ORIGINAL ARTICLE

Tool wear modelling using micro tool diameter reduction for micro-end-milling of tool steel H13

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Abstract

Micro components have been demanded increasingly due to the global trend of miniaturization of products and devices. Micro milling is one of the most promising processes for micro-scale production and differs from conventional milling due to the size effect introducing phenomena like the minimum chip thickness, making the prediction of micro milling process hard. Among challenges in micro milling, tool life and tool wear can be highlighted. Understanding tool wear and modelling in micro milling is challenging and essential to maintaining the quality and geometric tolerances of workpieces. This work investigates how to model the diameter reduction of a tool caused by tool wear for micro milling of H13 tool steel. Machining experiments were carried out in order to obtain cutting parameters affecting tool wear by considering the diameter reduction. Dry full slot milling with TiAlN (titanium aluminium nitride)-coated micro tools of diameter $d = 400$ μm was performed. Three levels of feed per tooth ($f_z = 2$ μm, 4 μm and 5 μm) and two spindle speed levels ($n = 30,000$ rpm and 46,000 rpm) were used and evaluated over a cutting length of $l_c = 1182$ mm. The results show that lower levels of feed per tooth and spindle speed lead to higher tool wear with a total diameter reduction over 22%. The magnitude of the cutting parameters affecting tool wear was determined by ANOVA (analysis of variance), and the model validation meets the statistical requirements with a coefficient of determination $R^2 = 83.5\%$ showing the feasibility of the approach to predict tool wear using diameter reduction modelling in micro milling.

Keywords Tool wear · Micro milling · Full slot milling · Machining parameters

1 Introduction

The increasing application of miniaturized devices raised demands on micro technologies systems production. Micro parts are required in industries of aerospace, energy and biomedicine [1]. Micro milling is characterized by the use of tools with a diameter $d < 1$ mm [2]. Micro milling can work with a variety of materials of workpiece and complex geometries, which makes this process one of the most suitable for micro-scale manufacturing [3]. Tool wear is a critical factor because it has an influence on component tolerance, surface quality, production time and costs [4]. In this way, the monitoring of process condition and the prediction of machining help to improve productivity and reduce process costs [5, 6]. Tool diameter is reduced, and flank wear is severely damaged by tool wear affecting machining accuracy and surface integrity [7]. As the machined feature goes down in size, the accuracy of the manufacture must be improved, and finding the optimum cutting conditions is essential to controlling and improving process capability [8].

There are some phenomena in micro milling that are not observed in conventional milling as the size effect, the presence of minimum chip thickness and the cutting edge radius [9]. In micro machining, the radius of the cutting edge becomes significant compared with the thickness of the material to be removed [8] and a chip will not be cut if the uncut chip thickness is less than a critical value, which is the minimum chip thickness [10]. As the tool diameters are so small, they are more susceptible to deflections and premature breakage, which makes tool wear modelling a challenge in micro milling [3].

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Tool wear and breakage is a subject that has not yet been fully clarified in micro tools. Tool wear depends on the tool material and geometry, workpiece material, cutting parameters (cutting speed, feed per tooth and depth of cut), cutting fluids and machine tool characteristics [11]. When selecting lower feed rates, the tool contacts the work surface more often compared with a larger feed rate for the same cutting length and spindle speed, causing greater tool wear [12].

Li et al. [13] described tool wear in micro milling as a complicated process, since the size effect can induce many random factors. The effect of reducing tool diameter and the geometry changes cannot be described in a simplified way due to the complexity of the geometry. The same authors performed tests with spindle speeds of 20,000 rpm $\leq n \leq$ 70,000 rpm and depths of cut of 6 μm $\leq a_p \leq$ 20 μm. They inferred that the wear effect significantly affects the roughness of the machined surface. However, the depth of cut showed low influence on tool wear. Kiswanto et al. [14] reported that lower feed rates of 0.05 mm/s $\leq v_f \leq$ 1 mm/s imply better surface quality, which is measured by R_a roughness. However, the machining time required for a given cut length is higher, causing a higher tool wear.

Lu et al. [1] identified tool tip wear as the main form of tool wear in micro milling. According to the authors, in micro milling, the feed per tooth can be less than the cutting edge radius, so the chips do not flow along the rake face, but through the tip of the tool directly, leaving the tip in the position with greater wear. Ucun et al. [15] investigated the effect of coating on tool wear on the micro milling of nickel alloy 718. The results showed that AlTiN-, TiAlN + AlCrN- and AlCrN-coated tools showed better performance in terms of built-up edge (BUE) formation and tool wear compared with TiAlN + WC/C and DLC coated. The authors provide an accurate description of the form of occurrence of wear. According to the results, tool wear is greater in the flank face with the occurrence of fractures along the faces. Less chipping was observed in the coated tools, concluding that the coating increases the hardness of the tools. A decrease in diameter was observed due to abrasive wear, and the cutting edge was significantly damaged.

To evaluate tool wear directly, the tool must be removed from the holder and wear should be measured at regular intervals with the help of a microscope [16]. Moreover, to investigate the influence of tool wear and rake angle on the cutting forces in the micro milling of AISI 4340 steel, Afazov et al. [12] measured the value of the cutting edge radius by removing the tools from the machining centre and measuring them with a scanning electron microscope (SEM) in four intervals of cutting length l_c = 168 mm. The results indicate that the cutting forces increase with the increase in the cutting edge radius and that the cutting forces are higher for the rake angle of α = 0 ° compared with the rake angle of α = 8°. The increase in cutting forces is mainly associated with changes in friction conditions between the workpiece and the tool.

Zhu and Yu [17] proposed a wear area analysis approach based on the top images of the worn tools. According to the authors, the area analysis generalizes the estimate wear providing a more accurate result than in traditional techniques that can better reflect the tool condition. It has been observed that the wear zone has a triangular shape, and that this zone expands gradually. Uhlmann et al. [18] have carried out micro milling tool analyses observing images of the tool cutting edges with scanning electron microscope (SEM) and cutting edge radius measurements using the Infinite Focus, Alicona.

