Experimental Investigation of the Effect of the Machine Kinematic Behavior on the Surface Topography and Roughness in High Speed Ball end Milling of the AISI4142 Steel

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Abstract

The analysis of the surface topography in ball end milling is an objective studied by many researchers, several methods were used and many combinations of cutting conditions and machining errors are considered. In the milling tool paths the trajectories presents a points of changing direction where the tool decelerates before and accelerates after respecting the velocity profiles of the machine. In this paper, we propose experimental investigations of the effect of the kinematic behavior of the machine tool on the surface quality. A poor topography and roughness are remarked on the deceleration and the acceleration zones compared to the stationary zone.

1 Introduction

To reach high surface quality, sculptured surfaces are generally obtained using a high speed milling process. Moreover, the tool trajectory is generated via CAM software which offers various machining strategies depending on the geometry of the surface to be machined. The machined surface quality thus results from the choice of the strategy and the corresponding cutting parameters as the tool inclination, the feed per tooth, the cutting speed and the radial depth of cut [1]. More other phenomena affect the surface topographies as the tool deflection, the tool runout errors and the vibration. Many researchers are focused in these phenomena and study their influence on the surface roughness.

Omar et al. [2] Developed a generic technique for calculating the specific cutting forces and generating a 3D surface topography for side milling operations. The technique takes into account the effects of tool runout, tool deflection, system dynamics, flank face wear, and the tilting of the tool on the surface roughness. Sonawane and Joshi [3] Presented the effect of machining parameters on the surface quality obtained in a single-pass of a ball-end mill with varying chip cross-sectional area. The maximum surface roughness is observed near the tool tip region on the machined surface. The minimum surface roughness is obtained in the stable cutting zone and it increases towards the periphery of the cutter. Arizmendi et al. [4–5] presented the effect of the tool errors on the surface topography when the end mill is held in the spindle. In the case of peripheral milling the study accounts the tool setting errors as cutter parallel axis offset and cutter axis tilt. Arizmendi et al. [6] developed a model for the prediction of heterogeneity bands in the surface topography machined by peripheral milling considering the radial tool runout. Vakondios et al. [7] studied the influence of the milling strategy on the surface roughness. The cutting parameters used are the axial and the radial depth of cut, the feed rate, and the inclination angles of the tool. The strategies considered are the vertical, the push, the pull, the oblique, the oblique push and the oblique pull and for each one the down and the up milling are considered. Ozturk et al. [8] used a combined approach of an empirical and an analytical surface model to simulate the kinematic and the stochastic topography in ball-end milling. Denkena et al. [9] Developed a method for the construction of surface topographies of peripheral milled surfaces based on measured cutting forces. Toh [10] Studied the surface texture produced by various cutter path orientations and tool inclinations. The best cutter path orientation with respect to the best surface texture is the milling in a single direction and in vertical upward orientation. Quinsat et al. [11] Studied the influence of each machining strategy parameter on the surface quality as
the machining direction, the transverse step, the longitudinal step and the feed rate. Buj-Corral [12] Developed a geometrical model that predicts topography and surface roughness in ball-end milling. The cutting parameters studied are the feed per tooth, the spindle speed, the radial depth of cut, the axial depth of cut, the number of teeth, the tool teeth radii, the helix angle, the eccentricity and the phase angle between teeth. Zain et al. [13] Presented the effect of the radial rake angle of the tool, combined with the speed and the feed rate cutting conditions in influencing the surface roughness results. Buj-Corral et al. [14] Studied the influence of the feed, the eccentricity and the helix angle on the surface roughness for side milling operations with cylindrical tools. A model was developed to predict surface topography as well as different roughness parameters. Wibowo and Desa [15] Studied the surface roughness in end milling process which is influenced by the machining parameters, the radial rake angle, the speed and the feed rate. Costes and Moreau [16] Predicted the surface topography based on tool displacements and tool center point methodology. From the recorded signals and the machining parameters, the tool deformation is modeled. Then, from the angular deflection and displacements in XY, the 3D surface topography can be predicted. Arizmendi et al. [17] Developed a method to predict the surface topography as a function of the runout the simulation is based on the equation of the cutting-edge trajectories and the envelope equation of the material swept by the tool. Layegh and Lazoglu [18] Presented a model based on the analytical equation of the trochoidal motion of the cutting edge. A finite number of parallel planes are defined perpendicular to the feed vectors. The points of the surface topography are extracted as the minimum height of the intersection points between the edge trajectory and the parallel planes. The model takes into account the tool orientation, federate, step over, depth of cut and runout. Karabulut [19] Investigated the effect of milling parameters on surface roughness with an uncoated carbide insert machining a AA7039/Al2O3 metal matrix composites. These milling tests were performed based on Taguchi method where the effects of the cutting parameters on surface roughness and cutting forces were studied using the analysis of variance method. The results show that the roughness was improved between 196% and 312% in milling of Al2O3 reinforced alloy composite compared to AA7039 alloy.

