

Determination of Cutting Tool Geometries with High Precise Measurement Techniques and Investigation of Their Effects on Workpiece Surface Properties

M. Numan Durakbaşı¹, Anıl Akdoğan², A. Serdar Vanlı², Aslı Günay²

¹Vienna University of Technology, Institute for Production Engineering and Laser Technology,
Department for Interchangeable Manufacturing and Industrial Metrology, Karlsplatz 13/3113, 1040 Vienna
Austria, Phone: +43 1 58801 31142 Fax: +43 1 58801 31196, e-mail: durakbasa@mail.ift.tuwien.ac.at

²Yildiz Technical University, Faculty of Mechanical Engineering, Department of Mechanical Engineering,
Istanbul, 34349, Turkey, Phone: +90 212 383 28 02 Fax: +90 212 383 30 25,
e-mail: nomak@yildiz.edu.tr, svanli@yildiz.edu.tr, günay@yildiz.edu.tr

Abstract- Cutting tool geometry including tool edge radius is not only important for determination of tool lifetime but also have a direct effect on workpiece surface characteristics. This geometry is created in manufacturing phase and changes occur in machining processes. In this regard, to indicate it precisely in different scales has vital importance. Most of the existing studies have focused on manufacturing parameters such as cutting speed, feed rate, depth of cut, tool geometry, and various coatings, to indicate effects of surface roughness of the machined part in two-dimensional. Limited number of studies searched the effects of tip radius in three dimensional. The purpose of this study is indicating the end milling tool geometries, their changes after milling processes and the following conditions after usage; as dimensional, form and surface deviations with modern precise measurement techniques and methods in 2D and as 3D. This paper studies the optimizing of process parameters and different coating materials which combined different tool radiuses to obtain the minimum R_a values for the end milling process of Al 7075 alloy.

Introduction

Quality assurance policies are used by many various companies to provide for clients high qualified products and technical support. Thus, in-process inspections should include all steps of production to meet the demands of quality management system standards [1]. Despite of recent developments, it's unknown that what causes cutting tool geometry deformations incurring by usage and not possible to precisely being estimated yet. Since the costs for cutting tools and their replacements in machining processes influenced total production costs by 3% and 12%, respectively, indicating the tool geometry accurately has vital importance to delay the tool deformations and to extend tool lifetime [2].

There are high demands on geometry variation of tools due to the technological developments especially on mould and die design industry. These high demands arise for high and ultra-high precision machining of different kinds of materials. For instance, while cutting of brittle materials in ductile mode using diamond tools, such as ductile cutting of silicon and quartz for wafer fabrication, one of the key conditions for achieving ductile chip formation is to get the right cutting edge radius of tool to the undeformed chip thickness. It has been shown that the undeformed chip thickness has to be in the order of nanometers and that the tool cutting edge radius has to be smaller than the undeformed chip thickness. Therefore, precise measurement of diamond cutting tools has become a key issue for ductile mode cutting of brittle materials [3].

As emphasized in literaturature that cutting tool tip radius changes during the machining according to the wear mechanism is still poorly understood and cannot be accurately predicted [4]. Determining significant factors which effect the tool tip radius changes is crucial for finish surface quality and life of the tool.

The precisely identification of tool geometry has a vital importance both in determination of tool life and machined material surface conditions. Tool geometry identification including edge radius determination not only gives crucial information on high precise manufacturing process but also explains the wear behavior of the tool. High precision measurement techniques are being used to determine the geometry and edge radius variations of various machining operations tools.

The purpose of this study is indicating the brand new and used end milling tool tip geometry and final workpiece surface quality by means of precise measurement techniques and methods. In addition we aimed to determine the optimal process parameters and tool radius by using design of experiment methodology.

Specially, the cutting edge radius geometry will be indicated with modern 3D dimensional methods. These geometries have significant effects on surface topography and there are limited numbers of studies on the subject matter. This work is aimed to determine at high accuracy mathematical model between the arithmetical mean surface roughness parameter (R_a) and the processing parameters by using the measuring data. The other purpose

of this work is to determine the relationship between the controllable factors and the response factor “surface roughness”.

