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THE EFFECT OF THE CUTTING SPEED ON THE SURFACE ROUGHNESS WHEN BALL-END MILLING

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Using freeform surfaces in advanced industries is becoming ubiquitous and widely applied in many fields such as the aerospace, automobile, consumer products as well as the die and mold industries. The ball-end mill is mainly used in machining such surfaces. However, the manufacture of this type of surface is still somewhat difficult when machining using a 3D ball-end milling machine. Due to changes in the surface inclination, the working diameter of the tool also changes. Variations in the working diameter leads to an unstable cutting speed, affecting the roughness homogeneity of the smoothed surface. This article discusses the effect of changing the cutting speed on the surface roughness in the case of concave and convex surfaces.

Keywords: surface roughness, cutting speed, concave surface, convex surface, milling

1. Introduction

The implementation of ball-end mills has become widespread in manufacturing, especially in high-speed machining processes. The extended product life, high-precision machining, low cost of the manufacturing process, its ability to feed axially and the unique shape of the cutting edge (Helix-type, S-type, etc.) of this tool mean it plays a vital role in machining freeform surfaces [1]. However, when freeform surfaces are machined using a ball-end mill, the working diameter of the tool continuously varies as the surface inclination changes, despite the constant toolpath. Using a five-dimensional milling machine can solve this problem. However, due to its high cost and difficulties associated with installing this machine at many workstations, 3D milling machines are still common.

Radhwan et al. [2] studied the effect of various cutting parameters, including cutting speed, feed rate and depth of cut on the surface roughness. Their findings show that the cutting speed and feed rate have significant effects on the surface roughness. Wojciechowski et al. [3] analyzed the forces and process efficiency whilst machining hardened 55NiCrMoV6 steel using ball-end milling. Their results indicate that the surface inclination has a significant effect on the cutting forces. Mersni et al. [4] used the Taguchi method to optimize the milling parameters to obtain a better surface finish using ball-end milling of a titanium alloy Ti-6Al-4V. They point out that the radial depth of cut (a_p) is the most important factor followed by the cutting speed (ν_c) and then the feed per tooth (f_z). Yao et al. [5] studied the influence of the tool orientation on the surface of the TC17 titanium alloy. Their findings emphasize the importance of tool orientation on surface roughness during ball-end milling. Similarly, Gao et al. [6] investigated the effect of the tool inclination angle on the surface roughness while machining the titanium alloy Ti-6Al-4V using a ball-end mill. They point out that tilting the tool has a significant effect on the quality of the grooveS and using the appropriate inclination angle can reduce the roughness of the surface and improve its form. Vyboishchik [7] presented a geometric model of the surface topology in the case of flat, concave (CV) and convex (CX) surfaces. According to this model, the surface inclination has a significant effect. Matras and Zębala [8] optimized the cutting data and tool path pattern for machining the freeform surface of steel in a hardened state using a ball-end mill. The results show that the surface roughness and cutting-force components can be controlled by modifying the feed rate based on the locally machined cross-sectional area. Magalhães and Ferreira [9] used different tool path strategies to machine parts with complex geometries from hardened H13 steel. Their findings show that the tool path has a significant effect on the roughness of the complex surface. Daymi et al. [10] highlighted the importance of the inclination angle in ball-end milling when machining the titanium alloy Ti-6Al-4V.

This research investigates the effect of changing the surface inclination on the cutting speed and the

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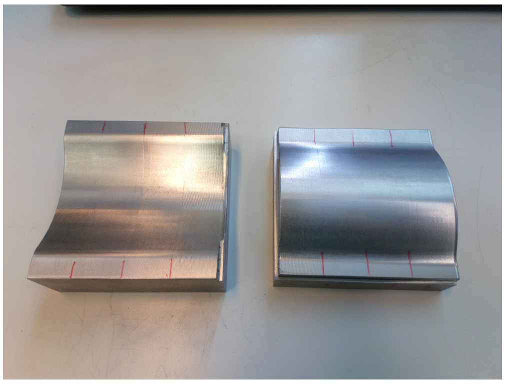

Figure 1: The CV and CX workpieces

consequences of a variable cutting speed on the surface roughness as well as provides an insight into the importance of the feed rate and width of cut on the machining process when using a 3D ball-end mill.

2. Materials and Methods

The machining tests were performed on CV and CX surfaces of the same material, namely the low-alloy steel 42CrMo4. 42CrMo4 is used to manufacture parts with high-TENSILE strengths of compressors, turbines and working elements of heavy equipment used aboveground and underground as well as components of agricultural machinery. The chemical composition of 42CrMo4 is given in Table 1.