In recent studies, Bo et al. [20] Proposed a geometrical simulation of a milled surface based on the skin model of the workpiece. The workpiece and the machine tool were supposed as rigid elements. They included in this study the effects of the machine tool errors, the workpiece clamping error and the cutter behavior in order to have a more accurate topography. The machined surface was evaluated and characterized using the modal parameters and the effect of cutting parameters were remarked. The predicted model was validated with experimental tests where a good agreement was found. Zhang et al. [21] Developed a surface topography model in ball-end milling using the relative motion between the tool and the workpiece. The surface roughness was optimized as a function of the feed per tooth and radial depth of cut. The proposed model was validated by experiments and a good agreement was found in the range of cutting parameters used for milling the AISI H13 steel. Chen and Wang [22] Proposed a biharmonic spline interpolation BSI model to have a more accurate topography eliminating problems related to the determining of discrete points in the most of the used topography models. The tool vibrations were taken into account in the kinematic model of the tool. The proposed model allows the prediction of free form machined surfaces using the BSI method. They proved the limits of other methods
related to the instability of the resolution of the nonlinear equations and to the discretization are avoided using this modeling where the results were improved by 7.9% and the time of execution were decreased. A set of experiments was carried out under various conditions and a good agreement was found with a maximum error 15.5% for the arithmetic surface roughness. Wojciechowski et al. [23] Established the relations between the instantaneous tool displacements and surface roughness in ball end milling of inclined surfaces. The machined surface roughness was measured with optical profile meters. The results show the effect of the tool overhang on the surface roughness in finishing operations. For rigid set-up with free length $l = 35$mm, the surface roughness correlates with geometric model considering machining errors. On the other side, in case of milling with the slender tool with a free length $l = 85$ mm, the surface roughness is mainly affected by the tool dynamic deflections caused by milling forces. Shujuan et al. [24] Used the Z-MAP modeling of the surface topography of machined surface in ball end milling. They improved the previous Z-MAP models based on the tool motion equation and its intersection with the workpiece by combining the angle summation technique and servo rectangular encirclement to get the instantaneous swept points of the workpiece. The height of the swept point was calculated using the Newton iterative method. The surface roughness was analyzed including the effect of the feed per tooth, the tool position and the initial phase angle and the proposed model was validated with experiments where the improved program gives results close to measured surfaces and takes less time than the previous algorithm with the same machining conditions. Nguyen [25] presented a method to optimize machining factors for decreasing specific cutting energy with a simultaneous improve of the material removal rate while the roughness properties were defined as constraints. The results show that a set of optimal solutions can be determined to observe a low specific cutting energy coupled with a better surface and high material removal rate.

Corner motion is a common and important case in contouring applications. A sharp corner is formed by two consecutive contours with discontinues in their first derivatives. In general, these two linear contours are fed into the acceleration and deceleration processor one after the other. Two modes are used in contouring applications the first is the Exact-Stop mode which the machine stop in the end of each block, the velocity reached zero and after that start the next block and the second is the continuous mode which the machine starts to execute the second command before the first one is completed executed. The second mode uses a Look-Ahead algorithm; this method was developed in many researches in terms of optimizing the machining time in rough milling.