I. Materials and Methods

In this study, it is planned to end mill the Aluminium Alloy workpieces by using 3 different coated milling tools of 3 different initial tip radiuses. Each tool has four flutes and 10 mm nominal diameter. The selected solid carbide cutting tools for experiments coated by 3 different material types by PVD technique.

Aluminium is widely using by aerospace and automotive industries with high-speed machining to manufacture parts in short processing periods to supply a large number of manufactured parts. To meet this amount of manufactured part an increased productivity is a need with an increased cutting speed and feed. In this study Al 7075 alloy blocks were used for each processing set. 27 different Al alloy blocks were sized 50×50 mm cross section and 160 mm in length. The chemical composition of the machined material is given in Table 1.

Table 1. Chemical Composition of Al 7075 Alloy

Material	Silicon	Iron	Copper	Manganese	Magnesium	Chromium	Zinc	Titanium
% wt.	0.08	0.36	1.52	0.08	2.59	0.21	5,62	0,04

The presented method in this study is an experimental design process called the Taguchi Design by which the inherent variability of materials and manufacturing processes has been taken into account at the design stage. Taguchi Design Procedure the parameter design stage has been widely using for optimization of manufacturing processes [5, 6]. The vital aim of this stage is to determine the optimal cutting conditions that yield the minimum arithmetical mean surface roughness value (R_a).

Many reviewed studies are all selected the three commonly applied machining parameters; feed rate, cutting speed and depth of cut [7-10]. For the experiments the orthogonal array L27 table is given in Table 2.

Table 2. Orthogonal Array L27 and the Results

Run	Control Factors and levels						Outputs		
	Radius (mm)	Coating Type	Cutting Speed V_c (mm/s)	Depth of Cut a_p (mm)	Feed Rate f_z (mm/tooth)	Mean R_a (μ m)	ΔR_{e0} (mm)	ΔR_{e1} (mm)	
1	1	1	1	1	1	0.581	0.034	0.024	
2	1	1	1	1	2	1.082	0.029	0.027	
3	1	1	1	1	3	0.617	0.044	0.039	
4	1	2	2	2	1	0.376	0.006	0.022	
5	1	2	2	2	2	0.355	0.033	0.025	
6	1	2	2	2	3	0.639	0.002	0.004	
7	1	3	3	3	1	0.528	0.029	0.024	
8	1	3	3	3	2	0.412	0.043	0.005	
9	1	3	3	3	3	0.648	0.033	0.029	
10	2	1	2	3	1	0.689	0.001	0.009	
11	2	1	2	3	2	1.099	0.018	0.320	
12	2	1	2	3	3	0.992	0.028	0.037	
13	2	2	3	1	1	0.487	0.005	0.018	
14	2	2	3	1	2	0.509	0.016	0.013	
15	2	2	3	1	3	0.684	0.003	0.003	
16	2	3	1	2	1	0.277	0.036	0.006	
17	2	3	1	2	2	0.340	0.012	0.019	
18	2	3	1	2	3	0.839	0.018	0.003	
19	3	1	3	2	1	0.366	0.005	0.006	
20	3	1	3	2	2	0.854	0.005	0.014	
21	3	1	3	2	3	0.758	0.010	0.011	
22	3	2	1	3	1	0.25	0.001	0.020	
23	3	2	1	3	2	0.77	0.014	0.002	
24	3	2	1	3	3	0.472	0.017	0.018	
25	3	3	2	1	1	0.271	0.014	0.017	
26	3	3	2	1	2	0.491	0.022	0.015	
27	3	3	2	1	3	0.697	0.016	0.014	

Manufacturers should test their functional geometry and wear characteristics to ensure that only the functionally capable tools are used in the production process as well as by the users. For these purposes, the initial geometrical and surface characteristics of the brand new tools are examined in both 2D and 3D in this experimental work. At the first phase of this experimental study the authors determined the tip radiuses of the brand new tools by Keyence Optical Microscope, Japan, tip radii measurements by stereomicroscope and a 3D laser scanner Zoller, Venturion 450, Germany. Then tools were processed according to the design of experiment. The tests were performed on a vertical CNC machining center, Mori Seiki, MillTap 700, Japan. The tools are with four fluted end mills of diameter 10, helix angle 30° , with different tip radiuses. DIN 6499 ER type tool holder was used for all experiments. After machining process surface roughness of machined parts were measured by the Taylor Hobson UK, Form Talysurf Intra, surface roughness profilometer, from five different locations as illustrate by Figure 1, with equal distances. Ra values were taken individually for selected end mills. Arithmetic average of absolute values of roughness profile was determined by means of Gauss filter with 0.8 mm cut off value and 4L access length. Also the used tool tip radiuses examined by the 3D laser scanner after machining process to determine the wear rate of tip radiuses.



