THE INFLUENCE OF CAM STRATEGIES ON THE TOOL WEAR AND SURFACE ROUGHNESS

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Abstract

The article deals with the tool life of ball nose end mills and surface roughness of steel C45 depending on contouring and copy milling. The aim was to determine and compare the wear of ball nose end mill and surface roughness parameter for different types of ball end milling strategies, as well as to specify particular steps of the measurement process. For tool life test, DMG DMU 85 monoBLOCK 5-axis CNC milling machine was used. In the experiment, the cutting speeds, feed rates, axial and radial depth of cut were constant. The coated cemented carbide was used as tool material. The cutting tool wear was measured on Zoller Genius 3s and laser Blum Micro Compact NT. Surtronic 3+ (Taylor Hobson) was used for surface roughness measurement. The results show different achieved surface roughness parameter of machined material C45 and tool life of ball nose end mills depending on milling strategy.

Keywords: Contouring; Copy Milling; Wear; Machining; Tool

1. Introduction

Tools wear is generally considered as negative factor that accompanies each of machining process. This affects the cutting forces, cutting temperature and surface quality. The complete elimination of wear is not possible, but with a well-selected material of tool, coating and machining conditions it can be minimized. Taking into account these general conditions research was focused on the impact of CAM strategies for wear and tool life of ball nose end mills. Research will be focused on contouring and copy milling strategies. In this case climb milling during up and down-copying and up and down-contouring were used. Nowadays research of wear of milling tools isn't focused in one field. The position of the tool in relation to the machined surface (inclination angle) has a strong impact on the cutting forces [1-3]. In [4] is an influence of up and down-copying on tool wear and [5] on the surface roughness. Tian et al. [6] studied effect of cutting force to wear mechanisms for down and up copying. Influence of inclination angles of cutting tool on wear of cutter after machining process are in [7] and [8]. Impact of different types of hard machining materials on the tool wear concretely Ti-6Al-4V [9], Hastelloy C-22HS [10], 3Cr13Cu [11], compacted graphite iron and graphite iron [12]. Zetek et al. [13] observed flank wear and measured cutting forces during the face milling of Inconel 718. They optimized size of edge

radius and increased tool life about 20%. Kasim et al. [14] found that notch wear was the predominant failure mode during end milling of Inconel 718. Begic-Hajdarevic et al. investigated the effect of cutting parameters on surface roughness in up- and down milling. In major part of these publications was flank wear, the main criterion for evaluation of experiments. In our experiment surface roughness and accuracy as a criterion were used.

2. Experiment

The experiment was focused on the basic principles of finish milling strategies (contouring, copy milling) with ball nose end mill see. Fig.1. Finish milling strategies during and down-copying and up and down-contouring were compared. The material was medium carbon steel ISO C45 (AISI 1045) grade. Block material had dimensions of 200×100×100 mm. The tested cutting tools material was coated cemented carbide. Diameter of tool was 8 mm. Model of workpiece was carried out in CAD system PowerShape 2017 and CAM strategies were created in PowerMILL 2017 software.

Fig. 1. Milling strategies used in experiment

For milling, DMG DMU 85 monoBLOCK 5-axis CNC milling machine was used. Air coolant in the machining process was used. For cutting tests, we set the same cutting conditions (cutting speed, feed rate, axial and radial depth of cut). Hence, we intended to investigate just the influence of cutter contact areas on the cutter plane on wear of ball nose end mill for the same cutting parameters. The inclination angle of the workpiece was 15°. Tonshoff et al. [15] found that the optimum inclined angle is 15° for ball end-milling of block materials.

Since the flank wear of ball nose end mill was dominant, it was measured on Zoller Genius 3s universal measuring machine. For nominal tool radius lost of Blum Micro Compat NT was used. Tool nominal radius lost (Nom-DR2) had influence on accuracy of machined surface. Blum measuring cycle 588 was used for measure 20 radiuses on the cutting edge from 0° (tool tip) to 45°. These settings were carried out because up to 45° tool wear did not occur. Surtronic 3+ was used for measurement of surface roughness.

