quadratic and cross-product terms, respectively. X reveals the coded variables.

3 RESULTS

The *S/N* ratios of the four factors from Equation (1) were calculated for each of the tool coatings, and convex and concave inclined surface types (Figures 3 to 8). The largest *S/N* ratios always yield the optimum quality with the minimum variance.⁵ Therefore, the level with the largest value determines the optimum level of each factor. From Figures 3 and 4, relating to the milling of the TiC-coated convex and concave inclined surfaces, the optimum levels in terms of the tool acceleration can be

observed at A4 for V_c (100 m/min), B1 for V_f (223 min⁻¹) and C1 for f_p (0.8 mm). For the tool-path styles, the optimum levels can be observed at D4 (UMC) for the convex inclined surface and D1 (DMR) for the concave inclined surface. From Figures 5 and 6, relating to the milling of the TiN-coated convex and concave inclined surfaces, the optimum levels in terms of the tool acceleration can be observed at A4 for V_c (130 m/min), B1 for V_f (318 min⁻¹), C1 for f_p (0.8 mm) and D1 (DMR) for the

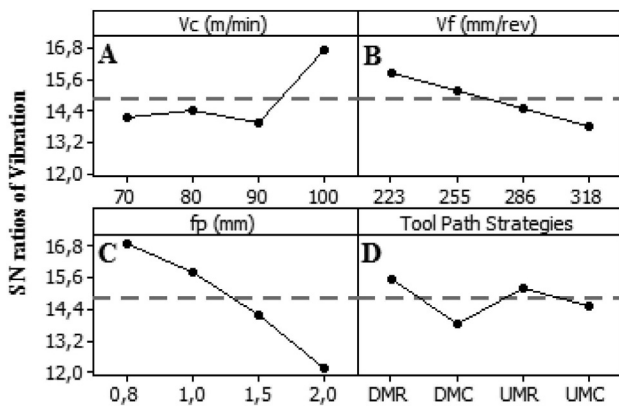


Figure 3: *S/N* ratios for milling a TiC-coated convex inclined surface

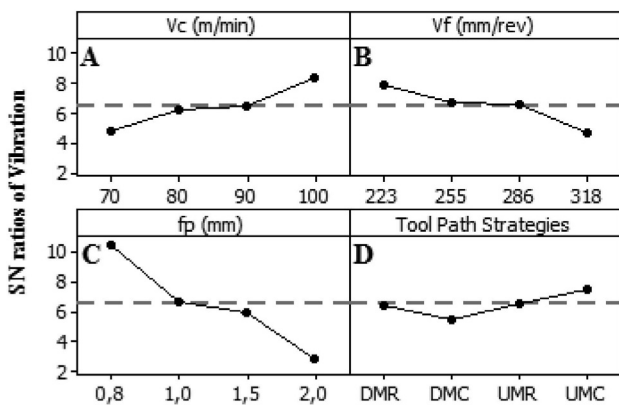


