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Optimal cutting conditions in ball-end milling of complex surfaces taking into account the desired surface roughness

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***Abstract*—Ball-end milling is widely used as a surface finishing process. The selection of the proper cutting conditions, that is the spindle speed as well as the feed rate, is crucial for the optimization of the process. This selection is made according to the cutting speed, which is specified by the cutting tool and workpiece materials. In the case of ball-end milling of complex surfaces, the cutting speed varies depending on the changing effective diameter at the point of contact between the cutting tool and the workpiece. Therefore the cutting speed does not remain stable during the process, which directly influences the quality of the finished surface. One way to overcome this problem would be to continuously change the rotational speed of the cutting tool according to the variable effective diameter so as to keep the cutting speed constant, yet this solution is not technically feasible. In the present study, an experimental method for the specification of the optimum cutting conditions based on the control of the surface quality that several ball-end milling strategies offer, is presented. The selection of the above mentioned cutting conditions is made in accordance with the desired predefined quality of the machined surface as specified by its roughness.**

***Keywords*—ball-end milling, cutting conditions, surface roughness**

I. Introduction

The increasing demand for precision and high-efficiency machining of products with freeform and complex surfaces has brought about the need for optimization of ball-end milling processes. There have been several studies on ball-end milling, examining the influence of the cutting conditions, namely the cutting speed, feed rate, inclination angle of the tool axis along with the depths of cut, on the machined surface roughness and texture. However, in international context the tendency is to consider the inclination angle of tool axis as the main parameter that significantly influences the surface roughness[1].

Kang et al. [2] established the change of cutting speed according to the angles of the inclined machined planes and tool paths in down cutting, using a ball-end mill, at 15°,30° and 45° but also examined the effect of the changing cutting direction on the cutting forces and the machined surface form and roughness. An analytic roughness model was proposed by Jung et al. [3,4] for the evaluation of the maximum geometrical roughness and texture of the machined surface in ball-end milling.

Mizugaki et al. [5] presented a theoretical estimation method of machined surface profile and examined the changes to the cusp height due to the tool orientation concluding that the maximum and minimum cusp height exist in a narrow range of tool orientation within few degrees near the normal direction of the workpiece but also that the boundary form of machined surface texture changes widely according to the tool direction.

Zhang et al. [6] studied the combined effects of feed rate and radial depth of cut on surface topography and roughness in both feed- and step-over direction and found, among others, that there can be roughness values achieved small enough to justify that hard-milling may replace grinding as a finish or semi-finish process. Liu et al. [7],[8] developed surface generation models of micro-end-milling for the prediction of deterministic and stochastic surface roughness components on sidewall and floor surfaces. De Oliveira and Diniz [9] tried to evaluate the influence of workpiece surface inclination and cutting conditions on tool life and tool wear mechanisms, by performing several high speed milling experiments and analysis which showed that the inclination of the machined surface significantly affected tool life which was decreased with the increase in surface inclination.

Wojciechowski et al. [10] investigated the surface texture generated during the ball end milling of hardened steel including surface inclination angle, concluding that this factor has significant influence on the generated surface texture. However, this study was limited to the examination of only two values of the inclination angle, 45° and 0°.

In the present study, several experiments have been conducted in order to examine the effect of the changes in the

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inclination angle of the ball nose endmill, the feed rate as well as the radial depth of cut on the roughness of the machined surface, in both down and up milling processes. Put simply, the goal of the study was to detect and record various combinations of the values of the above mentioned variables, so as to allow the effective specification of the complete milling strategy according to the desired surface quality and roughness.

II. Material equipment and experimental procedure

The experiments were carried out on a 5-axis Deckel Maho Gildemeister DMU 50 machining center, using a D20 ball-end mill with one carbide cutting insert. After the completion of each experiment, the cutting edge was replaced by a new one, so that the tool wear effect on surface topomorphy and roughness could be the same and the variation due to the wear could be minimized and therefore neglected. The workpieces used for the experiments were aluminum cylinders of diameter and length of about 80mm and 100mm respectively. Al7075-T6 was selected as workpiece material, since it has been widely used for structural components and especially for aircraft and aero-space structures.