The CV and CX parts consist of a cylindrical surface with a 45 mm radius connected to a horizontal plane with a 10 mm radius. Fig. 1 shows both workpieces and Table 2 shows the angles of the normal vector of the surface.

The machining was performed by a Mazak Vertical Center Nexus 410A-II CNC vertical machining centre. The surface roughness was measured by a Mahr's MarSurf GD120 instrument. The Ra and Rz parameters were measured in the x-direction perpendicular to the milling direction at 11 different positions. The milling was done using a Fraisa X7450.450 ball-end milling cutter with a diameter of 10 mm (D_c = 10 mm) and 4 teeth ($z = 4$).

Five test surfaces were created by ball-end milling with different feed rates and widths of cut. Table 3 shows the applied cutting parameters in machining these surfaces.

Since the surface inclination changes, the effective diameter also changes. A geometrical model is presented by Mikó and Zentay [11] to calculate the effective diameter. Fig. 2 shows the calculated effective diameter at each measured point in the case of the CV and CX workpieces.

The actual cutting speed can be calculated depending on the effective diameter at each measured point using the following formula:

$$\nu_c = \frac{D_{eff}\ n\ \pi}{1000} \quad (1)$$

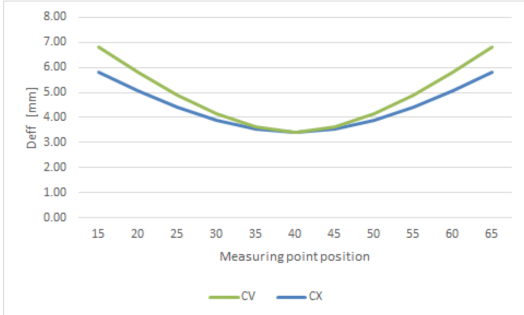

Figure 2: The Effective diameters at each measured point

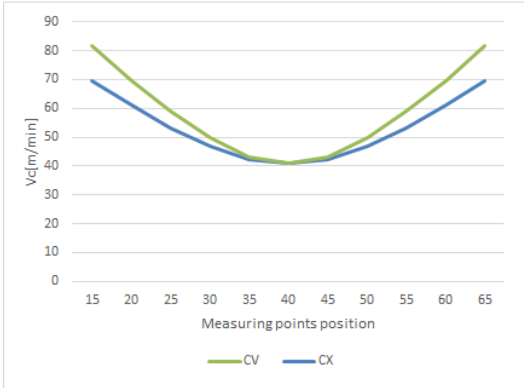

Figure 3: The actual cutting speed at each measured point

Figs. 2 and 3 show the effective diameter and actual cutting speed. Even though the diameter of the tool is 10 mm, the actual cutting diameter is smaller. In the case of the CV surfaces, it changes between (3.4 and 6.8 mm), while in the case of the CX surfaces, it changes between (3.4 and 5.8 mm). On the other hand, the effective diameter and, as a result, the cutting speed are the smallest in the middle of the workpieces, where the value of the normal vector is 0°. In addition, although it can be seen from Fig. 3 that the value of the cutting speed is higher in the case of the CV surfaces compared to the CX equivalents, the cutting speed curve is similar for both CV and CX test parts.

3. Results and Discussion

Fig. 4 shows the average surface roughness of the test pieces. The diagram shows that the surface of the CV test parts is better than that of the CX test parts under the same cutting parameters, as the actual cutting speed in the case of CV surfaces is higher than that of the CX equivalents.

On the other hand, when the feed rate is 0.08 mm and the width of cut is 0.35 mm, the surface roughness is the worst for both CV and CX surfaces.

The surface roughness of the workpieces was measured at several points. The results show that the surface inclination has a significant effect on the surface roughness, as can be seen in Figs. 5–9, since the quality of the surface is less at the middle of the test pieces where the cutting speed is at its minimum.

Table 1: Chemical composition of the low-alloy steel 42CrMo4: (analysis in %)

C	Si	Mn	P	S	Cr	Mo	Cu
$0.38 - 0.45$	$0.1 - 0.4$	$0.6 - 0.9$	≤ 0.025	≤ 0.035	$0.9 - 1.2$	$0.15 - 0.3$	≤ 0.4

Table 2: Angles of the normal vector of the surface

Measuring points (y)	25	20	15	10	5	0	5	10	15	20	25
CX angles (°)	30	23.58	17.46	11.54	5.74	0	−5.74	−11.54	−17.46	−23.58	−30°
CV angles (°)	−38.7	−30	−22	−14.5	−7.2	0	7.2	14.5	22	30	38.7

Table 3: Cutting parameters used in the test

Test part id.	CV-01 CX-01	CV-02 CX-02	CV-05 CX-05	CV-03 CX-03	CV-04 CX-04
Cutting speed v_c [m/min]			160		
Spindle speed n [rpm]			5100		
Feed per tooth f_z [mm]	0.08	0.08	0.08	0.12	0.16
Feed speed v_f [mm/min]	1630	1630	1630	2450	3260
Depth of cut a_p [mm]			0.3		
Width of cut a_e [mm]	0.35	0.25	0.15	0.15	0.15

In the case of CX-01 and CX-02, the surface roughness is worse than on the other three pieces. On these two pieces, Rz is approximately 16 μm at the middle compared to 10 μm at the middle of the other pieces.