For tool wear criteria Nom-DR2 = 0.025 mm and surface roughness parameter Ra = 1.6 µm were established. Flank wear VB = 0.15 mm was also evaluated in conjunction with Nom-DR2 and Ra.

All tool life tests were carried out with the following parameters: cutting speed $v_c = 452$ m/min, spindle speed $n = 18000$ rpm, feed rate $v_f = 2160$ mm/min, axial depth of cut $a_p = 0.3$ mm, radial depth of cut $a_e = 0.1$ mm, feed per tooth $f_z = 0.06$ mm. Effective cutting radius and effective cutting speed in up and down (copying, contouring) were different. In upward milling, tangential curve is placed on the one side from the axis of rotation of ball nose end mill. In downward milling, tangential curve is placed around the axis of rotation of ball nose end mill on the both sides, and crosses the centre of rotation of ball nose end mill. The scheme with symbols for copy milling is shown in Fig. 2.

Fig. 2. (a) Scheme of up-copying; (b) scheme of down-copying [16].

The symbols in Fig. 2:

R - radius of the cutter (mm)	a_p -depth of cut (mm)
v_f - feed rate (mm/min)	$a_{p,max}$ - maximum depth of cut (mm)
α - slope angle of milling surface ($^\circ$)	$a_{p,iden}$ - identical depth of cut (mm)
n - spindle speed (1/min)	$a_{p,crit}$ - critical depth of cut (mm)
R_{ef1} -effective radius of the cutter on machined surface (mm)	R_{ef2} - effective radius of the cutter on work surface (mm)

Determination of effective radius is very important for obtaining the effective cutting speed. Equations for effective radius and effective cutting speed have the following forms [17]:

$$\begin{aligned} R_{ef1} &= R \cdot \sin \alpha \\ R_{ef1} &= 4 \cdot \sin 15^\circ = 1.035 \text{ mm} \end{aligned} \quad (1)$$

$$v_{c1} = \frac{2\pi \cdot R_{ef1} \cdot n}{1000} = 117.06 \text{ m/min} \quad (2)$$

- The situations for up-contouring, copy milling:

$$R_{ef2} = R \times \sin \left(\alpha + \arccos \frac{R - a_p}{R} \right) = 2.4257 \text{ mm} \quad (3)$$

$$v_{c2} = \frac{2\pi \cdot R_{ef2} \cdot n}{1000} = 274.34 \text{ m/min} \quad (4)$$

- The situations for down-contouring, copy milling and provided that $a_p > a_{p,crit} \wedge a_p < R$:

$$R_{ef2} = R \times \sin \left(-\alpha + \arccos \frac{R - a_p}{R} \right) = 0.5104 \text{ mm} \quad (5)$$

From the equation for effective cutting speed results that the highest cutting speed is calculated for the larger of the effective radius R_{ef1} and R_{ef2} . Therefore, in up-contouring, copying (equation 3), $R_{ef2} > R_{ef1}$, the effective cutting speed was calculated for R_{ef2} (equation 4). Since in down-contouring, copying (equation 5), $R_{ef2} < R_{ef1}$, the effective cutting speed was calculated for R_{ef1} (equation 2).

3. Results

In the Fig.2 you can see time dependence of VB flank wear value (first evaluated criteria). Micrographs of flank wear of carbide ball nose end mills are shown in Fig.3. During contouring was flank wear bigger because constant (higher) cutting speeds were achieved. In down-contouring cutting tool had zero cutting speed (machining with of tool centre), but in down-copy milling not. In the copying milling deform layer of C45 could caused in a certain way lower cutting

speed and removing of material layer with the tool back. Cutting tool in down-contouring and copying had milling with the tool centre according effective radius formulas in these cases. But in copy milling did not have. Theoretical calculations based on Blum measuring in our conditions were confirmed only for contouring.