The cylindrical shape of the workpieces was selected in order to allow the collection of continuous data concerning the cutting characteristics at multiple inclination angles. Furthermore, the geometry of the cylinder enabled the division of the workpiece into areas machined with different feed rates. Fig.2 shows the different cutting strategies that were applied during the experimental procedure.

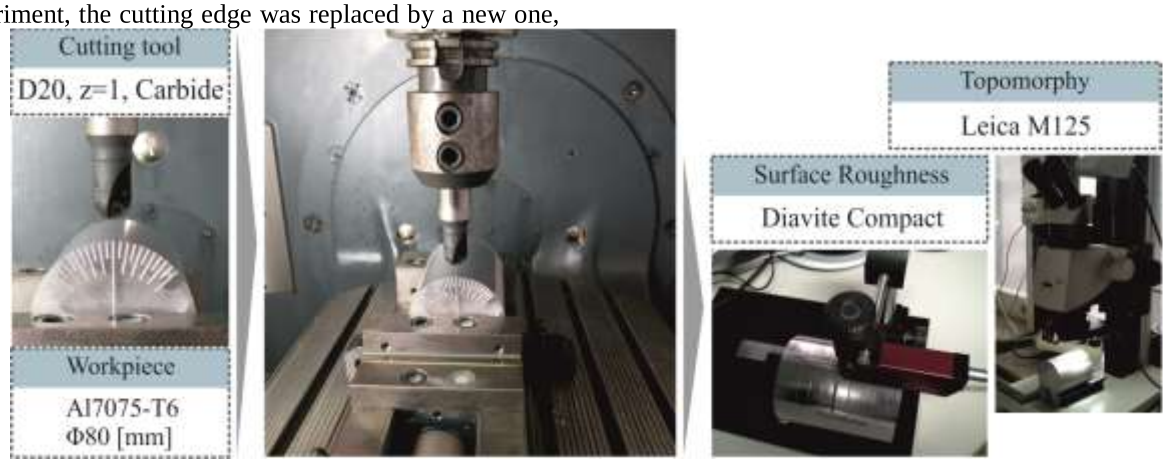

Figure 1. Workflow of the experiments

The spindle rotational speed was kept constant at 5000 rpm during all the experiments. As a result, the variation of the inclination angle φ, resulted in the variation of the effective tool diameter D_{eff}, thus the constant change of cutting speed v_c. It is well known that the cutting speed in the axis of a milling tool equals zero.

As a consequence, when a surface perpendicular to the tool axis is machined with a ball nose endmill, the tool drags on the surface impairing the quality of the process. As the inclination angle between the tool axis and the normal to the machined surface increases, the effective diameter of the cutting tool and consequently the cutting speed also increase.