In the case of the CV pieces, CV-05 exhibits the best surface roughness and the value of Rz is less than 6 μm at the middle, while it is approximately 12 μm on the other pieces.

This variation in the surface roughness from piece to piece is due to changes in the feed rate and width of cut. The feed rate is at its minimum when machining CX-01

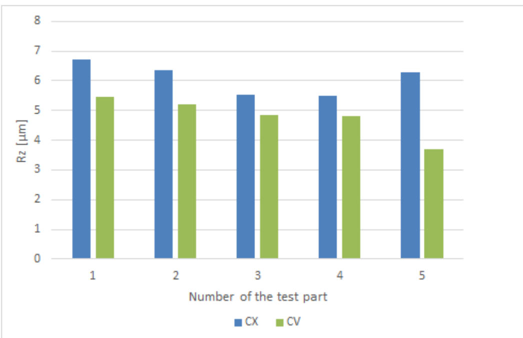

Figure 4: Average Rz of each test parts

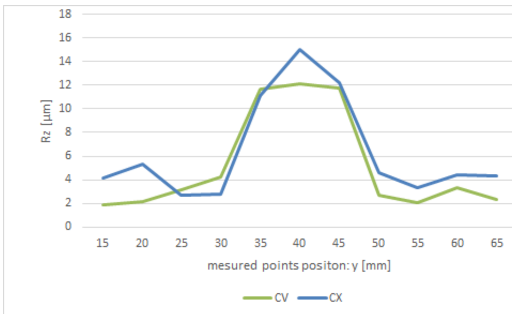

Figure 6: Rz surface roughness in the case of CX-02 and CV-02

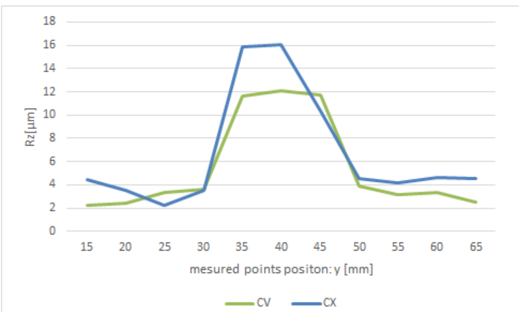

Figure 5: Rz surface roughness in the case of CX-01 and CV-01

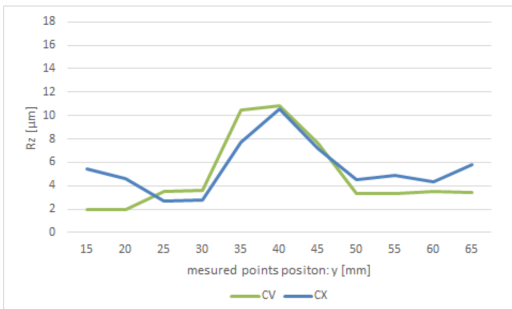

Figure 7: Rz surface roughness in the case of CX-03 and CV-03

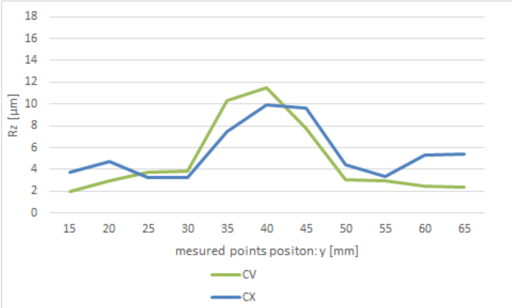

Figure 8: Rz surface roughness in the case of CX-04 and CV-04

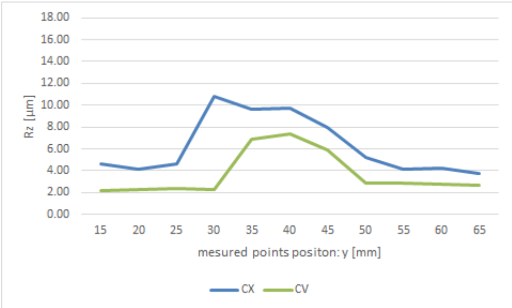

Figure 9: Rz surface roughness in the case of CX-05 and CV-05

and CV-01 but increases to its maximum when machining CX-04 and CV-04. However, the width of cut decreases gradually to its minimum when machining CX-04 and CV-04.

