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Application of factorial design for studying the burr behaviour during face milling of motor engine blocks

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Abstract

This paper studies the behaviour of the burrs' geometries generated during face milling of motor engine blocks. Ceramic and PCBN inserts mounted on a milling cutter with 160 mm of diameter and capacity for 22 inserts, 18 of them for roughing and 4 for finishing, were used. During the tests the cutting speed, the feed rate, the depth of cut and the flank wear were varied. The burr was measured in nine different positions of the edge of the workpiece, varying thus the tool exit angle. It was verified that the burr height was smaller when using PCBN than ceramic inserts. The wear and the tool exit angle had significant influences on the burr size. The greater the flank wear and the exit angle, the bigger the burr. The burr sizes were reduced with increasing the feed rate and in some cases with the depth of cut, but increases when the cutting speed was enhanced.

Keywords: Burr formation; Milling; Grey cast iron

1. Introduction

Burrs can form in many manufacturing processes and its presence is undesirable for several reasons, among them it can be cited: accidents that may compromise the physical integrity of the operator; difficulties of adjusting pieces in the assembling line because the burr modifies the part geometries; cracks at the vicinities of the burr can appear during heat treatments due to stress concentration; in fluid flows the burr will increase the head loss of the tube, compromising the fluid or gaseous flow.

There are several definitions for the burr [1], justified by its formation on several manufacturing processes, each of them with different characteristics. According to Ko and Dornefeld [2] burr is an undesirable protruding part of the workpiece caused by plastic flow during cutting or shearing operation. Studies of the mechanics of the burr formation in machining may allow its size and shape to be predicted and by manipulation of the cutting parameters the burr can be avoided or at least be minimized.

The majority of the works about burr classifies them in three different bases: (i) on their formation mechanisms; (ii) on the cutting edge that generated the burr; (iii) on a criterion taking in account the burr's shape and direction. Gillespie and Blotter [3] identified three basic mechanisms: (i) the lateral deformation involving the material flow towards the free surface of the workpiece; (ii) chip bending to the same cutting direction when the tool is reaching the end of the workpiece; (iii) tensile fracture between the chip and the workpiece. The burrs generated by these different mechanisms were classified into four different types: Poisson burr, Rollover burr, Tear burr and Cut-off (burr).

Nakayama and Arai [4] judged convenient to classify the burrs according to the cutting edge involved on its formation and according to the direction that the burr is formed at the workpiece border.

Gillespie [5], after studying the influence of the cutting parameters on the burr formation mechanism and on the burr dimensions during face milling, proposed the identification of the burr using the following criterion, according to Fig. 1: burr

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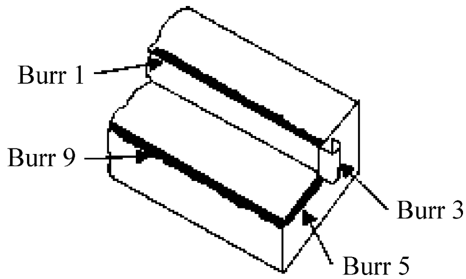


Fig. 1. Some types of burr formed during milling operations according to Gillespie [5].

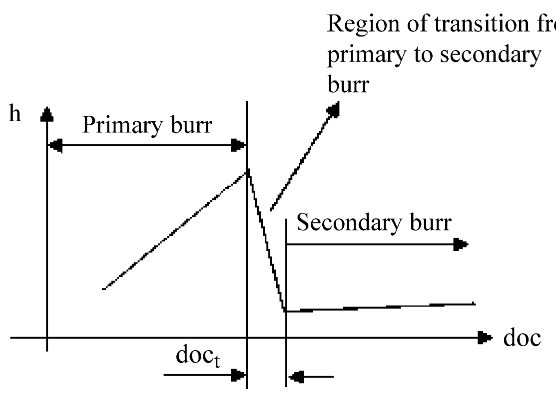


Fig. 2. Primary and secondary burrs according to Kishimoto et al. [6].