From the literature review, it can be concluded that the current researches was mainly focused on process parameters optimization and tool path planning algorithms. For analyzing the surface topography, all methods are limited to constant feed rate. But the dynamic behavior of the machine and the acceleration and deceleration process modifies the feed value which presents the important parameter influencing the surface topography and the roughness profiles. The impact of these phenomena on the surface topography is not studied. In this paper, an experimental study was conducted in order to analyze the surface profiles in ball end milling. We study the variation of the surface topography and the roughness profiles along the tool path. The study concern Normal-block which started by a zero velocity, accelerate to reach the stationary feed rate, decelerate at the end of the block to reach a zero velocity. The tool path
used is divided into three zones. The first region is the acceleration zone, the second is the stationary zone and the third is the deceleration zone. The surface topography is studied in high speed milling with a ball end tool in finishing conditions. The machining errors considered in this study are the tool runout, the tool bending and the tool vibrations. The kinematic behavior of the machine tool is studied where its effect on the acceleration and the deceleration zones was detailed. It is remarked that the surface topography is better in the stationary zone compared to the acceleration and deceleration zones. This is due to the stable behavior of this zone and the irregular behavior of the path bounding.

2 Problematic And Experimental Setup

The pocket contouring strategy presented discontinuities in the changing direction points where the tool traverses from the path \( i \) to a next path \( i + 1 \) as shown in the Fig. 1. The tool decelerates at the end of the path \( i \) and accelerate in the beginning of the path \( i + 1 \). This study is focused on the region near the point of the changing direction (zone of study) as shown in Fig. 1.

To simplify the study and measuring process, the experiments were conducted in this work with machining the workpiece using the “one-way” strategy and analyzing the different results of the feed rate evolution, the roughness profiles and the surface topography in the three zones Fig. 2. The beginning attack point was realized with an approach between the effective radius of the tool and the workpiece of 0.5 mm. This approach is less than the distance required to achieve the programmed value of the feed rate. The exit point of the tool from the workpiece is fixed in the end of the machined surface. These two conditions conduced to guarantee that the acceleration and deceleration motions exist on the machined surface.

The workpiece material used in the experiments was a AISI4142 Steel; the top surface is a circular part with diameter 100 mm. It was divided on three areas as shown in Fig. 2. two lateral areas for the fixation of the workpiece on the KISTLER table dynamometer and a middle surface with size 80 mm x 42 mm is prepared for the cutting tests to have a regular form in order to make easier the control of the traveled distances.

The cutting tool used is a ball end mill cutter coated with TiSiN with a diameter \( d = 10 \text{mm} \), two teeth \( N_f=2 \), the helix angle was \( i_0 = 30^\circ \), the total length was \( L = 100 \text{mm} \) and the active length was 15 mm as shown in Fig. 3-c. All cutting experiments were conducted in one way milling. The tests were conducted in dry milling which is recommended by the tool manufacturer. The machine used is a CNC HS Milling HURON KX10, Fig. 3-a. The maximum acceleration is \( A = 3 \text{m/s}^2 \) and a maximum jerk \( J = 50 \text{m/s}^3 \). A KISTLER three components dynamometer model 9257B was used for force data acquisition.

The surface topography in 3D image is measured by an infinite focus Alicona machine with an extension multiplied by x20 Fig. 4. and the topography analysis was conducted using the software Mountains Map 7 from Digital Surf.
To determine the length traveled by the tool on the acceleration and the deceleration zones, the velocity profile is measured using a SINUCOM Software connected to the machine by an acquisition card Simatic Net. For example, the measured velocity profile, for the programmed feed rate equal to $V_f = 3900 \text{ mm/min}$ is shown in Fig. 5. For this test, the total acceleration time is 0.172s, and the total deceleration time is 0.16s. Knowing these times, the measuring zones are determined.