A criterion to evaluate the wear of cutting edges in micro milling is challenging to establish. The diameter reduction and average flank wear can be used as two different measures to quantify the tool wear [19]. Alhadeff et al. [20] proposed a protocol for measuring, characterising and reporting wear on micro milling; wear was measured using SEM techniques removing the tool at a pre-determined interval.

Statistical methods have been used to build models for predicting cutting conditions in micro milling such as tool wear, cutting forces and surface roughness. ANOVA have been successfully applied by Saedon et al. [21] to understand the effect of cutting speed, feed per tooth and depth of cut on tool life in micro milling of AISI D2 steel using TiAlN-coated micro mills. The cutting speed range was 14.77 $\leq v_c \leq$ 68.30 m/min, and feed per tooth was f_z = 1 μm and 2.5 μm for tools with a diameter 15 μm $\leq d \leq$ and 85 μm. Adequacy of the models has been evaluated by ANOVA which indicates significance at 95%. The tool life equation established in the paper showed that the cutting speed is the main factor affecting tool life, followed by feed per tooth. Also, Wang et al. [22] used ANOVA to validate the feasibility of using the spindle current signal to estimate tool wear on micro milling. Wang et al. [23] investigated the influence of micro-end-milling cutting conditions on roughness using factorial experiments and ANOVA methodology. They established a model for micro-end-milling surface roughness based on tool diameter, depth of cut, spindle speed and feed rate.

Given the state of art, this work presents an approach to model the tool diameter reduction in the micro end milling of tool steel H13 using full-factorial design of experiments (DoE) in a range of feed per tooth 2 $\leq f_z \leq$ to 5 μm, spindle speed 30,000 $\leq n \leq$ to 46,000 rpm and cutting length of 1182 mm.

2 Methodology

The workpiece material is the tool steel H13. The main chemical compositions of the test pieces used for experimentation are presented in Table 1.

TiAlN two-flute coated ultra micrograin carbide tools were used. The tool diameter is d = 400 μm with a 30° helix angle. The cutting edge radius estimated is r_e = 2.5 μm for a new tool. Images using a Jeol JCM-5000 NeoScope Scanning

Table 1 H13(X40CrMoV5-1) chemical composition

C	Mn	Si	Cr	Mo	V
0.37/0.42	0.20/0.50	0.85/1.20	5/5.5	1.20/1.70	0.85/1.20

Electron Microscope were taken for new and worn tools. Some images for a new tool are presented in Fig. 1.

The machining tests were carried out on a Primacon PFM 4024-5D machine tool with position accuracy of linear axes = 0.0015 mm (VDI/DGQ 3441) at the IWF (Institut für Werkzeugmaschinen und Fabrikbetrieb) of TU Berlin (Technische Universität Berlin). Figure 2 presents the machining set-up.

Experiments are planned using the DoE methodology. A full-factorial design using two factors, the feed per tooth f_z and the spindle speed n, with three and two levels, respectively, were performed in order to obtain independent and interactive effects of those factors on tool wear. The combination of parameters is presented in Table 2. Three repetitions for each set of parameters were performed. Channels with of cutting length $l_c = 197$ mm were machined in the first step of the
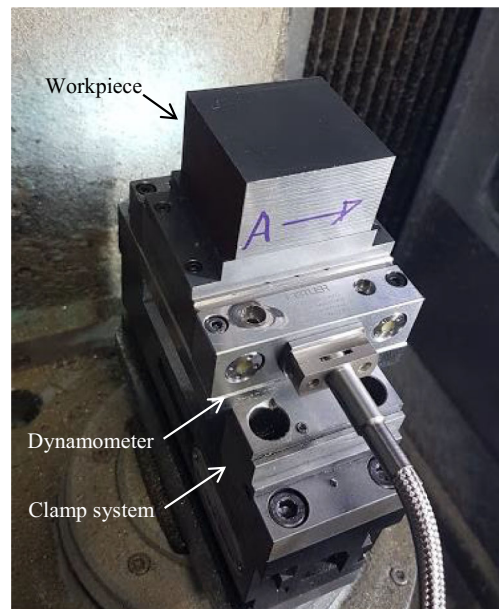
Fig. 2 Experimental set-up

experiments. Then, the cutting tools are removed from the machine tool for wear analysis and diameter measurement. This procedure is repeated five times more,

Fig. 1 **a** Micro tool. **b** Zoom for tool tip: A: major cutting edge, B: minor cutting edge, C and D: flank face and E: relief face. **c** Detail for tool tip and diameter. **d** Micro tool top view
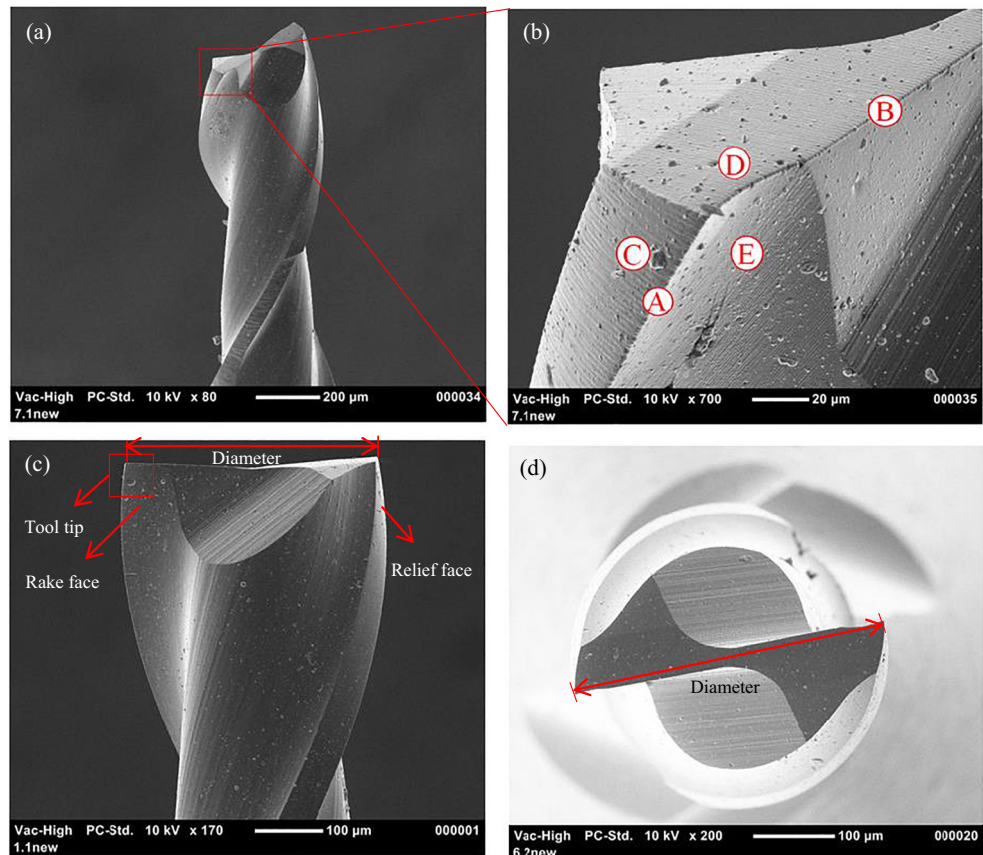
Table 2 Cutting parameters applied to machining tests