#1—the burr that appears at the top of the workpiece border; burr #3—the burr that appears at the border perpendicular to the generated surface; burr #5—exit burr in the feed direction; burr #9—burr formed at the cutting direction.

Kishimoto et al. [6] investigated the formation of burrs #5 and #9 and introduced the terms primary and secondary in order to identify the distinct periods of their formation. In this study, the authors determined the cutting conditions at which the burr will form. The depth of cut and the exit angle are determining factors for the dimensions of the burrs #5 and #9. They observed that for a given exit angle (θ) there is a determined depth of cut interval responsible for the transition from the primary to secondary burr. A term called depth of cut of transition (doc$_t$) is then introduced and identified in Fig. 2, where h is the burr height. In face milling with small depth of cut the secondary cutting edge will work considerably, where the cut mainly takes place, generating thus the primary burr. As the depth of cut increases the participation of the secondary cutting edge diminishes and the action of cutting is shared with the main cutting edge, generating the transition burr. The secondary burr will be formed when the action of the cut is mostly done by the main cutting edge. The curve in Fig. 2 shows that the secondary burrs have reduced height compared to the primary burrs. Due to their small sizes Kishimoto et al. [6] and lately Olvera and Barrow [7] considered borders with secondary burr as burr free borders.

The machining process used to remove burrs is called deburring. It can be done using appropriate equipments such as in high-pressure water washing stations, abrasive jet machining and electrochemical machining, all installed in the production line. However, they can also be removed manually, using small grindings equipments. The burr dimensions as well as the work material involved are particularly important when choosing a particular deburring process. Studying the burr geometry is therefore useful mainly when the most important variables involved are considered, since the burr size can be greatly influenced by them, including the cutting conditions [8].

The main objective of this work is to verify the influence of the tool wear, the exit angle and the cutting conditions (cutting speed, feed per tooth and the depth of cut) on the burr dimensions, when face milling motor engine blocks of grey cast iron using ceramic and PCBN tool inserts. A 2^5 factorial design was used in the experiments which helped the analysis of the results.

2. Experimental procedure

A general factorial design 2^5 was used with five input variables: cutting speed (v_c), feed per tooth (f_z), depth of cut (doc), exit angle (θ) and the maximum flank wear (VB_{Bmax})—the burr height was the output variable. Two levels were used for each input variables, according to Table 1. The experimental tests were divided in two parts, first for the ceramic inserts and second for the PCBN inserts, with 32 tests for each. Three replications were carried out totalizing thus 128 tests for the ceramic inserts and 128 for the PCBN.

The workpiece was a Fiat-GM Powertrain FIRE engine block motor of GH 190 UNI grey cast iron with the following chemical composition: 3.2–3.5% C; 1.5–2.0% Si; 0.20% Cr; 0.15% S; 0.10% P. Fig. 3 shows the surface of the engine block that was machined. This is the surface where the cylinder head will be mounted on it with a gasket in between.