Figure 4: *S/N* ratios for milling a TiC-coated concave inclined surface

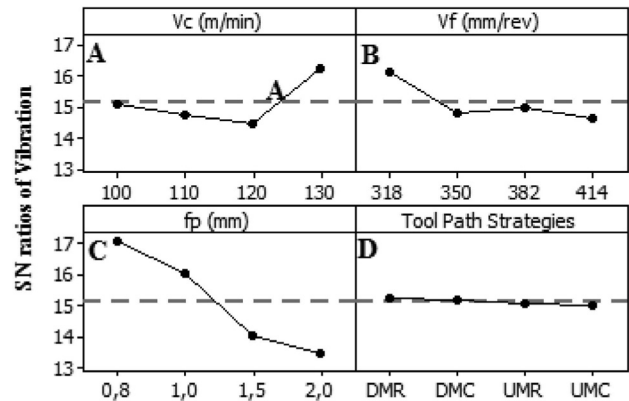


Figure 5: *S/N* ratios for milling a TiN-coated convex inclined surface

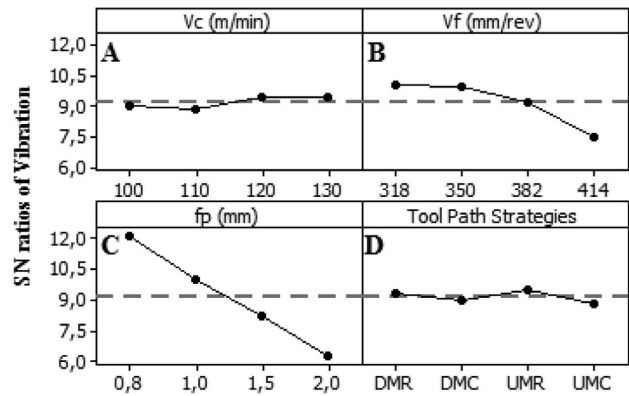


Figure 6: *S/N* ratios for milling a TiN-coated concave inclined surface

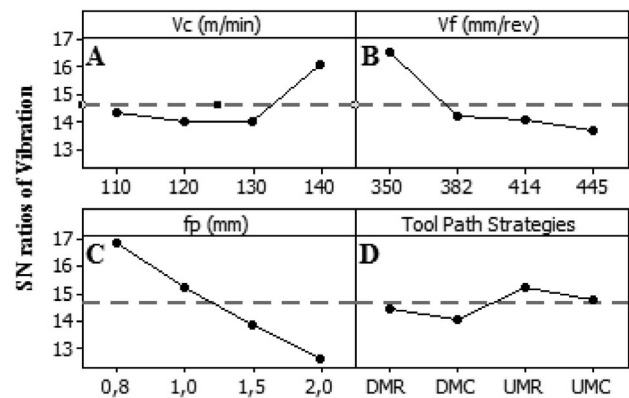


Figure 7: *S/N* ratios for milling convex inclined surfaces with a TiAlN-coated cutter

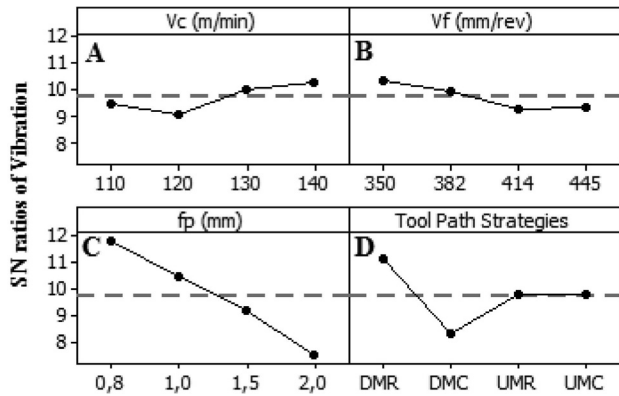


Figure 8: S/N ratios for milling a TiAlN-coated concave inclined surface

tool-path style. Likewise, from Figures 7 and 8, relating to the milling of the TiAlN-coated convex and concave inclined surfaces, the optimum levels in terms of the tool acceleration can be observed at A4 for V_c (140 m/min), B1 for V_f (358 mm/rev), C1 for f_p (0.8 mm) and D1 (DMR) for the tool-path style.

In the machining of inclined surfaces, as seen in Figures 3 to 8, the tool-acceleration values decreased slightly with an increase of V_c , in line with the data from references^{4,18,21}. The literature emphasizes that a slight increase in V_c is caused by the following reasons: deformations of the main cutting edge of the cutting tool increase with a decrease in V_c , and this causes an increase in the contact length between the cutting tool and