Experiment	Feed per tooth f_z (μm)	Spindle speed n (rpm)	Cutting speed v_c (m/min)	Feed rate v_f (mm/min)	Deep of cut a_p (μm)
#1	2	30,000	37.7	120	15
#2	4	30,000	37.7	240	15
#3	5	30,000	37.7	300	15
#4	2	46,000	57.8	184	15
#5	4	46,000	57.8	368	15
#6	5	46,000	57.8	460	15

completing six evaluation points over a cutting length l_c = 1182 mm. A machined workpiece and its 2D drawing are shown in Fig. 3.

2.1 Tool wear evaluation for model building

SEM images of the worn tools were taken in each evaluation point of the experiments for comparison with new tools and to help understanding the wear behaviour. The indicator chosen in order to quantify the tool wear was the tool diameter. Tool chipping occurs due to abrasive wear during the machining which causes tool diameter reduction. The measuring machine Helicheck Plus was used to determine the tool diameter as shown in Fig. 4, the measuring machine tool has multiple cameras with ×400 magnification and the micro milling tool is held at the centre and rotate in order to obtain its profile. Technical specifications of Helicheck Plus are presented in Table 3. An example of a profile obtained is presented in Fig. 5. The red cursor in Fig. 5 is positioned 5 μm from the top, and

the tool is rotated to determine the greatest diameter. The data obtained for effective diameter are analysed by ANOVA method and used to build a numerical model for tool diameter reduction. The model is validated by statistical tests.

To check the effect of tool wear on the machined surface, the profile of machined channels was obtained with an Alicona Infinite Focus microscope with magnification lenses of ×50 and lateral and vertical resolutions of 1 μm and 500 nm, respectively. Figure 6 a shows a 3D image obtained with the microscope for a machined surface, and Fig. 6b how the profile is measured.
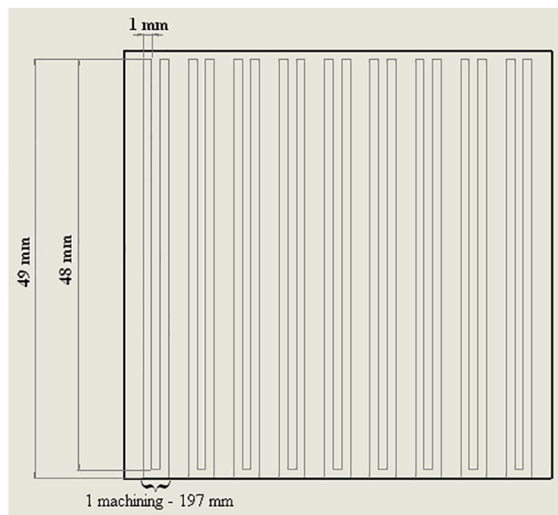
3 Results and discussion

3.1 Tool wear affecting diameter reduction

Figure 7 shows the tool wear for one tool of each experiment after a cutting length of l_c = 985 mm. The tools
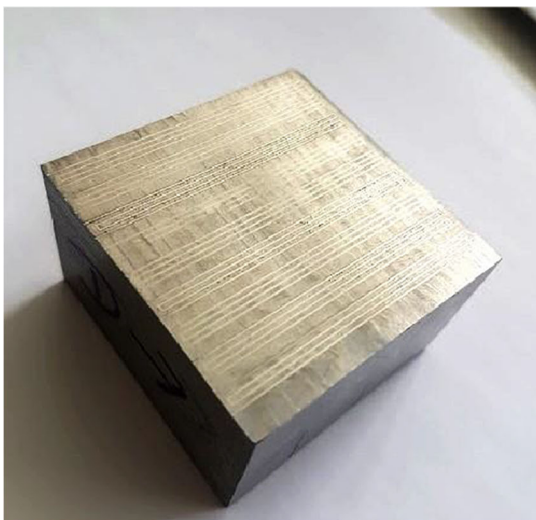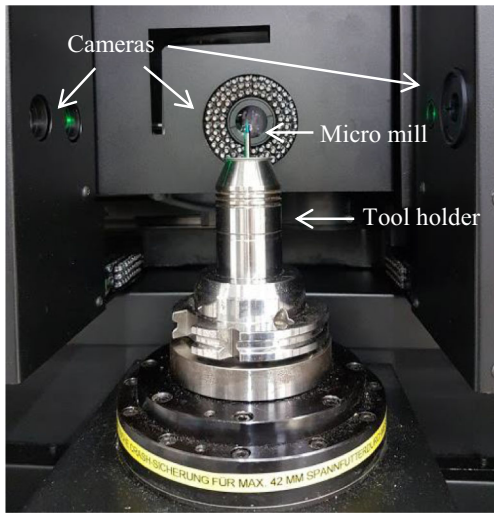

Fig. 3 Workpiece channels machining

Fig. 4 Set-up for diameter measurement

show a severe wear in the nose region with tool chipping starting in the tool tip and expanding to flank and relief faces. The cutting edge is severely deformed due to abrasion between the tool and the workpiece. It can be seen that the wear is more pronounced for low levels of feed per tooth and spindle speed. The tool tip shows a rounded geometry due the tool wear (comparison with Fig. 1a); as the wear increases, the geometry is deformed, for example, the tool with n = 30,000 rpm and f_z = 2 μm on Fig. 7. This change in tool shape will have

an effect on machined geometry and surface quality; when this kind of worn tool is rotated, it leaves its shape on the workpiece, producing channels with bevelled corners instead of sharp corners, as shown in Fig. 8: a profile obtained with a microscope for a tool from experiment 1 (n = 30,000 rpm and f_z = 2 μm) is overlapped to the profile of a new tool.