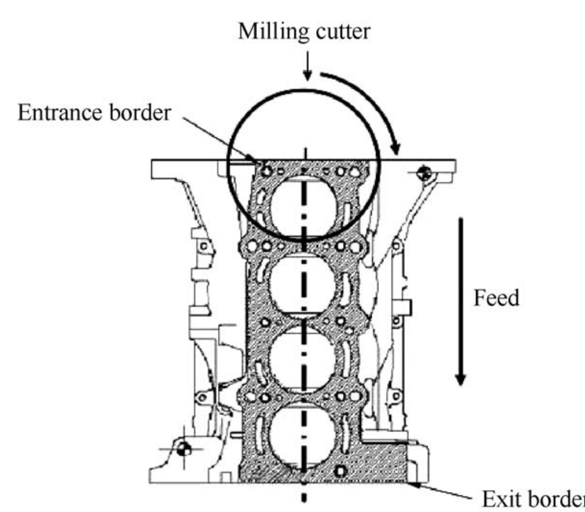
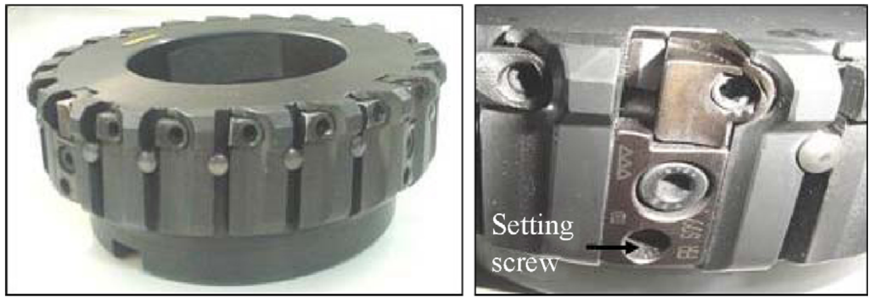


Fig. 3. The surface of the engine block machined.

Table 1
The input variables and their respective levels

Input variables	v_c (m/min)	f_z (mm/tooth)	doc (mm)	VB_{Bmax} (mm)	θ (°)
Level 1 (minimum)	1000	0.04	0.2	0.00	120
Level 2 (maximum)	1500	0.08	0.5	0.60	180



(a) (b)

Fig. 4. (a) The milling cutter used and (b) detail of the screw that adjust the wiper inserts.

(a) (b) (c) (d)

Fig. 5. The tools used in the tests. Ceramic tools: (a) roughing and (b) wiper. PCBN tools: (c) roughing and (d) wiper.

A milling cutter with 160 mm of diameter manufactured by Walter was used. It has the following designation: F-2146.0.40.063.160. It allows 22 octal inserts to be mounted, 18 of them are roughing and 4 are wiper inserts (see Fig. 4). Views of the inserts are seen in Fig. 5. Axial adjustment of the inserts is possible to guarantee flatness of the whole set and thus good surface roughness.

The geometry of the inserts is octal with the ISO designation OPHN0504-AZTM for the roughing and OPHX0505ZZRA27TM for the wiper inserts. The ceramic tools are Si_3N_4 base and the PCBN are small layer brazed on cemented carbide insets, both manufactured by Walter.

The system used to measure the burr was developed at the LEPU, Machining Research and Teaching Laboratory of UFU, Federal University of Uberlandia, Brazil. It consists of an open circuit, which closes and switches on a light and sound alert signal when a gauge touches the workpiece in the tip of the burr. The burr height is determined by reading the machine tool axe control indicator. Fig. 6 shows the system schematically.

3. Results and discussions

After carrying out all the tests a matrix was built showing the average burr height, the main individual and interaction effects. The results are shown in Tables 2 and 3 for the ceramic and for the PCBN inserts, respectively. Analysis of significance of the main individual parameters as well as of the interactions can be determined by the matrixicial equation (1), where "Y" is the numerical significance value, "X" the complete matrix of the coefficient of contrast, 32×16, derived from Table 2 for the ceramic and from Table 3 for the PCBN inserts, and "h" is the average height of the burrs.

$$Y = X^t h \tag{1}$$

After obtaining the numerical value of the significance of the effects they have to be divided by a factor that will depend upon the factorial design. For 2^k factorial design the divisor for the effects will be 2^{k-1} and 2^k for the mean. The values of the standard error, represented by S_{effect} were obtained through Eq. (2), where "s" is the estimative of the variance and "n" is the number of repetition of each test. The estimative of the variance is given by the arithmetic average of the variance for the 32 tests