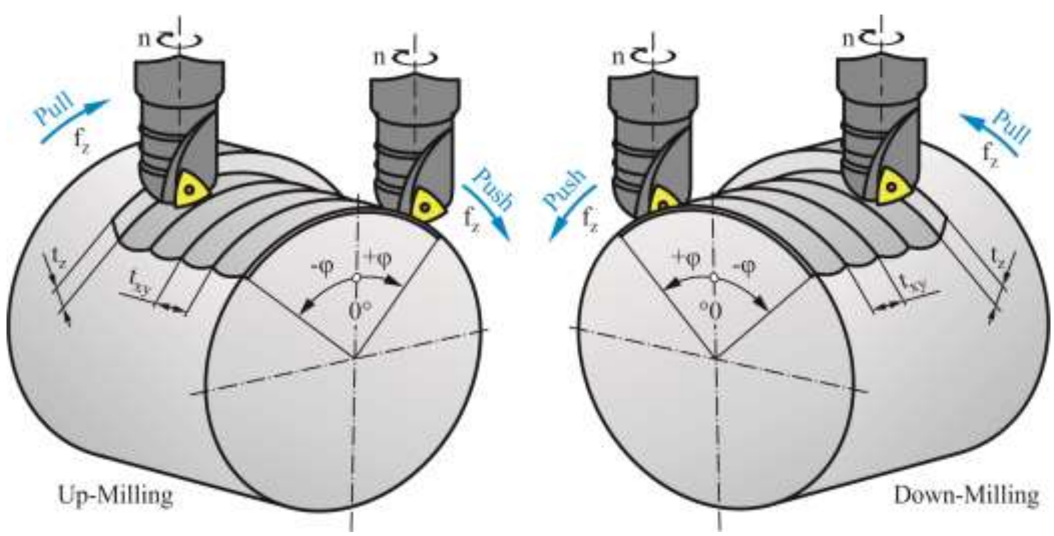

Figure 2. Different strategies in ball-end milling of the cylindrical workpiece

III. Results

The results were obtained by measuring the roughness of the machined surface and by recording several values for all combinations of the various aforementioned cutting conditions. The measurements were taken with the use of a Diavite Compact surface roughness tester.

In addition, a Leica M125 stereoscope was used so as to capture the resulted profile and therefore allow the detection of different patterns on the topomorphy of the machined surface according to the varied cutting parameters.

Table 1 shows the cutting conditions under which the experiments were performed.

TABLE 1.CUTTING CONDITIONS OF THE EXPERIMENTS

Experiment	Axial depth of cut t_Z (mm)	Radial depth of cut t_{XY} (mm)	Milling strategy	Feed rate f_z (mm/rev,z)	Inclination angle φ (°)
1	0.3	0.3	Up	0.2 → 1.0 0.2-0.4-0.6-0.8-1.0	-40 → 40
2			Down		
3		0.6	Up		
4			Down		

A. *Surface roughness according to the inclination angle φ*

Fig. 3 illustrates the variation of the measured values of mean surface roughness in up milling, with axial and radial depth of cut equal to t_Z=0.3mm and t_{XY}=0.6mm respectively. Mean surface roughness stays at low levels for a wide range of the examined inclination angles up to the point where φ=5°.

When the gradient between the tool axis and the normal to the surface exceeds the level of 5°, surface roughness increases sharply to reach the highest values when the tool axis is perpendicular to the machined surface (φ=0°), since cutting speed in the center of the tool approaches zero.

B. *Surface roughness according to the radial depth of cut t_{XY}*

As easily observed in Fig. 4 roughness values are higher when setting the radial depth of cut at t_{XY}=0.6mm compared to the roughness measured at t_{XY}=0.3mm. This was inferred after examining all measured roughness values of the resulted surface. In several cases, as in up milling at φ=7° which is presented in Fig.6, surface roughness values are even doubled at t_{XY}=0.6mm.

C. *Surface roughness in down and up milling*

During push milling (positive values of inclination angle φ) surface roughness reaches higher values in down milling than in up milling process, as presented in Fig. 5.

In sharp contrast to this, pull down milling (negative values of inclination angle φ) results in a higher-quality surface. This conclusion was drawn after examining the measured mean roughness values for all the experiments that were carried out.