The tool deformation observed in Fig. 7 reduces effective tool diameter, so it was chosen as an indicator for model building. The mean value of the tool diameter obtained for the experiment repetitions and its respective standard deviation are presented in Figs. 9 and 10. Figure 9 compares tool diameter reduction over the cutting length for the three levels of feed per tooth and two levels of spindle speed. In both graphs, it can be seen that a greater tool diameter reduction occurred for lower feed per tooth. For all graphs, when cutting length of l_c = 0 mm is considered, it means that the measurement was collected as near as possible of the beginning of the cut.

In Fig. 10, the effective diameter is compared over the cutting length for the experiments with the same spindle speed and different levels of feed per tooth. In all graphs, the lower level of spindle speed caused greater tool diameter reduction. In the work of Kuram and Ozcelik [24], a similar behaviour is observed in the micromilling of Ti6Al4V. The authors investigated the cutting parameters and the tool path effect on tool wear and roughness. The increment in spindle speed gave lower
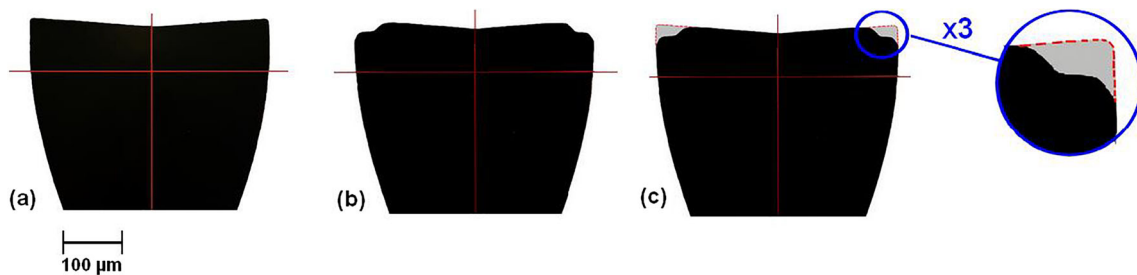

Fig. 5 Profile obtained for micro mills by Helicheck Plus. **a** New tool. **b** Worn tool. **c** Overlap of new and worn tool
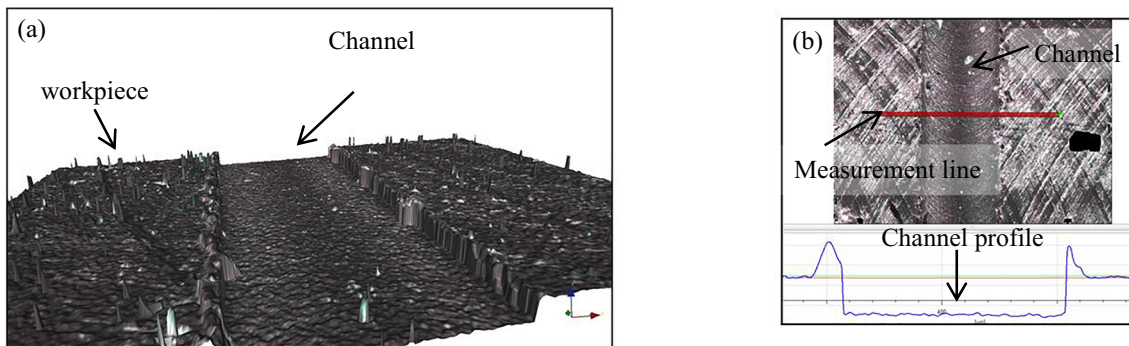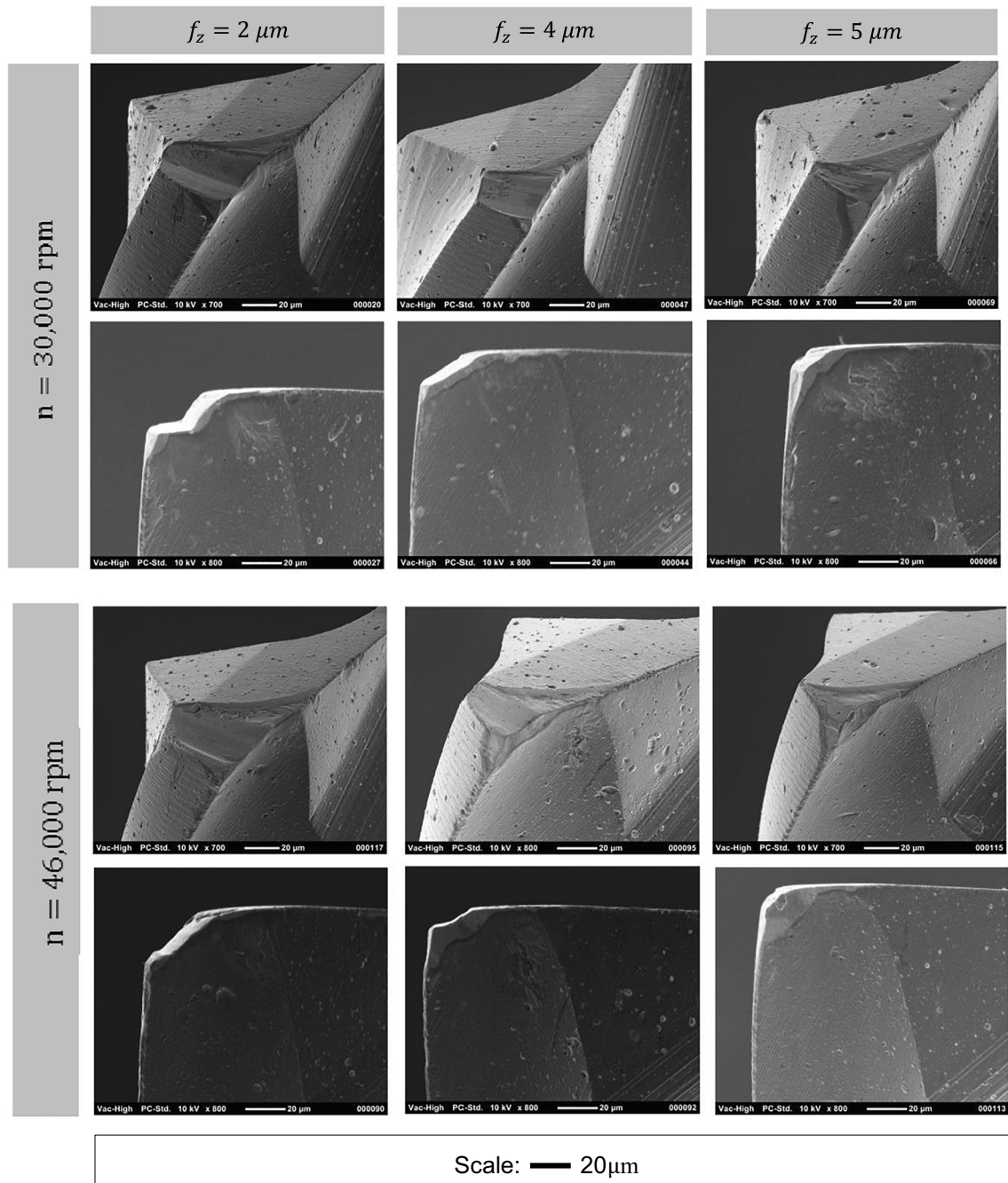