Table 3: ANOVA of the tool acceleration for inclined surface types

Source of variance	DOF, ν	SS	Variance, V	F ratio ($\alpha=5\%$)	p	PCR (%)
Convex inclined surface (TiC)						
Cutting velocity, V_c (m/min)	3	0.0050203	0.0016734	5.92	0.049	11.70
Feed rate, V_f (m/rev)	3	0.0092032	0.0030677	10.85	0.041	21.50
Step over, f_p (mm)	3	0.0255268	0.0085089	30.09	0.010	59.60
Tool-path style	3	0.0022432	0.0007477	2.64	0.223	5.20
Error, e	3	0.0008483	0.0002828			2.00
Total	15	0.0428417				100.00
Concave inclined surface (TiC)						
Cutting velocity, V_c (m/min)	3	26.015	8.672	1.84	0.050	13.63
Feed rate, V_f (m/rev)	3	21.613	7.204	1.53	0.048	11.32
Step over, f_p (mm)	3	120.608	40.203	8.52	0.036	63.19
Tool-path style	3	8.455	2.818	0.6	0.659	4.43
Error, e	3	14.148	4.716			7.41
Total	15	190.839				100.00
Convex inclined surface (TiN)						
Cutting velocity, V_c (m/min)	3	0.002192	0.0007307	3.54	0.490	10.99
Feed rate, V_f (m/rev)	3	0.002838	0.0009461	4.58	0.042	14.23
Step over, f_p (mm)	3	0.014166	0.0047221	22.88	0.014	71.03
Tool-path style	3	0.000126	0.0000419	0.2	0.888	0.63
Error, e	3	0.000619	0.0002064			3.1
Total	15	0.019941				100.00
Concave inclined surface (TiN)						
Cutting velocity, V_c (m/min)	3	0.006494	0.002165	0.44	0.048	3.22
Feed rate, V_f (m/rev)	3	0.04115	0.013717	2.81	0.040	20.42
Step over, f_p (mm)	3	0.133717	0.044572	9.14	0.021	66.37
Tool-path style	3	0.005465	0.001822	0.37	0.780	2.71
Error, e	3	0.014633	0.004878			7.26
Total	15	0.20146				100.00
Convex inclined surface (TiAlN)						
Cutting velocity, V_c (m/min)	3	0.005747	0.001916	1.42	0.050	15.07
Feed rate, V_f (m/rev)	3	0.009267	0.003089	2.29	0.045	24.3
Step over, f_p (mm)	3	0.017734	0.005911	4.37	0.028	46.51
Tool-path style	3	0.00132	0.00044	0.33	0.809	3.46
Error, e	3	0.004055	0.001352			10.63
Total	15	0.038123				100.00
Concave inclined surface (TiAlN)						
Cutting velocity, V_c (m/min)	3	0.005838	0.001946	5.53	0.047	6.37
Feed rate, V_f (m/rev)	3	0.020738	0.006913	19.63	0.018	22.63
Step over, f_p (mm)	3	0.059669	0.01989	56.49	0.004	65.12
Tool-path style	3	0.004318	0.001439	4.09	0.139	4.71
Error, e	3	0.001056	0.000352			1.15
Total	15	0.091619				100.00

the workpiece. The longer contact length between the cutting tool and the workpiece increases the friction force on the cutting-tool rake face and this leads to an increase in the tool acceleration depending on the cutting forces.^{4,21} The chip cross-sectional area generated by f_p and V_f is the most influential factor in determining the tool acceleration. As the f_p and V_f values increase, the tool acceleration increases as seen in **Figures 3 to 8**.

3.1 Analysis of variance

A statistical analysis of variance (ANOVA) was performed to examine, which cutting parameters were statistically significant for the tool acceleration. The p values of ANOVA for all the cutting parameters and tool-path styles are shown at a significance level of 95 % (**Table 3**). Thus, it can be stated that the differences between the measured values meaningfully result from the differences between the levels.⁵

For the response value of the tool acceleration (**Table 4**) of the TiC-coated cutter, the most significant parameters were f_p ($p = 0.010$), V_f ($p = 0.041$) and V_c ($p = 0.049$) when machining the convex inclined surfaces. Similarly, in the machining of the concave inclined surfaces, f_p , V_f and V_c were again the significant parameters with the p values of 0.036, 0.048 and 0.05, respectively. For the cutting-force values of the TiN-coated cutter, f_p ($p = 0.014$), V_f ($p = 0.042$) and V_c ($p = 0.049$) were significant parameters when machining the convex inclined surfaces. Likewise, f_p , V_f and V_c were the most significant control factors with the p values of 0.021, 0.04 and 0.048 when machining the concave inclined surfaces. Lastly, for the cutting-force values of the TiAlN-coated cutter, f_p ($p = 0.028$), V_f ($p = 0.045$) and V_c ($p = 0.05$) were the most significant control factors when machining the convex inclined surfaces. Similarly, when machining the concave inclined surfaces with the TiAlN-coated cutter, f_p , V_f and V_c were the most significant control factors with the p values of 0.004, 0.018 and 0.047, respectively. According to the response values of the tool acceleration (**Table 3**), when machining both convex and concave inclined surfaces with the TiC-, TiN- and TiAlN-coated cutters, the most significant control factors were f_p , V_f and V_c . It is worth mentioning that f_p was superior to V_f in all the cases.