Fig. 3. Time dependence of average values of flank wear during climb milling

So if we had a set criterion $VB = 0.15$ mm, then copy milling strategies were the most appropriate. For the R_a criterion showed below, the most appropriate was different. In the figures you can see that in running-in stage of wear were little differences for all strategies.

Fig. 4. Flank wear on tooth 1 measured in Zoller Genius 3

When the surface roughness parameter R_a was evaluated, we determine that impact of flank wear was less than influence of CAM strategy. Used milling strategy had significant affect of the R_a parameter of machined surface and also on the tool life. For example in up-contouring was $R_a = 1.6 \mu\text{m}$ obtained for $VB = 0.154$ mm ($VB = 0.162$ mm for down-contouring), while in up-copying was $VB = 0.064$ and $VB = 0.074$ during down-copying. It follows that VB criteria must be different for copy milling and contouring. This fact was probably closely related to the constant Z axis value in contouring to the machining area. Positioning of the tool in Z axis during copy milling has a significant negative effect on the quality of the machined surface. It is closely related to the material removal stability, which was reflected by the worse R_a parameter see Fig. 5.

Fig. 5. Average values of Ra measured in cross direction on the tool paths

The last evaluated parameter obtained in experiment was nominal tool radius lost (Nom-DR2). Evaluating of this parameter in the research was focused on the common correlation between VB and Nom-DR2. The main reason for finding of correlation was aimed to the measuring of tool wear directly on the CNC machine. Second one was directional on the surface accuracy.

Fig. 6. Time dependence of Nom-DR2

In the Fig. 6 is showed time dependence of Nom-DR2. Results indicate that values from VB and Nom-DR2 were very similar. Little differences between results in copy milling strategies were obtained. During up-copying was the most suitable for VB criteria, but for Nom-DR2 was the best strategy of down-copying. We must realise that differences in copy milling strategies was abreast approximately 0,002 mm. Copy milling strategies deviation arose in running-in stage of wear. Reason of the less nominal tool radius lost in the copy milling strategies are in lower values of effective cutting speeds. Specific situation in down-contouring arose (Tab. 1 and Fig. 6). As has been said tool machining with the centre. This fact was reflected in the Nom-DR2 results, that values were in positively numbers. According Tab.1 down-contouring had the lower values to the VB. But In this specific case, the bigger nominal tool lost was in the tool length. In begin of experiment was tool $L = 129.165$ mm and in the end (100 min) $L = 129.1275$ mm (approximately deviation 0.04 mm). Positively numbers in Blum measuring device indicates to us machining with the tool centre, because ellipse shape is created. Blum device needs to measure of Nom-DR2 with the 588 cycle position of the tool tip and centre of ball nose shape, which represented nominal radius (4 mm in our case). Ratio of length to the radius can be reflected only in positively numbers – ellipse shape. Based on the results we can say that downward contouring had the worst influence on the surface accuracy. Influence of the Nom-DR2 to the surface accuracy is closer explained in the Fig. 7 and Tab. 2.

Copy milling					
down	up	down	up	down	up
VB (mm)	VB (mm)	Nom-DR2(mm)	Nom-DR2(mm)	coefficient	coefficient
0,0275	0,0285	-0,003	-0,0055	9,16667	5,18182
0,04	0,0355	-0,004	-0,0064	10	5,54688
0,0605	0,045	-0,0068	-0,0104	8,89706	4,32692
0,088	0,064	-0,0096	-0,0158	9,16667	4,05063
0,1065	0,083	-0,0131	-0,0165	8,12977	5,0303
0,113	0,087	-0,0172	-0,0176	6,56977	4,94318
0,121	0,1	-0,0201	-0,0194	6,0199	5,15464
0,1385	0,1135	-0,0204	-0,0219	6,78922	5,18265
0,1505	0,133	-0,0212	-0,0235	7,09906	5,65957
0,165	0,1485	-0,0227	-0,0287	7,26872	5,17422
0,194	0,1685	-0,0282	-0,0302	6,87943	5,57947
Average value				7,81693	5,07548