Fig. 6 Machined profile obtained with an Alicona Infinite Focus microscope

Fig. 7 Tool wear under different cutting parameter conditions after cutting length of $l_c = 985$ mm channels with depth of cut of $a_p = 15$ μm

tool wear in down and zigzag micro-milling. However, tool wear was greater for an up-milling path. The spindle speed used was $n = 20,000$ rpm and 28,000 rpm. Another study of Kuram and Ozcelik [25] also concluded that the tool wear during micro-milling of Ti6Al4V titanium alloy decreased with an increment of spindle speed and in a range of 10,000 rpm $< n <$ 12,000 rpm. However, in the same work the effect of the spindle

speed is different for Inconel 718 increasing tool wear

Table 3 Helicheck Plus technical specifications

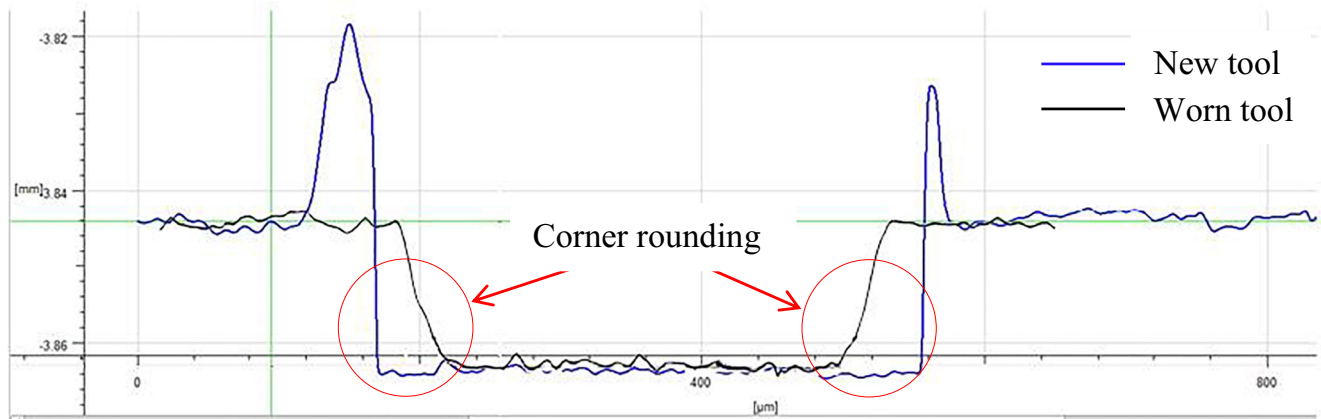|	
Repetition accuracy	≤ 1 μm
Position resolution for all linear axes X, Y, Z	0.004 μm
Position resolution for rotation axis A	0.0025°
Measurement value resolution	0.25 μm

Fig. 8 Channels profile for a new and worn tool

with the increment of spindle speed. In the work of Santos et al. [26], the micro milling of UNS S32205 duplex stainless steel also showed a higher tool wear with the increment of spindle speed (20,000 rpm < n <30,000 rpm). From the works mentioned and from the results obtained in this work, it can be concluded that spindle speed is a variable of influence on the tool wear though its effect can variate in function of the workpiece material, range of parameters and path strategy.

3.2 Analysis of variance and model building

To analyse the cutting parameters, significance on the tool wear ANOVA was applied. Table 4 shows the results of ANOVA using Action Stat, a supplement software for Excel. A significance level of $\alpha = 0.05$ is adopted. According to the ANOVA table, the feed per tooth, f_z, the spindle speed, n, the cutting legth, l_c, and the interaction f_z: l_c are significant to the tool wear effect.