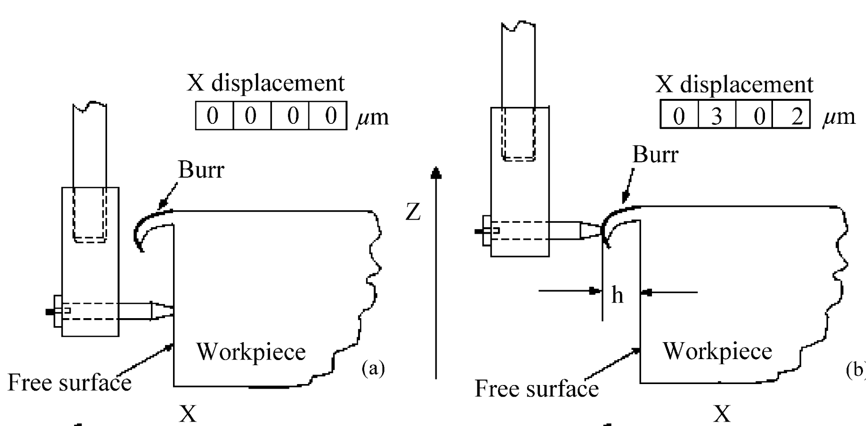


Fig. 6. (a and b) System of measurement of the burr height developed at LEPU, UFU.

Table 2
Matrix of the coefficient of contrast of the main effects, of interaction and of the average height of the burr for the ceramic inserts

Test number	M	v_c	f_z	doc	VB_{Bmax}	θ	$v_c f_z$	$v_c$doc	$v_c VB_{Bmax}$	$v_c\theta$	$f_z$doc	$f_z VB_{Bmax}$	$f_z\theta$	docVB_{Bmax}	docθ	$VB_{Bmax}\theta$	h (μm)
1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	255.83
2	+1	−1	+1	+1	+1	+1	−1	−1	−1	−1	+1	+1	+1	+ 1	+1	+1	250.08
3	+1	+1	−1	+1	+1	+1	−1	+1	+1	+1	−1	−1	−1	+1	+1	+1	270.50
4	+1	−1	−1	+1	+1	+1	+1	−1	−1	−1	−1	−1	−1	+1	+1	+1	304.67
5	+1	+1	+1	−1	+1	+1	+1	−1	+1	+1	−1	+1	+1	−1	−1	+1	242.58
6	+1	−1	+1	−1	+1	+1	−1	+1	−1	−1	−1	+1	+1	−1	−1	+1	189.17
7	+1	+1	−1	−1	+1	+1	−1	−1	+1	+1	+1	−1	−1	−1	−1	+1	284.83
8	+1	−1	−1	−1	+1	+1	+1	+1	−1	−1	+1	−1	−1	−1	−1	+1	244.67
9	+1	+1	+1	+1	−1	+1	+1	+1	−1	+1	+1	−1	+1	−1	+1	−1	84.58
10	+1	−1	+1	+1	−1	+1	−1	−1	+1	−1	+1	−1	+1	−1	+1	−1	76.75
11	+1	+1	−1	+1	−1	+1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	91.42
12	+1	−1	−1	+1	−1	+1	+1	−1	+1	−1	−1	+1	−1	−1	+1	−1	87.67
13	+1	+1	+1	−1	−1	+1	+1	−1	−1	+1	−1	−1	+1	+1	−1	−1	68.25
14	+1	−1	+1	−1	−1	+1	−1	+1	+1	−1	−1	−1	+1	+1	−1	−1	76.92
15	+1	+1	−1	−1	−1	+1	−1	−1	−1	+1	+1	+1	−1	+1	−1	−1	94.00
16	+1	−1	−1	−1	−1	+1	+1	+1	+1	−1	+1	+1	−1	+1	−1	−1	96.08
17	+1	+1	+1	+1	+1	−1	+1	+1	+1	−1	+1	+1	−1	+1	−1	−1	249.83
18	+1	−1	+1	+1	+1	−1	−1	−1	−1	+1	+1	+1	−1	+1	−1	−1	232.08
19	+1	+1	−1	+1	+1	−1	−1	+1	+1	−1	−1	−1	+1	+1	−1	−1	235.33
20	+1	−1	−1	+1	+1	−1	+1	−1	−1	+1	−1	−1	+1	+1	−1	−1	189.83
21	+1	+1	+1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	−1	+1	−1	202.33
22	+1	−1	+1	−1	+1	−1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	189.00
23	+1	+1	−1	−1	+1	−1	−1	−1	+1	−1	+1	−1	+1	−1	+1	−1	268.33
24	+1	−1	−1	−1	+1	−1	+1	+1	−1	+1	+1	−1	+1	−1	+1	−1	227.83
25	+1	+1	+1	+1	−1	−1	+1	+1	−1	−1	+1	−1	−1	−1	−1	+1	61.25
26	+1	−1	+1	+1	−1	−1	−1	−1	+1	+1	+1	−1	−1	−1	−1	+1	50.33
27	+1	+1	−1	+1	−1	−1	−1	+1	−1	−1	−1	+1	+1	−1	−1	+1	37.00
28	+1	−1	−1	+1	−1	−1	+1	−1	+1	+1	−1	+1	+1	−1	−1	+1	45.25
29	+1	+1	+1	−1	−1	−1	+1	−1	−1	−1	−1	−1	−1	+1	+1	+1	46.58
30	+1	−1	+1	−1	−1	−1	−1	+1	+1	+1	−1	−1	−1	+1	+1	+1	49.25
31	+1	+1	−1	−1	−1	−1	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	69.00
32	+1	−1	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	43.08