Figs. 10 and 11 show the main effect of changing the width of cut and feed rate on the surface roughness in the case of CV and CX surfaces. As is shown, the width of cut has a significant effect on the surface roughness. By increasing the width of cut, the Rz value of surface roughness increases. On the other hand, the feed rate has a minor effect on the surface roughness, especially in the case of CV surfaces.

The actual cutting speed and the effective diameter have exactly the same effect on the surface roughness, as can be seen in Figs. 12 and 13. The Rz value of surface roughness decreases by increasing the effective diameter and the cutting speed. However, in the case of CX surfaces, the roughness of the surface increases again by about 1 μm at a cutting speed of 70 m/min.

4. Conclusion

In this article, the effect of the cutting speed on surface roughness has been studied. Based on the obtained data, under the same cutting parameters, the surface roughness of the CV test parts is better than that of the CX equivalents. However, changes in the surface inclination cause the actual cutting speed to vary, which affects the surface quality. The cutting speed reduces to a very low value when the normal axis of the ball-end mill is applied on the workpiece surface. Given that the

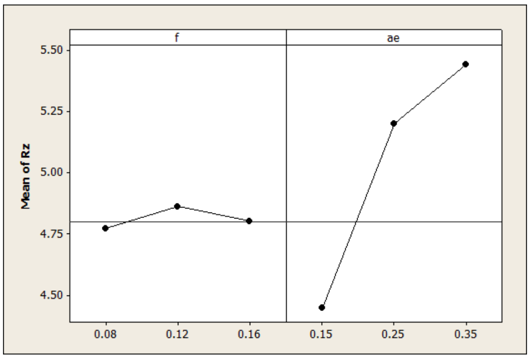

Figure 10: The effect of the width of cut and feed rate in the case of CV surfaces

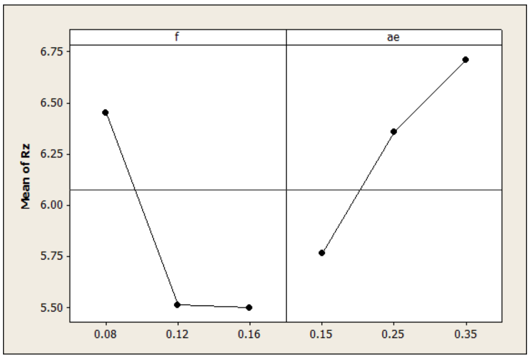

Figure 11: The effect of the width of cut and feed rate in the case of CX surfaces

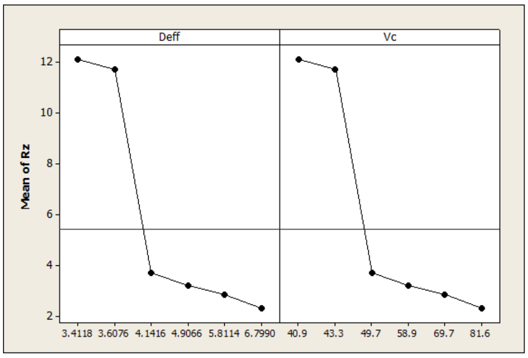

Figure 12: The effect of the effective diameter and actual cutting speed in the case of CV surfaces

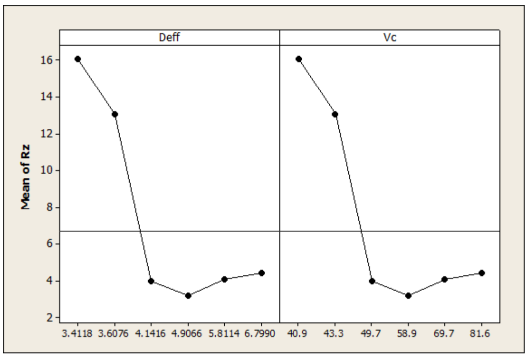

Figure 13: The effect of the effective diameter and actual cutting speed in the case of CX surfaces

variation in cutting speed is a major problem in the case of 3-axis milling machines, modifying the cutting speed during the milling process can solve this problem and ensure a higher surface quality.

On the other hand, the surface roughness depends on other cutting parameters as well such as feed rate and width of cut. It has been determined that by increasing the width of cut, the surface roughness is increased, while changing the feed rate only has a minor effect.

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