In the two carried tests which the cutting parameters are presented in the Table 1. The surfaces topography ($S_a$: 3D average roughness) and ($S_q$: 3D root mean square roughness) are measured and presented as a 2D surfaces. The 2D roughness profiles are extracted from the selected 2D surface and the value of ($R_z$: the maximum peak value) and ($R_a$: the mean roughness) are determinate.

| Table 1  
Machining test conditions | Spindle speed $N$(rev/min) | Feed $f_z$ (mm/tooth) | Radial depth $a_e$(mm) | Axial depth $a_p$(mm) | Runout $e$ (µm) | Eccentricity $\rho$ (°) |
|--------------------------|---------------------------|-----------------------|------------------------|------------------------|----------------|------------------------|
| Test 1                   | 15000                     | 0.1                   | 0.5                    | 1                      | 5.97          | 0                      |
| Test 2                   | 22000                     | 0.088                 | 0.5                    | 1                      | 5.55          | 106                   |

3 Results And Interpretations

The acceleration and deceleration phenomena affect the feed per tooth related to the feed rate. It increases from zero to the programmed feed in the acceleration zone and decreases from the programmed feed to the zero in the deceleration zone. This variation influences the instantaneous uncut chip thickness and the cutting width where their product represented the instantaneous cutting section. Since the cutting forces are proportional to the cutting section, in the linear path used in our study, they increase in the acceleration zone from a null value and they decrease in the deceleration zone to the same null value.

The experimental tests were carried out in up milling, where the cutter and workpiece engagement begins with a null value until achieving the maximal chip thickness in the end of each engagement. This engagement mode favors the bending of the tool from the beginning where it evolves according to the cutting forces. In addition to the tool bending, the dynamic behavior of the ball end mills also exists where the instantaneous displacements of the tool related to the forced vibrations.

In general, from the machining tests analyses, the surface topography and roughness values are better in the stationary zone and the surface quality is poor in the acceleration and deceleration zones. The machining errors as the deflection, the vibrations are more important in the stationary zone according to the higher cutting forces, in addition to the radial runout, these machining errors increase the deviation of
the tool center. The equivalent rotation radius of the tooth around the spindle axis is bigger and the
scallop heights in the feed and cross feed directions during stationary feed motion are deteriorated
comparing with the theoretical values. As a result the machining surface topography and roughness are
ameliorated.

The measured topographies and roughness for the two experimental tests are presented respectively by
the Fig. 6. and Fig. 9. for the topography. By the Fig. 7. And Fig. 10. For the roughness profiles measured
in the feed direction and by the Fig. 8. And the Fig. 11. for the roughness profiles measured in the cross
feed direction. The effects of the dynamic of the machine on the surface topography and roughness
profiles in both directions are explicated as follows:

3.1 Surface topography

When analyzing the surface topography value as \((S_a: 3D\ \text{average roughness})\) and \((S_q: 3D\ \text{root mean}
\text{square roughness})\). A poor surface topography is noted on the tool path changing direction regions and a
good one is noted in the stationary zone. The mean values for the test 1 are \((S_q=4.55\mu m\ \text{and} \ S_a=4.08\mu m
\text{for the acceleration zone})\), \((S_q=4.17\mu m\ \text{and} \ S_a=3.97\mu m \text{for the deceleration zone})\) and ameliorated to an
\((S_q=3.95\mu m\ \text{and} \ S_a=3.81\mu m \text{for the stationary zone})\) as shown in Fig. 6. For the test 2 the mean values
are \((S_q=5.19\mu m\ \text{and} \ S_a=4.49\mu m \text{for the acceleration zone})\), \((S_q=4.82\mu m\ \text{and} \ S_a=4.16\mu m \text{for the}
deceleration zone)\) and ameliorated to an \((S_q=4.74\mu m\ \text{and} \ S_a=4.01\mu m \text{for the stationary zone})\) as shown
in Fig. 9. The results prove that the high values of the machining errors in the stationary zone due to the
high values of the cutting forces increase the equivalent rotation radius of the teeth around the spindle
axis and deteriorate the feed and cross feed picks. The mean values of the topography decreases for the
stationary zone. In the acceleration and deceleration zones, the cutting forces decreases, the machining
errors as the deflection and the vibration are neglected and the teeth rotates with their nominal radius the
feed and cross feed picks are not deteriorated and means values of the topography are high.