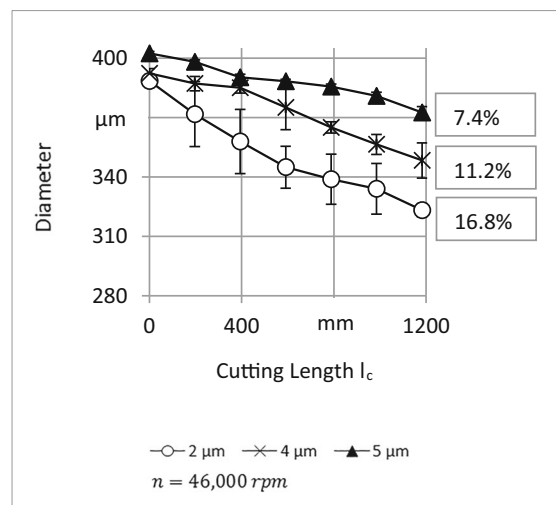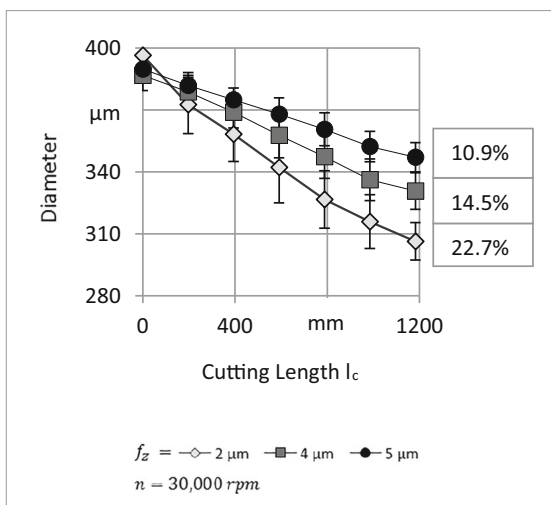| Process:	Tool:	Parameters:
Micro milling PFM4024-5D, Primacon	Two flute end mill Ultra micrograin carbide, TiAlN coat Diameter D = 400 µm	f_z = 2 µm, 4 µm and 5 µm n = 30,000 rpm and 46,000 rpm a_p = 15 µm a_e = D
Measurement device:		
Helicheck Plus		

Fig. 9 Effective diameter for experiments with constant spindle speed in different levels of feed per tooth and total diameter percentual reduction

Process:	Tool:	Parameters:
Micro milling PFM4024-5D, Primacon	Two flute end mill Ultra micrograin carbide, TiAlN coat Diameter d = 400 µm	f_z = 2 µm, 4 µm and 5 µm n = 30,000 rpm and 46,000 rpm a_p = 15 µm a_e = D
Measurement device:		
Helicheck Plus		

$$f_z = -\diamond- \; 2\,\mu m \quad n = 30{,}000\,rpm$$
$$f_z = -\blacksquare- \; 4\,\mu m \quad n = 30{,}000\,rpm$$
$$f_z = -\bullet- \; 5\,\mu m \quad n = 30{,}000\,rpm$$
$$f_z = -\circ- \; 2\,\mu m \quad n = 46{,}000\,rpm$$
$$f_z = -\times- \; 4\,\mu m \quad n = 46{,}000\,rpm$$
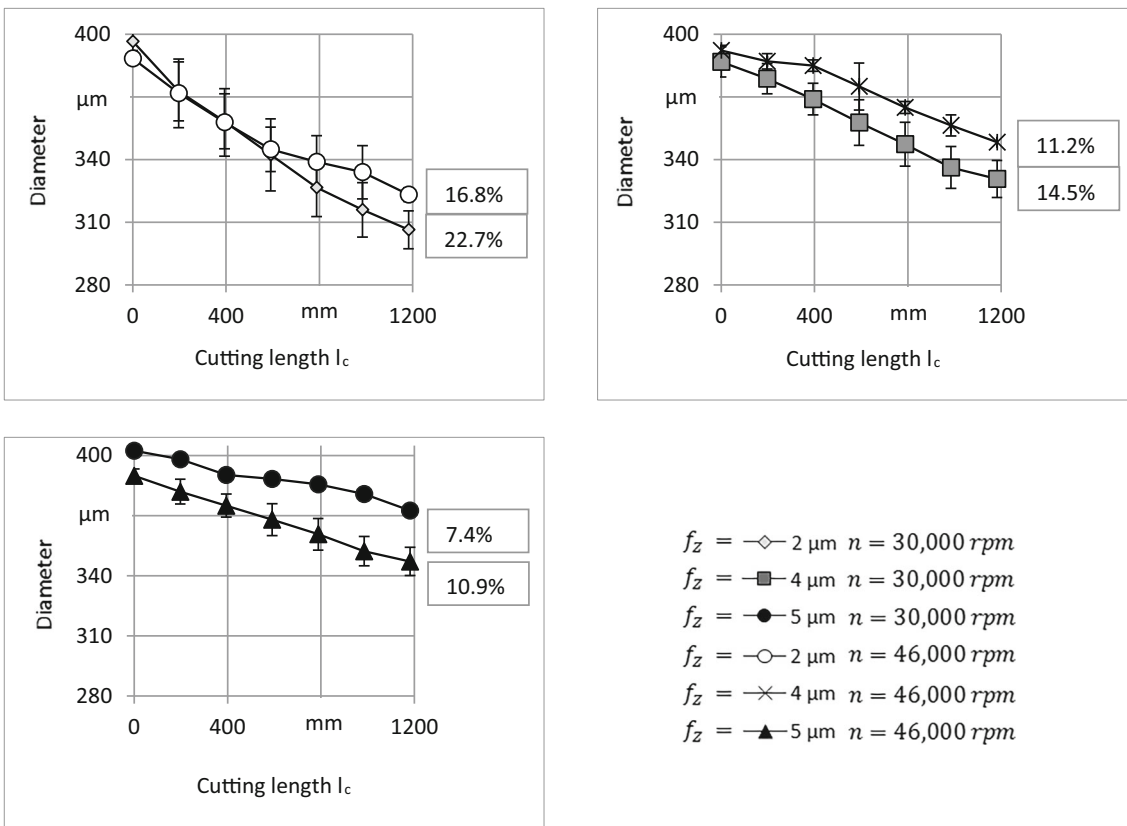$$f_z = -\blacktriangle- \; 5\,\mu m \quad n = 46{,}000\,rpm$$

Fig. 10 Effective diameter for experiments with fix feed per tooth in different levels of spindle speed and total diameter percentual reduction

The graph in Fig. 11 is used to demonstrate the interaction between two factors and the response variable. From the first graph in Fig. 11, it can be understood that the feed per tooth has the same effect in different levels of cutting length, and lower feed causes greater wear. The interaction appointed in the p value in Table 4 is due a dependency between f_z and l_c: different feeds per tooth levels can be compared only for the same cutting lengths. In Fig. 11b, it can be seen that the feed per tooth has the same effect for different levels of spindle speed, the lower the feed greater the tool wear. In the third graph, the effect of spindle speed is the same in different levels of cutting length: the lower the spindle speed, the greater the tool wear. The dependency interaction between spindle speed and cutting length also occurs but less pronounced (p value of 0.07).