3.2 Determination of the optimum machining parameters and confirmation experiments

The optimum parameters in machining convex inclined surfaces were A4B1C1D1 for the TiC-coated cutter; A4B1C1D1 for the TiN-coated cutter; and A4B1C1D3 for the TiAlN-coated cutter. On the other hand, in terms of the tool acceleration, the optimum parameters in machining concave inclined surfaces were A4B1C1D4 for the TiC-coated cutter; A4B1C1D1 for the TiN-coated cutter; and A4B1C1D1 for the TiAlN-coated cutter. By making a prediction considering the para-

eters, the results can be calculated in advance using Equations (3) to (4) (**Table 4**):⁸

$$\eta_{cal} = \bar{\eta}_m + \left(\text{Max} \frac{S}{N_1} - \bar{\eta}_m \right) + \left(\text{Max} \frac{S}{N_2} - \bar{\eta}_m \right) + \left(\text{Max} \frac{S}{N_3} - \bar{\eta}_m \right) + \left(\text{Max} \frac{S}{N_4} - \bar{\eta}_m \right) \tag{3}$$

where η_{cal} is the calculated S/N ratio under the optimum machining conditions; $\bar{\eta}_m$ is the arithmetic mean of the S/N ratio of the studied surface form.

$$Acc_{cal} = 10^{-\frac{\eta_{cal}}{20}} \tag{4}$$

Acc_{cal} is the calculated base quantity; η_{cal} is the calculated S/N ratio.

Table 4: Calculated values for convex and concave inclined surfaces

Coatings	Convex inclined surface		Concave inclined surface	
	η_{cal} (dB)	Acc_{cal} (m/s ² peak)	η_{cal} (dB)	Acc_{cal} (m/s ² peak)
TiC	20.727	0.092	20.915	0.090
TiN	19.337	0.108	13.722	0.206
TiAlN	14.991	0.178	14.379	0.191

Two test trails for each coating type at the optimal-control-factor settings were conducted as confirmation experiments. The tests were carried out with new cutters, one for each coating type in order to prevent undesirable effects caused by worn cutting tools.⁵ The results of the experiments are presented in **Table 5**, showing the acceleration values (Acc_{mea}) and S/N ratios (η_{mea}).

Table 5: Comparison between confirmatory-test results and calculated values for convex and concave inclined surfaces

	Exp. No.	Acceleration (m/s ² peak)	Acceleration _{mea} (m/s ² peak)	Acceleration (η_{mea} ,dB)	Absolute differences (%) [*]
Convex inclined surface					
TiC	1	0.086	0.090	20.906	0.2
	2	0.094			
TiN	1	0.091	0.101	19.871	0.7
	2	0.111			
TiAlN	1	0.153	0.172	15.236	0.6
	2	0.191			
Concave inclined surface					
TiC	1	0.101	0.103	19.741	1.3
	2	0.105			
TiN	1	0.202	0.203	13.849	0.3
	2	0.204			
TiAlN	1	0.179	0.188	14.506	0.3
	2	0.197			

^{*} $\frac{Acc_{cal} - Acc_{mea}}{Acc_{mea}} \times 100$

3.3 Confidence interval

Estimating the mean is only a point estimate based on the average of the results obtained from the experiment. It gives a 50 % chance of being greater or lower than the mean.²² Therefore, confidence interval (CI) should be calculated. A confidence interval includes the maximum and minimum value between which the true average should be at some stated percentage of confidence. Confidence interval is used to verify the quality characteristics of confirmation experiments. The following formula is used to verify the predictions:²³

$$CI = \sqrt{F_{0.05}(1, v_e) V_e \left(\frac{1}{n_{\text{eff}}} + \frac{1}{r} \right)} \quad (5)$$

Where $F_{0.05}(1, v_e)$ is the F ratio at a 95 % confidence²⁴ against degree of freedom 1 and the error of v_e ; V_e is the error variance; n_{eff} is the effective number of replication and r is the number of test trials ($r = 2$).

$$n_{\text{eff}} = \frac{N}{1 + V_T} \quad (6)$$

where N is the total number of experiments; v_T is the total main factor of degrees of freedom ($V_T = 12$). The confidence-interval (CI) values for the convex and concave inclined surfaces obtained using Equations (5) and (6) are provided in **Table 6**.

