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A STUDY OF OPTIMIZATION OF MACHINING CONDITIONS IN MICRO END-MILLING BY USING RESPONSE SURFACE DESIGN

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ABSTRACT
In cases of end-milling removal rate, depth of cut, cutting velocity and feedrate were taken into account as important factors affecting machining quality, tool fracture, tool wear and so on. Generally cutting conditions were determined on the basis of field experiences and many researches about cutting force acquisition by using dynamometer and tool shape design have been actively achieved, however quantitative data of the important influential factors for cutting conditions cannot be actually suggested. In this study axial depth of cut and radial depth of cut were taken into account as design factors among cutting conditions such as spindle RPM, feedrate, axial depth of cut and radial depth of cut by using a 3-axis micro machining system. Choosing width of machining errors as a criterion for machining quality, an approximate model was established by using "Response Surface Design". A relationship between design factors and response values was realized and cutting conditions of micro end-milling processes were optimized by using an optimization program called VisualDOC.

Keywords: Central composite design; Cutting conditions; Micro end-milling; Optimization; Response surface design

1. INTRODUCTION
Recently micro end-milling processes widely used in industrial fields and various useful cutting tools have been developed to manufacture various shapes of models. The need for such processes and tools is growing day by day. The micro end milling processes were also applied to high-precision and high-efficient cutting processes along with rapid progress of and advances in mechanical and material industries. The one of micro/nano machining technologies, the micro end-milling process allows us to manufacture materials in micro- and meso-scale which cannot be handled by other MEMS processes as well as very complicated modeling shapes. In cases of end-milling removal rate, depth of cut, cutting velocity and feedrate were taken into account as important factors affecting machining quality, tool fracture, tool wear and so on. Generally cutting conditions were determined on the basis of field experiences and many researches about cutting force acquisition by using dynamometer and tool shape design have been actively achieved. However, quantitative data about important influential factors for cutting conditions cannot be actually suggested.

In this study axial depth of cut and radial depth of cut were taken into account as design factors among cutting conditions such as spindle RPM, feedrate, axial depth of cut and radial depth of cut by using a 3-axis micro machining system. Choosing width of machining errors as a criterion for machining quality and central composite design, as one of the experimental design methods, an approximate model was established by using "Response Surface Design".

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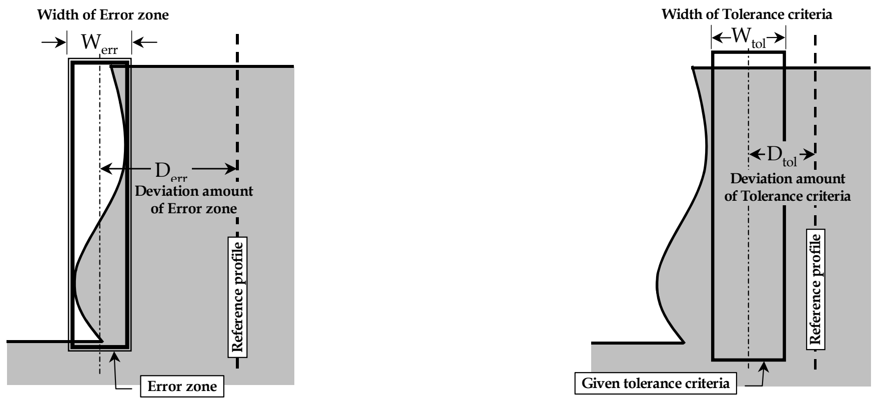
Therefore, a relationship between design factors and response values was realized and cutting conditions of micro end-milling processes were optimized by using an optimization program called VisualDOC. It is expected that the proposed approach could be a methodology providing certain information of cutting conditions for micro end-milling processes.