and can be determined by Eq. (3).

$$S_{\text{effect}} = \sqrt{\frac{s^2}{n_n}} \tag{2}$$

$$s^2 = \frac{\nu_1 s_1^2 + \nu_2 s_2^2 + \cdots + \nu_n s_n^2}{\nu_1 + \nu_2 + \cdots + \nu_n} \tag{3}$$

With the help of computational facilities the solution of Eqs. (1)–(3) became more rapid and reliable. The main effects and the interactions together with the standard errors of each effect are distributed as follow.

For the ceramic inserts, main effects are:

$v_c = 13.06 \pm 19.403$; $f_z = -16.54 \pm 19.403$;

$\text{doc} = 8.15 \pm 19.403$; $VB_{Bmax} = 175.46 \pm 19.403$;

$\theta = 32.60 \pm 19.403$.

and the interaction effects are:

$v_c f_z = -0.85 \pm 19.403$; $v_c\text{doc} = -6.92 \pm 19.403$;

$v_c VB_{Bmax} = 9.71 \pm 19.403$; $v_c\theta = -4.81 \pm 19.403$;

$f_z\text{doc} = -16.42 \pm 19.403$; $f_z VB_{Bmax} = -10.34 \pm 19.403$;

$f_z\theta = -12.16 \pm 19.403$; $\text{doc}VB_{Bmax} = 9.26 \pm 19.403$;

$\text{doc}\theta = 7.46 \pm 19.403$; $VB_{Bmax}\theta = -1.63 \pm 19.403$.

Reasonable significances of the exit angle and of the maximum flank wear are observed. The high significance of the latter obfuscated the significance of the other effects where their values can be neglected. The insignificance of the cutting speed, feed per tooth depth of cut and of the interactions proved that the 2^5 factorial design is not so interesting for this application. The solution would be to apply two 2^4 factorial design, one for each tool wear level.

From the matrix of coefficient of contrast of Table 2 it is possible the creation of two new matrixes with 16 tests each, one for $VB_{Bmax} = 0.00$ mm and other for $VB_{Bmax} = 0.60$ mm. This is shown in Tables 4 and 5, respectively. From these tables the effects can be calculated using the same methodology used previously.