Table 6: CI values

	Tool acceleration (m/s ² peak)		
	TiC	TiN	TiAlN
Convex inclined surface	0.047	0.023	0.062
Concave inclined surface	2.027	0.120	0.061

The S/N ratio differences between the estimated values obtained using Equations (2) and (3), and the results obtained with the confirmation experiments are shown in **Table 5**. The differences appear to be the smallest at a confidence-interval value of 5 % given in **Table 6**. Therefore, both inclined surfaces and all the coatings used are confirmed as safe, having the optimal control-factor settings.

3.4 Prediction of the tool acceleration

A tool-acceleration prediction model based on the cutting-parameter values was developed using the response-surface methodology (RSM). The RSM is a methodology that uses a combination of statistical and mathematical techniques for the development and optimization of processes. The RSM optimizes (maximizes, minimizes or makes nominal) the response using a polynomial model of the first order or second order.⁵ As a result of the machinability experiments conducted, a first-order model and a quadratic polynomial tool-acceleration model depending on the values of V_c , V_f and f_p were obtained as shown in Equation (7):

$$RMS = k_0 + k_1 \cdot V_c + k_2 \cdot V_f + k_3 \cdot f_p \quad (7)$$

$$RMS = k_0 + k_1 \cdot V_c + k_2 \cdot V_f + k_3 \cdot f_p + k_4 \cdot V_c^2 + k_5 \cdot V_f^2 + k_6 \cdot f_p^2 + k_7 \cdot V_c \cdot V_f + k_8 \cdot V_c \cdot f_p + k_9 \cdot V_f \cdot f_p \quad (8)$$

The values of the polynomial and first-order model regression coefficients and the correlation coefficient for the mathematical model of R_a are given in **Tables 7** and **8**.

Table 7: First-order-model coefficients and correlation coefficients

Coefficient	Multiplier	Regression coefficients					
		Convex inclined surface			Concave inclined surface		
		TiC	TiN	TiAlN	TiC	TiN	TiAlN
k_0	Sabit	0.195	0.183	0.197	0.533	0.376	0.344
k_1	V_c	-0.025	-0.011	-0.020	-0.099	-0.025	-0.022
k_2	V_f	0.023	0.013	0.029	0.095	0.059	0.021
k_3	f_p	0.051	0.037	0.042	0.183	0.116	0.078
%	Correlation coefficients						
		89.19	88.80	86.26	85.77	83.48	83.72

Table 8: Polynomial-regression coefficients and correlation coefficients

Coefficient	Multiplier	Regression coefficients					
		Convex inclined surface			Concave inclined surface		
		TiC	TiN	TiAlN	TiC	TiN	TiAlN
k_0	Sabit	0.205	0.206	0.217	0.534	0.322	0.333
k_1	V_c	-0.037	-0.015	-0.024	-0.166	-0.005	-0.043
k_2	V_f	0.016	0.010	0.030	0.132	0.063	0.017
k_3	F_p	0.045	0.030	0.025	0.181	0.060	0.037
k_4	$V_c \times V_c$	-0.028	-0.020	-0.022	-0.010	0.012	-0.005
k_5	$V_f \times V_f$	0.002	-0.009	-0.018	0.023	0.055	0.000
k_6	$f_p \times f_p$	0.057	-0.012	0.000	-0.014	0.015	0.014
k_7	$V_c \times V_f$	-0.010	-0.012	-0.029	-0.004	-0.096	-0.070
k_8	$V_c \times f_p$	-0.008	-0.004	0.002	0.082	0.000	-0.027
k_9	$V_f \times f_p$	-0.017	-0.006	-0.006	-0.125	0.031	0.000
%	Correlation coefficients						
		91.79	94.54	90.57	92.13	97.04	85.29

The correlation coefficients for the convex inclined surface were 91.79, 94.54 and 90.57 % for the TiC, TiN, and TiAlN coatings, respectively. On the other hand, the related coefficients for the concave inclined surface were 92.13, 97.04 and 85.29 % for the coatings of TiC, TiN and TiAlN, respectively. The values indicate that the model generated is successful at predicting the tool-acceleration values for both inclined surfaces.