Figure 1. Roughness measurement procedure of Al 7075 alloy workpiece

II. Results and Discussions

In this experimental research tool tip radius stability performance was wanted to be related with the workpiece final surface roughness. Therefore an experimental design was employed and all test specimen end milling tool radiuses were measured before machining and after machining for obtaining deviations from nominal geometry. By this approach changes of surface topography and tool tip geometry might be obtained more accurately. Figure 2 shows the initial tip geometry figures of the ZrN coated tools 1.0 mm and 1.5 mm nominal radiuses respectively with X50 magnification.

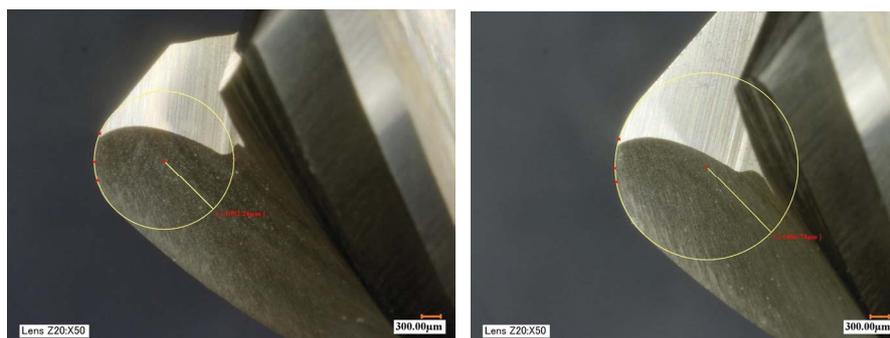


Figure 2. Optical microscope images of ZrN coated tools

To response today's high sensitive manufacturing needs, a low surface roughness of the machined work piece is an important index to evaluate cutting performance. On the basis of this the output R_a values was selected as an index to determine end milling performance.

In order to reach the objective of this experimental research, processing parameters, different coating materials and tip radiuses combined to obtain the lowest R_a values for the optimum processing parameters. Process parameters that affect the characteristics of turned parts are cutting tool parameters (tool radius and coating material) and cutting parameters (cutting speed, feed rate, depth of cut). In this research firstly important processing parameters were determined with their critical levels and then L27 orthogonal array employed for design of the experiments as given in Table 3.

Table 3. Experimental Design Factors and Their Levels

Symbol	Factor	Level 1	Level 2	Level 3
A	Radius	0.5	1.0	1.5
B	Coating	AlTiN	AlTiCN	ZrN
C	Cutting Speed	50	75	100
D	Depth of Cut	0.50	0.75	1.00
E	Feed Rate	0.05	0.10	0.15

Table 4. Results of the ANOVA for Surface Roughness

Source	Degree of Freedom	Seq SS	Adj MS	F	P	Mean S/N Ratio			Max.-Min.
						Level 1	Level 2	Level 3	
A	2	0.05669	0.02835	0.92	0.419	5.172	4.431	5.993	1.562
B	2	0.46854	0.23427	7.59	0.005	2.575	6.395	6.625	4.050
C	2	0.01027	0.00513	0.17	0.848	5.671	4.939	4.986	0.732
D	2	0.06228	0.03114	1.01	0.387	4.917	6.203	4.476	1.727
E	2	0.40359	0.20180	6.53	0.008	7.935	4.464	3.196	4.739
Error	16	0.49415	0.03088						
Total	26	1.49552							

For investigating the most effective process parameters ANOVA method was used. As seen from ANOVA table, P value indicated that coating type was the most effective parameter for the surface roughness according to the selected parameters and their levels. The adequacy of the models is provided at the 95% confidence level, $\alpha=0.05$. For obtaining significant parameters for the minimum roughness value; P values should not exceed or should be equal to α value for the contribution of that factor on the basis of given quality characteristic hypothesis. The coating parameter founded to be significant according to the P value. Also F test was employed to compare the model variance with a residual variance. To apply the F test, firstly f_{crit} was obtained. From the F distribution table, for $\alpha=0.05$, f_{crit} equals to the 3.63. F values should exceed f_{crit} for being significant according null hypothesis. The results show that feed rate seems to be significant as the coating type.