Figure 12 represents the graph for the main effects. As all three variables feed per tooth f_z, spindle speed n and cutting length l_c present lines that are transversal to the x

Table 4 Analysis of variance for main and interaction effects

Source	d.f.	SS	F	P value
f_z	2	15,254.49	88.65	≈ 0.00
n	1	5622.57	65.35	≈ 0.00
l_c	6	41,349.24	80.10	≈ 0.00
$f_z : n$	2	132.78	0.77	0.47
$f_z : l_c$	12	4719.23	4.57	≈ 0.00
$n : l_c$	6	1047.16	2.03	0.07
$f_z : n : l_c$	12	168.10	0.16	1.00
Residual	71	6108.61		

Fig. 11 Interaction graph for tool wear
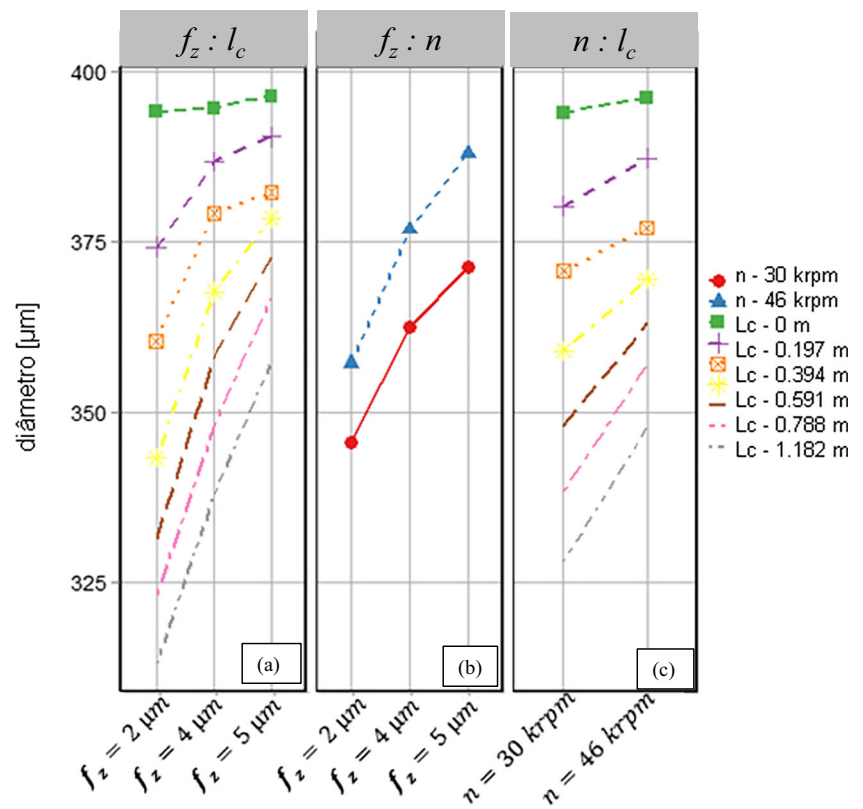
axis, it means they have a main effect, which is the same discussed before: the lower the feed per tooth f_z as well as spindle speed n, the greater the cutting length l_c, resulting in a greater tool wear.

To validate the ANOVA method, the residual analysis is presented in Fig. 13. From the residual histogram and the QQ plot (quantile-quantile plot), it can be seen that the residuals have a normal distribution. The residuals are randomly