3.2 Roughness profiles in feed direction

Theoretically, in the ideal conditions whit no machining errors the feed-peak is proportional to the feed per
tooth. For theses hypothesis in the deceleration and acceleration zones the feed-peak height decrease as
the feed per tooth decreases for a constant spindle speed and the roughness decreases. Contrary in the
stationary zone the feed-peak height is more important according to this data the roughness must be
more important.

But it can be seen from the experimental results that the machining errors as the deflection, the vibrations
and the runout deteriorate the feed-pick cusp and ameliorate the surface roughness in feed direction on
the stationary zone.

For the two tests, the measured roughness \(R_z\) and \(R_a\) in the acceleration and deceleration zones are
higher than in the stationary zone. It can be seen from the Fig. 7. For the test 1, that the roughness
profiles are rougher respectively in the Fig. 7(a) in the acceleration zone. with \((R_z=4.73\mu m \text{and}
\text{and} \ R_a=4.49\mu m)\)
\( R_a = 0.95\mu m \) and Fig. 7(c) in the deceleration zone. with \( (R_z = 3.3\mu m \text{ and } R_a = 0.50\mu m) \), than the profiles respectively in Fig. 7(b) in the stationary zone. with \( (R_z = 1.32\mu m \text{ and } R_a = 0.195\mu m) \). In the same way for the test 2. Figure 10. the roughness profiles are rougher respectively in the Fig. 10(a) for the acceleration zone. with \( (R_z = 9.11\mu m \text{ and } R_a = 2.41\mu m) \) and Fig. 10(c) for the deceleration zone. with \( (R_z = 9.21\mu m \text{ and } R_a = 2.31\mu m) \), than the profiles respectively in Fig. 10(b) in the stationary zone. with \( (R_z = 7.15\mu m \text{ and } R_a = 1.61\mu m) \).

### 3.3 Roughness profiles in cross-feed direction

The cross-feed peak is proportional to the radial depth of cut. In the acceleration and the deceleration zones the errors are minimal because the low cutting forces values. In the stationary zone the feed rate is at its maximum, the dynamic of the machine and the high-cutting forces cause a tool deflection and vibration, in addition to the runout, these machining errors increase the equivalent radius of the tooth around the spindle axis as shown in the Fig. 5. These fluctuations deteriorate the cross-feed-pick and minimize its value.

It can be seen from the Fig. 8. For the test 1, that the roughness profiles are rougher respectively in the Fig. 8(a). with \( (R_z = 11.6\mu m \text{ and } R_a = 3.3\mu m) \) for the acceleration zone and Fig. 8(c). with \( (R_z = 11.3\mu m \text{ and } R_a = 3.61\mu m) \) for the deceleration zone, than the profiles respectively in Fig. 8(b). with \( (R_z = 11.9\mu m \text{ and } R_a = 3.07\mu m) \) for the stationary zone. In same way for the test 2, Fig. 11. the roughness profiles are rougher respectively in the Fig. 11(a). with \( (R_z = 13.4\mu m \text{ and } R_a = 4.7\mu m) \) for the acceleration zone and Fig. 11(c). with \( (R_z = 13.6\mu m \text{ and } R_a = 4.7\mu m) \) for the deceleration zone, than the profiles in Fig. 11(b). with \( (R_z = 13.4\mu m \text{ and } R_a = 4.41\mu m) \) for the stationary zone.
**Table 2**
Surface roughness and topographies values