In this experimental research for optimum tip radius selection according to the optimal working parameter to achieve better surface qualities Taguchi method was used. As it is known Taguchi method provides observing results by means of fewer experimental runs. These experimental runs are limited by orthogonal arrays which means the results may not be optimal however can be optimized according to the results.

Quality characteristic for this research was the lowest surface roughness for the optimum machining conditions. According to the measurement results the minimum surface roughness obtained with the third level of radius, third level coating, first level of cutting speed, second level of depth of cut and first level of feed rate.

The average S/N ratios according to the smaller the better rule for surface roughness significant values are plotted in Figure 2 according to the Taguchi method. Tool radius was selected as the first factor to understand the effect of radius on surface roughness. These outputs suggesting that 1.5 mm radius gives the best surface roughness comparing to the 0.5 mm and 1.0 mm.

According to the ANOVA analysis the coating type was founded to be significant according to the hypothesis. Taguchi analysis show ZrN provides the best surface quality with the lowest surface roughness of the workpiece. From previous studies it is observed that the increase in the cutting speed conduce decrease for the surface quality [11,12]. Our experimental result also showed similar results as 50 mm/h gave the lowest surface roughness.

The S/N ratio graph indicates 0.75 mm depth of cut gave the best surface roughness. This value also changes according to the tool radius. Because of geometrical conditions the depth of cut has a vital importance for the cutting procedure. This is strongly effective on the cutting forces on the tool and also effects thermal changes during the machining. For instance in this experimental research 0.75 mm depth of cut resulted the best roughness value with the cutting tool that has a tip radius of 1.0 mm. Depth of cut also effects chip flow angle which is crucial for heat dissipation and cutting pressures. Thus controlling depth of cut is effective on surface quality and tool lifetime [13-15].

In the literature decreasing the feed rate increases the surface roughness value [16,17]. The Taguchi analysis also validated the results that the lowest feed rate gave the lowest surface roughness (Figure 3).

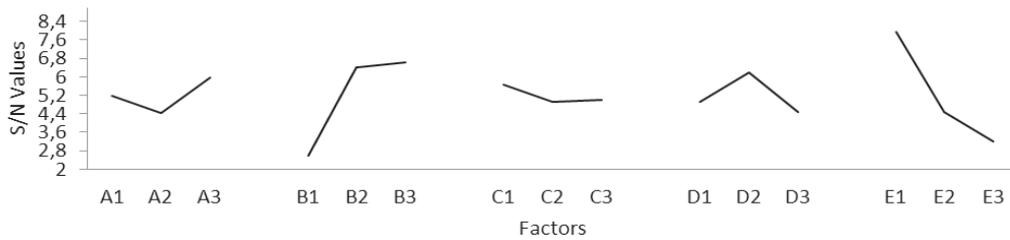


Figure 3. The Smaller the Better S/N graph for Surface Roughness

According to the Taguchi analysis the best tip radius resulted as 1.5 mm radius. In this research initial tip radius and the final tip radiuses also measured by means of a stereo microscope and the laser scanner according to the nominal values of the tip radius. The differences of tool tip radiuses from their nominal values are given in the Table 1. As mentioned before, determining the relation between tip radius wear and surface roughness according to the processing parameters and tool geometrical characteristics was the aim of this experimental study. From the Taguchi analysis 1.5 mm tip radius resulted the lowest surface roughness. After this determination regression analysis was employed to understand the relation between selected parameters and surface roughness change. Mathematic models for the Ra are shown as followed;

$$R_a = 0.05540 - 1.88253 \Delta r_{e0} - 28.05360 \Delta r_{e1} + 0.00024 V_c + 0.50330 a_p + 5.59793 f_z \quad (1)$$