For the ceramic inserts with $VB_{Bmax} = 0.00$ mm the main effects are:

$v_c = 3.33 \pm 8.01$; $f_z = -8.20 \pm 8.01$;

$\text{doc} = -1.11 \pm 8.01$; $\theta = 34.27 \pm 8.01$

Table 3
Matrix of the coefficient of contrast of the main effects, of interaction and of the average height of the burr for the PCBN inserts

Test number	M	v_c	f_z	doc	VB_{Bmax}	θ	$v_c f_z$	$v_c$doc	$v_c VB_{Bmax}$	$v_c\theta$	$f_z$doc	$f_z VB_{Bmax}$	$f_z\theta$	docVB_{Bmax}	docθ	$VB_{Bmax}\theta$	h (μm)
1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	152.00
2	+1	−1	+1	+1	+1	+1	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	139.33
3	+1	+1	−1	+1	+1	+1	−1	+1	+1	+1	−1	−1	−1	+1	+1	+1	128.83
4	+1	−1	−1	+1	+1	+1	+1	−1	−1	−1	−1	−1	−1	+1	+1	+1	187.83
5	+1	+1	+1	−1	+1	+1	+1	−1	+1	+1	−1	+1	+1	−1	−1	+1	108.00
6	+1	−1	+1	−1	+1	+1	−1	+1	−1	−1	−1	+1	+1	−1	−1	+1	117.33
7	+1	+1	−1	−1	+1	+1	−1	−1	+1	+1	+1	−1	−1	−1	−1	+1	168.83
8	+1	−1	−1	−1	+1	+1	+1	+1	−1	−1	+1	−1	−1	−1	−1	+1	135.33
9	+1	+1	+1	+1	−1	+1	+1	+1	−1	+1	+1	−1	+1	−1	+1	−1	106.00
10	+1	−1	+1	+1	−1	+1	−1	−1	+1	−1	+1	−1	+1	−1	+1	−1	79.17
11	+1	+1	−1	+1	−1	+1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	116.00
12	+1	−1	−1	+1	−1	+1	+1	−1	+1	−1	−1	+1	−1	−1	+1	−1	134.33
13	+1	+1	+1	−1	−1	+1	+1	−1	−1	+1	−1	−1	+1	+1	−1	−1	92.17
14	+1	−1	+1	−1	−1	+1	−1	+1	+1	−1	−1	−1	+1	+1	−1	−1	86.67
15	+1	+1	−1	−1	−1	+1	−1	−1	−1	+1	+1	+1	−1	+1	−1	−1	110.50
16	+1	−1	−1	−1	−1	+1	+1	+1	+1	−1	+1	+1	−1	+1	−1	−1	96.33
17	+1	+1	+1	+1	+1	−1	+1	+1	+1	−1	+1	+1	−1	+1	−1	−1	150.33
18	+1	−1	+1	+1	+1	−1	−1	−1	−1	+1	+1	+1	−1	+1	−1	−1	64.00
19	+1	+1	−1	+1	+1	−1	−1	+1	+1	−1	−1	−1	+1	+1	−1	−1	93.83
20	+1	−1	−1	+1	+1	−1	+1	−1	−1	+1	−1	−1	+1	+1	−1	−1	154.83
21	+1	+1	+1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	−1	+1	−1	69.33
22	+1	−1	+1	−1	+1	−1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	88.67
23	+1	+1	−1	−1	+1	−1	−1	−1	+1	−1	+1	−1	+1	−1	+1	−1	129.67
24	+1	−1	−1	−1	+1	−1	+1	+1	−1	+1	+1	−1	+1	−1	+1	−1	80.00
25	+1	+1	+1	+1	−1	−1	+1	+1	−1	−1	+1	−1	−1	−1	−1	+1	100.00
26	+1	−1	+1	+1	−1	−1	−1	−1	+1	+1	+1	−1	−1	−1	−1	+1	72.33
27	+1	+1	−1	+1	−1	−1	−1	+1	−1	−1	−1	+1	+1	−1	−1	+1	104.67
28	+1	−1	−1	+1	−1	−1	+1	−1	+1	+1	−1	+1	+1	−1	−1	+1	103.67
29	+1	+1	+1	−1	−1	−1	+1	−1	−1	−1	−1	−1	−1	+1	+1	+1	87.33
30	+1	−1	+1	−1	−1	−1	−1	+1	+1	+1	−1	−1	−1	+1	+1	+1	72.83
31	+1	+1	−1	−1	−1	−1	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	106.83
32	+1	−1	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	91.50