**Test 1:** $N = 15000$ rev/min, $f_z = 0.1$ mm/tooth, $a_p = 1$ mm, $a_e = 0.5$ mm, $e = 5.97$ µm and $\rho = 0^\circ$.

|                     | Acceleration zone | Stationary zone | Deceleration zone |
|---------------------|-------------------|-----------------|-------------------|
| $S_q$ (µm)          | 4.55              | 3.95            | 4.17              |
| $S_a$ (µm)          | 4.08              | 3.81            | 3.97              |

Roughness Value in Feed direction

|                     |                  |                  |
|---------------------|------------------|------------------|
| $R_z$ (µm)          | 4.73             | 1.32             | 3.3               |
| $R_a$ (µm)          | 0.95             | 0.195            | 0.50              |

Roughness Value in Cross-Feed direction

|                     |                  |                  |
|---------------------|------------------|------------------|
| $R_z$ (µm)          | 11.6             | 11.9             | 11.3              |
| $R_a$ (µm)          | 3.30             | 3.07             | 3.61              |

**Test 2:** $N = 22000$ rev/min, $f_z = 0.088$ mm/tooth, $a_p = 1$ mm, $a_e = 0.5$ mm, $e = 5.55$ µm and $\rho = 106.26^\circ$.

|                     | Acceleration zone | Stationary zone | Deceleration zone |
|---------------------|-------------------|-----------------|-------------------|
| $S_q$ (µm)          | 5.19              | 4.74            | 4.82              |
| $S_a$ (µm)          | 4.49              | 4.01            | 4.16              |

Roughness Value in Feed direction

|                     |                  |                  |
|---------------------|------------------|------------------|
| $R_z$ (µm)          | 9.11             | 7.15             | 9.21              |
| $R_a$ (µm)          | 2.41             | 1.61             | 2.31              |

Roughness Value in Cross-Feed direction

|                     |                  |                  |
|---------------------|------------------|------------------|
| $R_z$ (µm)          | 13.4             | 13.4             | 13.6              |
| $R_a$ (µm)          | 4.7              | 4.41             | 4.7               |

### 4 Conclusion
In this paper we studied the influences of the dynamic behavior of the machine caused by the high speed on the roughness profiles and topographies. A description of the teeth path in the initial state and considering the machining errors and the tool behavior was presented in order to facilitate the interpretation of the machined surface topography. It can be seen clearly that the acceleration and the deceleration in the changing direction zones increase the maximum peak value $R_Z$ and the mean roughness $R_a$ compared to the stationary zone in the both feed and cross feed directions. The results are the same when analyzing the surface topography the 3D root mean square roughness $S_q$ and the average roughness $S_a$.

The surface quality is deteriorating in the changing direction. The amelioration of the surface topography resides in many solutions as the cutting strategy, changing the spindle speed in the acceleration and deceleration zone, or adopts a strategy which decreases this effect.

For further works, a predictive model will be developed in order to define the machine surface topography taking into account the tool behavior, the kinematic behavior and the machining parameters according to the experimental interpretations processed in this paper.

**Declarations**

**Conflict of interest:**

Lotfi Sai, Rami Belguith, Maher Baili, Gilles Dessein and Wassila Bouzid declare that they have no conflict of interest.

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**Human/Animal Rights:**

This article does not contain any studies with human or animal subjects performed by any of the authors.

**Availability of data and material (data transparency):**

This experimental study was carried out by the authors within the LGP-ENIT and the UGPMM-ENIS and results were extracted from the used machines described in the manuscript under the studied conditions.

**Ethical Approval:**

The manuscript is submitted to this journal only.
The manuscript is original and is not published elsewhere in any form or language.

**Consent to Participate** “Not applicable”

**Consent to Publish:**

The Author declares that any person named as co-author of the contribution is aware of the fact and has agreed to be so named and that the manuscript will be published in your journal.
Authors Contributions:

Experiments were carried out by R. Belguith and M. Baili. L. Sai wrote the manuscript after interpreting with all authors, the obtained results. W. Bouzid and G. Dessein have checked and approved the manuscript. All authors read and approved the final manuscript.

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