For the regression analysis indicator variable were chosen for the undeformed tip radius r_{e0} , deformed tip radius r_{e1} , cutting speed, depth of cut and feed rate respectively. Here undeformed tip radiuses were measured before beginning machining process. Deformed tip radiuses were measured after machining process. As Eq. (1) indicated, the model incorporates the effect of tip radiuses, coating type, cutting speed, feed rate on surface roughness of work piece. The best tip radius 1.5 mm with the best coating type, ZrN, was selected for the regression modelling according to the Taguchi results. Thus the equation didn't contain these factors as indicators. The Eq. (1) indicates that the model incorporates the effect of tip radiuses with cutting speed, depth of cut and feed rate on surface roughness.

Tip radius changes, Δr_{e1} , during the machining procedure were also found to be an important parameter according to the Taguchi method. As the tip radius increased the surface quality increased in cooperation with depth of cut values. As the feed rate decreased surface quality increased, feed rate was founded to be most effective parameter after the coating type for a good surface quality. According to these observations, regression method was used to determine a mathematical model. In the regression analysis the best tool tip radius, 1.5 mm, with the best coating type, ZrN, was employed. Proportion of total variability in the Δ deviation that can be explained by Eq. (2) is;

$$R^2 = SS_{Model} / SS_{Total} = 0.9322 \quad (2)$$

Here the SS is the abbreviation of "sum of squares" for the model and the total. For the regression method R_a value was selected as response and tip radius, coating, cutting speed, depth of cut, feed rate were the controllable factors. Tip radiuses were measured by the laser scanner at each step. These results were added to the regression methods as the first and the second factors.

Additional to the statistical descriptions of the regression models accuracy, experimental confirmation tests were necessary according to the Taguchi results.

Table 5. Confirmation Tests Results

Control Factors and Levels				Roughness Values (μm)			
Radius (mm)	Cutting Speed (mm/s)	Depth of Cut (mm)	Feed Rate (mm/tooth)	Exp.1	Exp. 2	Exp.3	Predicted
1.5	50	0.75	0.05	0.269	0.262	0.196	0.283

After the optimal level of the processing parameters and tool tip radius were determined, verifying these levels of the optimal parameters with tool radius tip was used. Three repetitive machining processes were applied. Afterwards repetitive measurements taken from work piece and the results are indicated in Table 5. It compares the results of the confirmation experiments using the optimal processing parameters obtained by the proposed method. The accuracy of the comparisons was convenient to the results. The experimentally obtained results of surface roughness were comparable to the predicted values. The accuracy of the comparisons was very fine and the values measured in each experiment were very well predicted by the appropriate for the optimal processing parameters and tool characteristics.

V. Conclusion

This paper studies the optimizing processing parameters and different coating materials which combined different tool radiuses to obtain the minimum R_a values for the end milling process of Al 7075 alloy. According to the Taguchi method, ANOVA and regression models and confirmation tests of optimal parameters and the tip radius were determined by means of the high precise measurement results.

In this research, tip radiuses of tools were measured before machining and the deviations from nominal geometry was obtained. Experimental results and the regression model confirmed that the increased deformation of tip radiuses degreased the surface quality of the machined workpiece. Also regression model indicate the relation between the tip radius changes and the final surface roughness of the work piece in Eq. 1. According to the proposed optimization method, 1.5 mm tip radius with optimal processing parameter combination which was the minimum cutting speed, 0.75 mm depth of cut and the minimum feed rate among the selected values are expected to give the lowest surface roughness for Al 7075 alloy. The confirmation tests were applied to validate this approach and the mathematical model. After machining procedure the workpiece roughness and tool tip radius inspected with same measurement conditions and the results validated the model. Considerably better surface roughness values were obtained. Additionally, in this experimental research, a relation between work piece surface roughness and cutting tool tip radius was indicated according to the experimental runs. It is observed that, cutting tool radius change in other words tip radius deformation founded to be a crucial parameter besides feed rate, depth of cut and cutting speed. This observation provides an insight into the relation between the wear mechanism of the tools and the surface quality of the workpiece according to the processing parameters for further works.

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