Contouring					
down	up	down	up	down	up
VB (mm)	VB (mm)	Nom-DR2(mm)	Nom-DR2(mm)	coefficient	coefficient
0,0405	0,0215	0,0054	-0,0021	7,5	10,2381
0,0635	0,0285	0,0067	-0,0054	6,04478	5,27778
0,096	0,046	0,0078	-0,0075	8,14103	6,13333
0,139	0,064	0,0166	-0,0104	5,78313	6,15385
0,162	0,085	0,0182	-0,0164	7,63736	5,18293
0,185	0,107	0,0232	-0,02	6,98276	5,35
0,2015	0,1265	0,0233	-0,0253	7,93991	5
	0,154		-0,02865		5,37522
	0,1675		-0,0303		5,52805
Average value				7,1474	6,02658

Table 1. Measured values of VB and Nom-DR2 with the calculated coefficients of their correlations

In Tab. 1 are values of Nom-DR2 and their coefficients of correlation with VB calculated. It is obvious that lower coefficient in up-copying and contouring were obtained. Lower coefficient means higher values of tool nominal radius lost to the VB. The highest effective cutting speed caused, that the biggest Nom-DR2 was in up-copying and contouring. In down-copying was length coefficient 5,512. Downward copy milling was based on the accuracy criteria the most applicable strategy for finish milling. During the down-copying was layer of material distributed over the biggest part of cutting edge with the lowest values of effective cutting speed. In the Tab. 2 are added values from measuring of surface accuracy with the touch probe Heidenhain TS649. Measuring with the probe was carried out in end position of time cycle in four points along Y axis.

Time[min]	Accuracy for up-contouring					Nom-DR2	Deviation
	1	2	3	4	average value		
5	-0,3408	-0,3418	-0,3427	-0,341	-0,34158	0,0021	-
10	-0,34	-0,3398	-0,336	-0,3356	-0,33785	0,0054	0,0037
20	-0,3361	-0,336	-0,336	-0,3356	-0,33593	0,0075	0,00565
40	-0,333	-0,3331	-0,333	-0,3322	-0,33283	0,0104	0,00875
60	-0,3272	-0,3281	-0,3277	-0,3282	-0,3278	0,0164	0,01378
80	-0,321	-0,322	-0,323	-0,322	-0,322	0,02	0,01958
100	-0,3169	-0,3169	-0,3199	-0,3189	-0,31815	0,0253	0,02343
130	-0,3137	-0,314	-0,316	-0,3151	-0,3147	0,02865	0,02688
160	-0,3108	-0,313	-0,3117	-0,312	-0,31188	0,0303	0,0297

Table 2. Measured values of surface accuracy with touch probe in CNC machine and Nom-DR2

$$k = \frac{VB}{NomDR2} \quad (6)$$

Dependence of Nom-DR2 to the final accuracy of machined surface according the measured values in the Tab. 2 and Fig.7 were obvious. It is very hard to say how exactly depends Nom-DR2 wear or another causes of inaccuracies to the final accuracy. In general, we would suggest taking into account the values from Blum device for accuracy criteria.

In Fig. 7 shows the measured deviation of surface and Nom-DR2. During the measurements we have not been made automatic correction of tool. If we use auto-correction, the value of the correction from Nom-DR2 = -0.02 is written to the tool table in positive values, e.g. DR2 = 0.02 mm. In principle, it is the same as without correction. Basic our experiments we recommend to done correction manually, e.g. Nom-DR2 = -0.02 correction will be DR2 = -0.02. Then the cutting tool should machine of surface accurately.