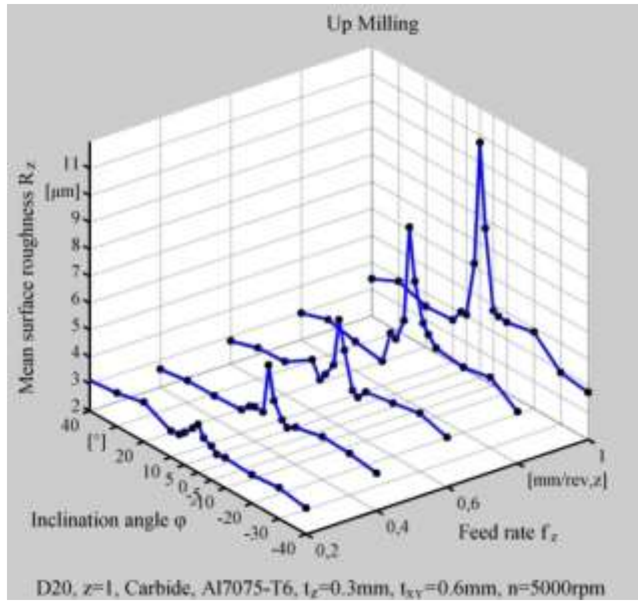

Figure 3. Mean Surface Roughness in up milling with t_Z=0.3mm and t_{XY}=0.3mm

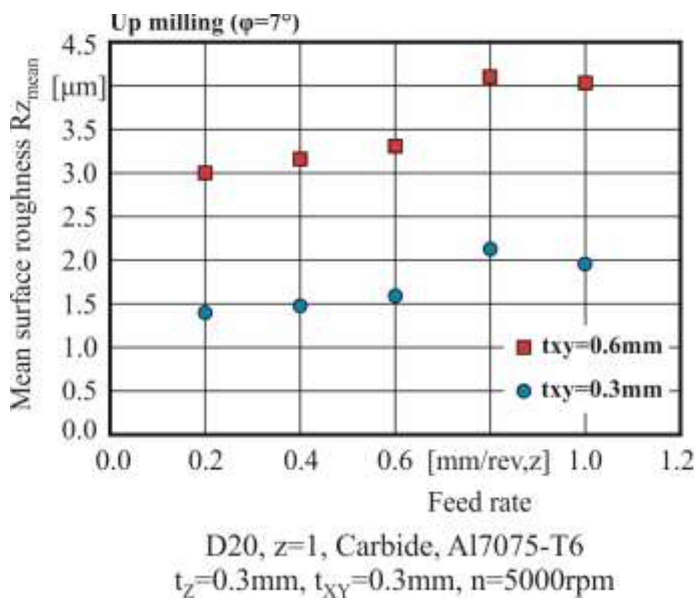

Figure 4. Mean surface roughness in up milling at φ=7°

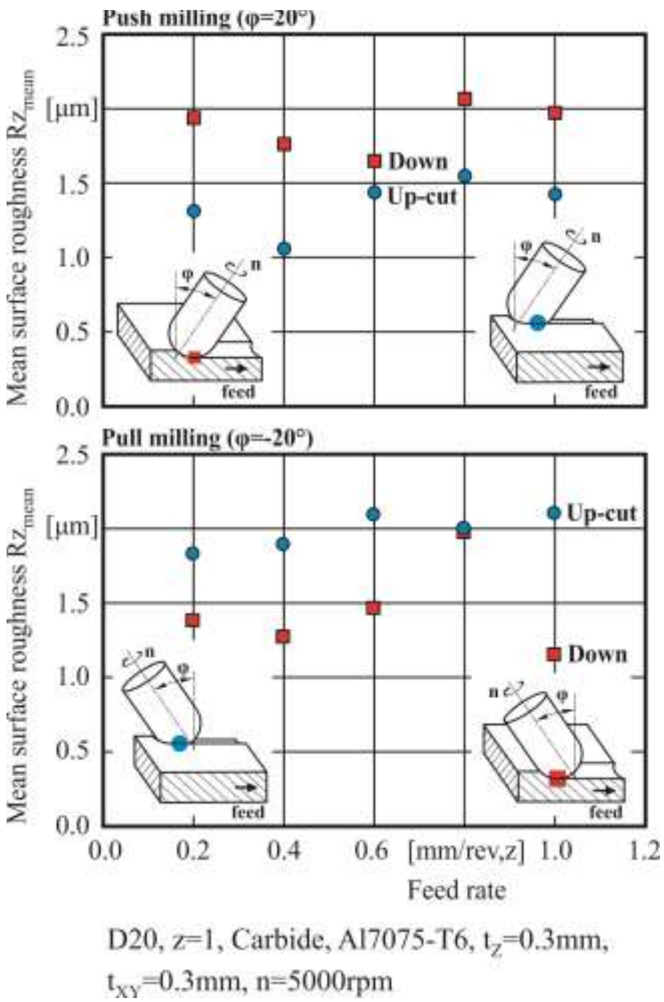

Figure 5. Comparison of down and up milling both in push and pull milling

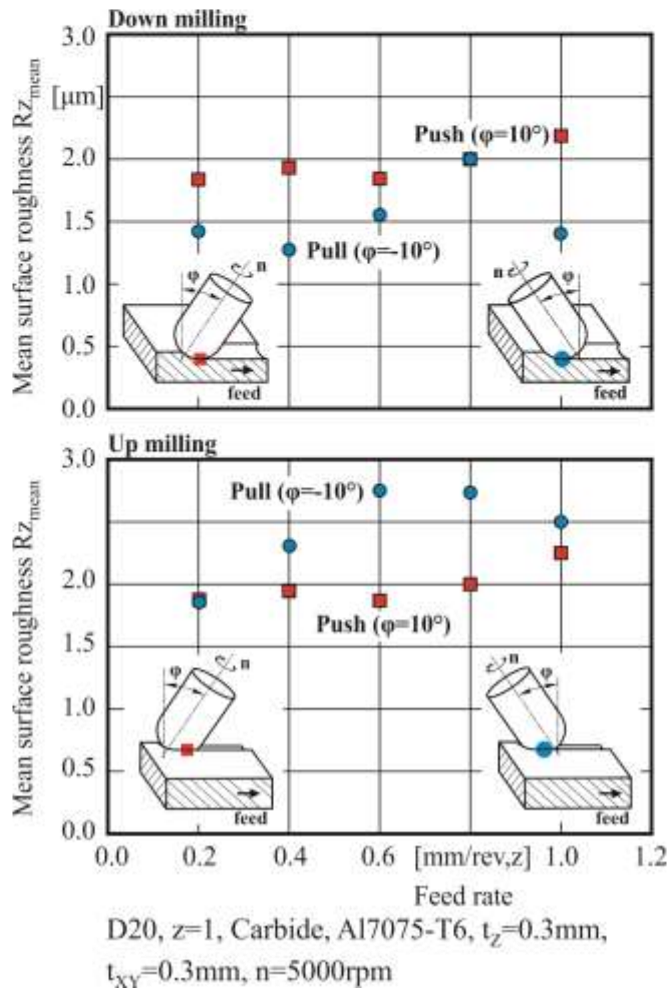

Figure 6. Surface roughness comparison in pull and push milling at φ=10° (down and up milling)

D. *Surface roughness in push and pull milling*

From the results presented in Fig. 6, for both down and up milling with radial and axial depths of cut t_{XY}=0.6mm and t_Z=0.3mm at φ=10° / φ=-10°, it can be concluded that in the first case surface roughness reaches higher values in push compared to pull milling, whereas roughness values are higher in pull than those in push milling in case of up milling. The above mentioned deduction was found to be valid for the vast majority of the measured mean roughness values.

E. *Selection of the optimal cutting conditions considering the desired surface quality as specified by its roughness*

Cutting speed v_c is calculated with the use of (1).

$$v_c = \frac{\pi \cdot D \cdot n}{1000} \quad \text{(mm/min)} \qquad (1)$$

where D=diameter of the cutting tool (mm) and n=spindle speed (rpm).In ball end milling the variable D is replaced by the effective diameter of the cutting tool D_{eff} which is calculated by (2).

$$D_{eff} = D \cdot \sin\left\{\left[arcos\left(\frac{\frac{D}{2}-t_Z}{\frac{D}{2}}\right)\right]/2+\varphi\right\} \text{ (mm)} \qquad (2)$$

where φ is the inclination angle of the cutting tool. As soon as the values of cutting speed v_c that correspond to the particular inclination angles φ are calculated, mean surface roughness can be mapped according to the changing feed rate f_z and cutting speed v_c, enabling the selection of the optimal cutting conditions. A sample map of mean surface roughness for down milling is shown in Fig. 7.