3.5 Optimization of the response

One of the most important aims of the experiments related to manufacturing is to achieve the desired tool acceleration of the optimal cutting parameters.⁹ To this end, the response-surface optimization is the ideal technique for determining the tool acceleration in ball-end milling. Here, the goal is to minimize the tool acceleration. The RSM-optimization result for the acceleration parameter for the convex inclined surface and the TiC

Table 9: Response optimization for tool-acceleration-parameter components

Parameter	Goal	Optimum combination			Lower	Target	Upper	Pre-response	Desirability
		V_c (mm/min)	V_f (m/rev)	f_p (mm)					
Convex surface, TiC									
Acceleration (m/s^2 peak)	Min.	100	223	0.8	0.125	0.125	0,292	0.119	1
Convex surface, TiN									
Acceleration (m/s^2 peak)	Min.	130	318	0.8	0.117	0.117	0.239	0.116	1
Convex surface, TiAlN									
Acceleration (m/s^2 peak)	Min.	140	350	0.8	0.103	0.103	0.286	0.112	1
Concave surface, TiC									
Acceleration (m/s^2 peak)	Min.	100	223	0.8	0.287	0.287	0.637	0.249	1
Concave surface, TiN									
Acceleration (m/s^2 peak)	Min.	130	318	0.8	0.254	0.254	0.471	0.226	1
Concave surface, TiAlN									
Acceleration (m/s^2 peak)	Min.	140	350	0.8	0.241	0.241	0.465	0.222	1

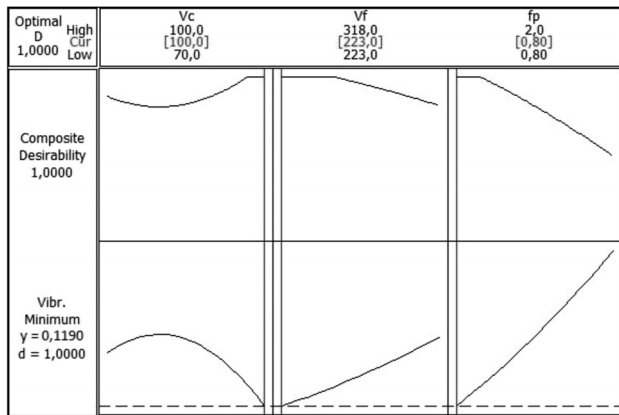


Figure 9: Response-optimization plot for the tool-acceleration-parameter components for the convex surface and TiC coating

coating is shown in **Figure 9**. The optimum cutting parameters obtained for all the surface types and all the coatings are shown in **Table 9**.

4 CONCLUSIONS

The tool acceleration in a ball-end-milling process with cutting parameters and different tool-path strategies was measured, along with the orthogonal array, during the experiments. The results obtained are as follows:

- Both the Taguchi and response-surface statistical analyses indicated that the main effect of the step over is the most significant factor for the tool acceleration.
- According to the confirmation experiments under the optimal conditions, the measured tool-acceleration values for the convex inclined surfaces were found to be smaller than those of the calculated tool-acceleration values. On the other hand, for the concave inclined surfaces, the measured tool-acceleration values were found to be larger than those of the calculated tool-acceleration values. Nevertheless, the absolute difference in the percentile of the measured

and calculated values was not more than 3.57 for both inclined surface types.

- The tool-acceleration values obtained for the machining of the convex inclined surfaces were found to be smaller in comparison to the values obtained for the machining of the concave inclined surfaces (**Table 3**). This is because the chip was comfortably removed from the cutting zone of the convex inclined surface. Besides, the cutting tool affects the inner surface and the contacts with the workpiece, resulting in a longer cutting edge during the tool acceleration.
- The tool-acceleration values for the contouring tool-path style were found to be smaller than those for the ramping tool-path style (**Figures 3 to 8**). This is because the contouring tool-path style causes movements parallel to the axis of the inclined surface. Previous studies support the finding that the movements made in parallel to the surface axis are ideal to move the chips away.
- The RSM was found to be effective for the identification and development of the significant relationships between the cutting parameters.
- The highest correlation coefficients were obtained with the tool-acceleration prediction model. The prediction model can be employed in relative studies.
- The optimum combination of the cutting parameters for the response optimization of all surface types includes the values of the largest cutting velocity, the smallest step over and the feed rate.

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