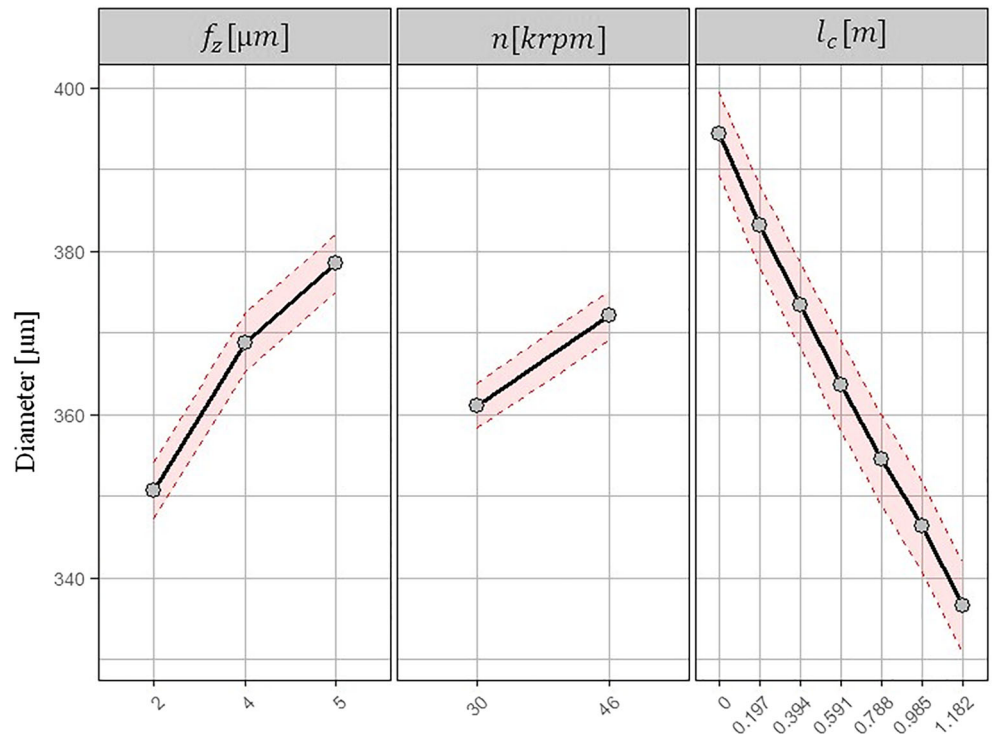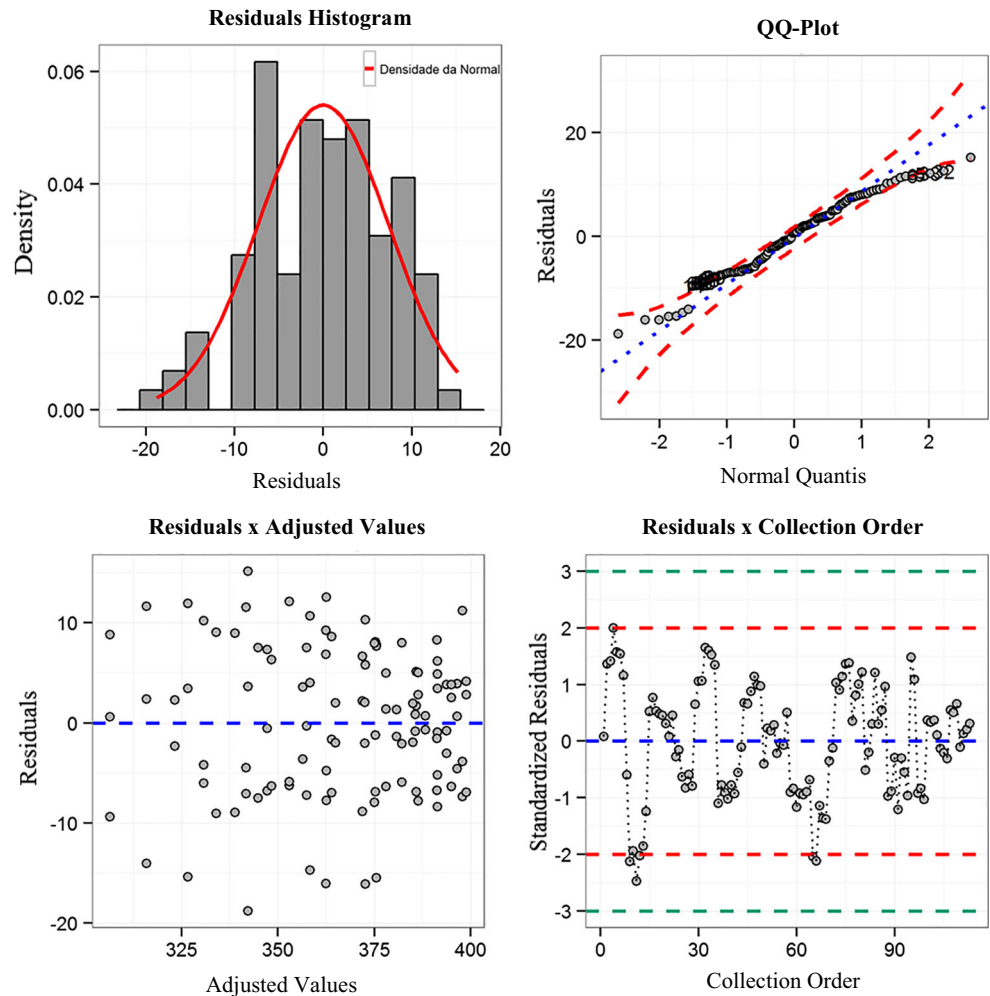**Fig. 12** Main effects for diameter reduction

Fig. 13 Residual analysis graphs

distributed around the zero in the graph "Residuals × adjusted values" attending the assumption of homoscedasticity. Also, there is no tendency on the residual distributions on the graph "Residuals × collection order" indicating residual independence.

Linear regression is used to estimate a function that can predict tool diameter reduction for the range of parameters used in this work. The variables used to build the model function are presented in Table 5.

The model established using Action Stat software is given by Eq. 1.

$$d = 9.3f_z + 0.68n - 48.3l_c + 333.6 \quad (1)$$

The coefficient of determination R^2 obtained is 83.5% indicating a good model fit. Test t was applied, and it was

verified that all coefficients are significant to the model. The p value according to the Bonferroni method calculated was 0.7552. That means that there are no outliers in the model. The analysis for influential observations was done using DFFITS, D-COOK and DFBETAS methods; no DFFITS, D-COOK or DFBETA presented an absolute value over 1 which means that there is no influential observation in the model. The model also attends the requirements for low collinearity as shown in Table 6 and multicollinearity once the VIF (variance inflation factor) found was less than 10 for all variables (f_z = 1.00, n = 1.01 and l_c=1.01). The assumptions of normality, homoscedasticity and independence of residuals were verified in the ANOVA step (Fig. 13).

Table 5 Variables for the tool wear model

Independent variable 1	f_z	Feed per tooth (μm)
Independent variable 2	n	Spindle speed (krpm)
Independent variable 3	l_c	Cutting length (m)
Dependent variable	d	Effective diameter (μm)

Table 6 Variable collinearity for the tool wear model

Variable	f_z	n	l_c
f_z	1.00	≈ 0.00	≈ 0.00
n	≈ 0.00	1.00	− 0.08
l_c	≈ 0.00	-0.08	1.00

4 Conclusions

This work shows the development and validation of tool diameter reduction modelling in the micro-end-milling of tool steel H13. A full DoE factorial design was used to build the experimental set-up. ANOVA was applied to analyze experimental data to verify the impact of the cutting parameter feed per tooth and spindle speed in tool wear and diameter reduction. The following conclusions can be drawn:

1. A new tool diameter reduction model based on effective tool diameter with three parameters, which are feed per tooth, spindle speed and cutting length, was built using linear regression and presented a coefficient of determination $R^2 = 83.5\%$. The model meets statistical requirements and can be successfully applied to predict tool wear based on diameter reduction.

2. The magnitude of the cutting parameters affecting tool wear was determined by ANOVA. It was found that the feed per tooth, spindle speed and cutting length as well as the interactions between feed per tooth and cutting length and the interactions between spindle speed and cutting length are significant over the tool wear. The tool wear was more pronounced (total diameter reduction between 16.8 and 22.7%) in the low level of feed per tooth (f_z < 2 μm) and in the low level of spindle speed (n < 30,000 rpm) in the machined channel of cutting length l_c = 1182 mm.

3. The developed approach can predict the diameter reduction that can strongly influence the channel geometry and cutting speed along the cutting length and can be useful for micro end milling which requires high surface precision and high-dimensional geometry control. Those results will be linked to studies on surface roughness and tool wear and roughness prediction algorithms.

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