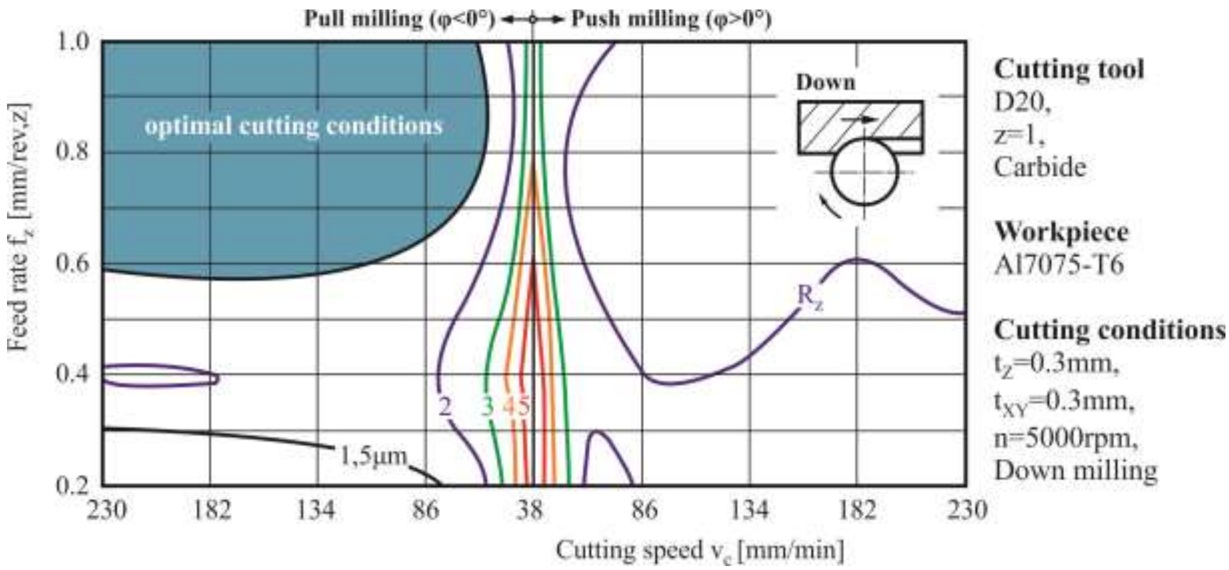

Figure 7. Mean surface roughness R_Z map under the combined influence of feed rate f_Z and cutting speed v_C

IV. Conclusions

An investigation to determine the combined effects of various cutting conditions on the machined surface roughness in ball-end milling of Al7075, was performed within the context of this study. The experimental procedure that was implemented followed by the examination of the resulted surface, led to the following conclusions.

1. High values of mean surface roughness exist when the tool axis is perpendicular to the machined surface or within few degrees from the normal direction. As the inclination between the tool axis and the normal to the surface increases, roughness decreases to drop to a much lower level from φ=5° and above.

2. For all tested sets of feed rate f_z and inclination angle φ, surface roughness increases when the workpiece is machined with larger radial depth of cut t_{XY}.

3. *Down and pull* or *up and push* milling strategies are preferable to *down and push* or *up and pull* milling respectively, since these strategies were found to lead to lower values of surface roughness.

4. The final outcome of this study was a mapping of the surface roughness depending on the varying cutting parameters, which enables the selection of optimal cutting conditions considering the desired surface quality.

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