and the interaction effects are:

$$v_c f_z = -1.48 \pm 8.01; \quad v_c\text{doc} = 0.22 \pm 8.01;$$

$$v_c\theta = -3.13 \pm 8.01; \quad f_z\text{doc} = 9.08 \pm 8.01;$$

$$f_z\theta = -9.46 \pm 8.01; \quad \text{doc}\theta = 2.4 \pm 8.01.$$

When using new ceramic inserts the results show that the most important factors are: the exit angle, the feed per tooth, the interaction between the feed per tooth and the depth of cut and the interaction between the feed per tooth and the exit angle. The cutting speed and the depth of cut did not alter the burr height

Table 4
Matrix of coefficient of contrast for the ceramic inserts with $VB_{Bmax} = 0.00$ mm, after applying a 2^4 factorial design

Test number	M	v_c	f_z	doc	θ	$v_c f_z$	$v_c$doc	$v_c\theta$	$f_z$doc	$f_z\theta$	docθ	h (μm)
1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	84.58
2	+1	−1	+1	+1	+1	−1	−1	−1	+1	+1	+1	76.75
3	+1	+1	−1	+1	+1	−1	+1	+1	−1	−1	+1	91.42
4	+1	−1	−1	+1	+1	+1	−1	−1	−1	−1	+1	87.67
5	+1	+1	+1	−1	+1	+1	−1	+1	−1	+1	−1	68.25
6	+1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	76.92
7	+1	+1	−1	−1	+1	−1	−1	+1	+1	−1	−1	94.00
8	+1	−1	−1	−1	+1	+1	+1	−1	+1	−1	−1	96.08
9	+1	+1	+1	+1	−1	+1	+1	−1	+1	−1	−1	61.25
10	+1	−1	+1	+1	−1	−1	−1	+1	+1	−1	−1	50.33
11	+1	+1	−1	+1	−1	−1	+1	−1	−1	+1	−1	37.00
12	+1	−1	−1	+1	−1	+1	−1	+1	−1	+1	−1	45.25
13	+1	+1	+1	−1	−1	+1	−1	−1	−1	−1	+1	46.58
14	+1	−1	+1	−1	−1	−1	+1	+1	−1	−1	+1	49.25
15	+1	+1	−1	−1	−1	−1	−1	−1	+1	+1	+1	69.00
16	+1	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	43.08

Table 5
Matrix of coefficient of contrast for the ceramic inserts with $VB_{Bmax} = 0.60$ mm, after applying a 2^4 factorial design

Test number	M	v_c	f_z	doc	θ	$v_c f_z$	$v_c$doc	$v_c\theta$	$f_z$doc	$f_z\theta$	docθ	h (μm)
1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	+1	255.83
2	+1	−1	+1	+1	+1	−1	−1	−1	+1	+1	+1	250.08
3	+1	+1	−1	+1	+1	−1	+1	+1	−1	−1	+1	270.50
4	+1	−1	−1	+1	+1	+1	−1	−1	−1	−1	+1	304.67
5	+1	+1	+1	−1	+1	+1	−1	+1	−1	+1	−1	242.58
6	+1	−1	+1	−1	+1	−1	+1	−1	−1	+1	−1	189.17
7	+1	+1	−1	−1	+1	−1	−1	+1	+1	−1	−1	284.83
8	+1	−1	−1	−1	+1	+1	+1	−1	+1	−1	−1	244.67
9	+1	+1	+1	+1	−1	+1	+1	−1	+1	−1	−1	249.83
10	+1	−1	+1	+1	−1	−1	−1	+1	+1	−1	−1	232.08
11	+1	+1	−1	+1	−1	−1	+1	−1	−1	+1	−1	235.33
12	+1	−1	−1	+1	−1	+1	−1	+1	−1	+1	−1	189.83
13	+1	+1	+1	−1	−1	+1	−1	−1	−1	−1	+1	202.33
14	+1	−1	+1	−1	−1	−1	+1	+1	−1	−1	+1	189.00
15	+1	+1	−1	−1	−1	−1	−1	−1	+1	+1	+1	268.33
16	+1	−1	−1	−1	−1	+1	+1	+1	+1	+1	+1	227.83