Fig. 7. Example of demand Nom-DR2 to surface accuracy during up-contouring

Based on experiments in terms of accuracy the copy milling strategies were the best. Mutual correlating between VB and Nom-DR2 was obtained. All copy milling strategies for Nom-DR2 criterion, which were related to accuracy, have been attained later. Opposite effect based on Ra criterion for contouring was reached. Smaller VB and Nom-DR2 values did not significantly affect the achieved surface roughness parameter Ra. The impact of VB on achieved surface roughness compared to use CAM strategy was secondary. This argument is also based on the fact that for contouring the values of VB were doubled and tool life for Ra was 2-3 times better see Tab. 3

1. Up-contouring		2. Down-contouring	
Criteria	Time [min]	Criteria	Time [min]
Ra = 1,6 [μm]	160	Ra = 1,6 [μm]	100
Nom-DR2 = 0,025 [mm]	100	Nom-DR2 = 0,025 [mm]	60
VB = 0,15 [mm]	130	VB = 0,15 [mm]	50
Tool life 100 [min]		Tool life 60 [min]	
VB value to criteria [mm] 0,154		VB value to criteria [mm] 0,162	
3. Up-copying		4. Down-copying	
Criteria	Time [min]	Criteria	Time [min]
Ra = 1,6 [μm]	40	Ra = 1,6 [μm]	30
Nom-DR2 = 0,025 [mm]	170	Nom-DR2 = 0,025 [mm]	195
VB = 0,15 [mm]	220	VB = 0,15 [mm]	160
Tool life 40 [min]		Tool life 30 [min]	
VB value to criteria [mm] 0,064		VB value to criteria [mm] 0,083	

Table 3. Established tool wear criteria for Ball nose end mill D8.

4. Conclusion

The article deals with the issue of CAM end milling strategies and their influence on the surface roughness parameter Ra and tool life of ball nose end mills. The aim was to investigate the wear of ball nose end mill for copy milling and contouring. Furthermore, surface roughness parameters Ra were determined and compared for each end milling strategy. For tool life test, DMG DMU 85 monoBLOCK 5-axis CNC milling machine was used. There were specified particular steps of the measurement process. In the experiment, the cutting speeds, feed rates, axial and radial depth of cut were constant. The coated cemented carbide was used as tool material. The cutting tool wear was measured on Zoller Genius 3s and laser Blum Micro Compact NT. Surtronic 3+ (Taylor Hobson) was used for surface roughness measurement.

The results show differences in use of CAM end milling strategies. Mutual correlating between VB and Nom-DR2 was obtained. All copy milling strategies for Nom-DR2 criterion, which were related to accuracy, have been attained later. Opposite effect based on Ra criterion for contouring was reached. Smaller VB and Nom-DR2 values did not significantly affect the achieved surface roughness parameter Ra. The impact of VB on achieved surface roughness compared to use CAM strategy was secondary. The CAM strategy has the most pronounced impact on tool life to the selected criteria (Contouring vs. Copy milling). Differences in CAM strategies are also reflected in different values of effective cutting speed. Another fact was arisen during small depths of cut of C45, because this kind of material in certain way was ductile and deformed. This was particularly evident in copy milling.

Based on experiment results, we can measure and quantify the amount of wear directly on the CNC machine. This is possible with a device that can measure the dimension of the shaped tool. For defined criteria is possible automatically control of cutting tools during or after machining of surface. For Blum device is possible use of R_BREAK or L_BREAK function. An example is possible to choose a value in the tool table R_BREAK = 0.025. Cutting tool will not machine after reaching this value. CNC machine can then automatically change the used tool for a new one. The second more complicated option is to change the tool tilting to the workpiece after tool wear, for example from 15° to 45°. With this setting, we would get a new unused cutting edge on the used tool. This would significantly increase the tool life.

Results from this research will be used for machining die and moulds when cutting tool microgeometry will be varied. Then, cutting tool microgeometry will be optimized to increase the tool life during the machining of Difficult-to-Machine materials. In the future work these strategies for conventional milling will be also investigated.

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6. References

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