significantly. The same can be said for the interaction involving the cutting speed.

For the ceramic inserts with $VB_{Bmax} = 0.60$ mm the main effects are:

$$v_c = 22.77 \pm 11.13; \quad f_z = -26.88 \pm 11.13;$$

$$\text{doc} = 17.42 \pm 11.13; \quad \theta = 30.97 \pm 11.13$$

and the interaction effects are:

$$v_c f_z = -0.21 \pm 11.13; \quad v_c\text{doc} = -14.07 \pm 11.13;$$

$$v_c\theta = -6.48 \pm 11.13; \quad f_z\text{doc} = 23.76 \pm 11.13;$$

$$f_z\theta = -14.83 \pm 11.13; \quad \text{doc}\theta = 12.53 \pm 11.13.$$

With the worn ceramic inserts several effects are significant, among them all main effects (v_c, f_z, doc and θ) and four interaction effects: $v_c$doc, $f_z$doc, $f_z\theta$ and docθ. The exit angle is the main factor since the dimension of its effect is the highest (30.97). The feed per tooth influences in a negative form (−26.88), which means that its increase causes reduction in the burr height. Less influent than the two first effects is the cutting speed and followed by the effect of the depth of cut. Although small (−14.07) in relation to the standard deviation (11.03) there is still a negative influence of the interaction between the last two effects ($v_c$doc).

The situation is different for the PCBN inserts where the dimensions of their effects are:

Main effects:

$$v_c = 7.51 \pm 10.85; \quad f_z = -22.34 \pm 10.85;$$

$$\text{doc} = 15.36 \pm 10.85; \quad VB_{Bmax} = 25.48 \pm 10.85,$$

$$\theta = 24.30 \pm 10.85$$

and the interaction effects are:

$$v_c f_z = 10.50 \pm 10.85; \quad v_c\text{doc} = -5.48 \pm 10.85;$$

$$v_c VB_{Bmax} = -3.32 \pm 10.85; \quad v_c\theta = -6.76 \pm 10.85;$$

$$f_z\text{doc} = 2.23 \pm 10.85; \quad f_z VB_{Bmax} = -1.42 \pm 10.85;$$

$$f_z\theta = -2.31 \pm 10.85; \quad \text{doc}VB_{Bmax} = 6.36 \pm 10.85;$$

$$\text{doc}\theta = 10.85; \quad VB_{Bmax}\theta = 14.05 \pm 10.85.$$

According to the calculations, the cutting speed has little influence on the burr height and although with small dimension the effect of the depth of cut is still significant.

Among the interactions, only the one between the tool wear and the exit angle is important while other interactions are insignificant.

4. Conclusions

- Using a factorial design it was possible to conclude that the burr is mainly dependant on the maximum flank wear and on the exit angle of the milling cutter from the workpiece.
- The feed per tooth always showed a negative influence on the burr height, that is, the burr diminishes its dimensions when the feed per tooth is increased.
- In the tests with new ceramic inserts and with new and worn PCBN inserts the cutting speed did not influence the burr dimension significantly.
- When using new ceramic inserts the depth of cut has only influenced the burr dimension when interacting with the feed per tooth.

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