2. RESEARCH BACKGROUND

2.1. Micro end-milling process

Micro end-milling process phenomenon is generally different from conventional end-milling because the size of micro cutting tools is significantly smaller in respect to all other components of cutting processes (Wang, et al., 2008; Cheng, et al., 2010). This can become an important factor for selecting research methods about micro end-milling. However both cutting processes and the size of tools cannot be analytically described just by using experimental methodologies. Moreover it is possible to use the same method for analysis of machining errors. The machining errors appear throughout in various forms and it is necessary to characterize the machining errors in order to analyze the outcome. Generally, machined surface shape is not the same as deflected tool shape because of the rotating and feeding motion of the tool. Under the same cutting conditions, the cutting forces vary according to the rotational position of the tool. It means that the deflection amount also varies according to angular position of the tool. Therefore, the machined surface forms are differently generated as compared to the deflected tool form.



(a) Characterization of error zone (b) Characterization of tolerance criteria

Figure 1 Characteristic parameters of surface error and tolerance

Figure 1 illustrates the machined surface generation steps considering tool deflection effects as the tool rotates. Since the surface errors are not uniformly distributed on the machined surface, it is necessary to characterize the errors in order to compare them with the given tolerance criteria. In the surface prediction process for error compensation according to the tolerance criteria, two extreme errors can be taken into account as the predominant factors regardless of the surface morphology. This means that it is inevitable to focus on the error interval and deviation amount rather than the precise surface shape. First, “maximal error Emax” and “minimal error Emin” are defined to quantitatively analyze the surface error distribution.

The maximal error Emax is the largest algebraic error on the milled surface with respect to a given coordinate on the desired profile. If this error leads to an undercut with respect to the desired profile, Emax has positive values. Contrarily, if it leads to an overcut, Emax has negative values. Similarly, minimal error Emin is the smallest algebraic error on the milled surface with respect to a given coordinate on the desired profile. If this error leads to an undercut with respect to the desired profile, Emin has positive values. Contrarily, if it leads to an overcut, Emin has negative values. Based on these two extreme errors Emax and Emin, the "error zone" is defined to characterize the distributed surface errors as shown in Figure 1(a). Under the deflection effects, this error zone deviates from reference profile. To analyze the error zone, it is necessary to define two characteristic parameters: "width of error zone Werr" and "deviation amount of error zone Derr". In fact, these parameters cannot represent all geometrical information of the machined surface shapes. However, these make it possible to effectively analyze the deflection effects on the machined surfaces because it is not necessary to recognize the precise surface shape in order to compare it with the tolerance criteria. These characteristic parameters are derived as follows:

$$Werr = \frac{Emax + Emin}{2}; \quad \text{and} \quad Derr = Emin + \frac{Werr}{2} \tag{1}$$

In this case, given manufacturing tolerances are investigated. Generally, the tolerance zone is decided by two surfaces enveloping the spheres of diameter Wtol, while the centers of the spheres are located on a desired surface. According to circumstances, this desired surface is not coincidental with the reference surface of the tolerance. It is obvious that the machined surfaces have to be in close vicinity to the desired surface in order to fulfill the tolerance. Similarly to represent the tolerance parameters of the characterized surface error parameters Werr and Derr, "width of tolerance criteria Wtol" and "deviation amount of tolerance criteria Dtol" are defined. Here, Wtol represents the diameter of the sphere defining the tolerances as mentioned and Dtol represents the distance between the desired surface and the reference surface. The approach mentioned above was developed by the authors for conventional machining processes. This allows compensating for machining errors through comparison between errors and tolerances. Additionally, this concept could be taken into account for micro cutting process.

2.2. Design of experiment central composite design

In general usage, design of experiments (DOE) or experimental design is the design of any information-gathering exercise where variation is present, whether under the full control of the experimenter or not. However, in statistics, these terms are usually used for controlled experiments. Other types of study and their design, are discussed in the articles on opinion polls and statistical surveys which are types of observational study, natural experiments and quasi-experiments, for example, specifically quasi-experimental design (VisualDOC Theory Manual, 2010).

In the design of experiments, the experimenter is often interested in the effect of some process or intervention (the "treatment") on some objects (the "experimental units"), which may be people, parts of people, groups of people, plants, animals, materials, etc. Design of experiments is thus a discipline that has very broad application across all the natural and social sciences (Hang et al., 2011; Oktem et al., 2005; Aslan, 2008; Vitanov, 2010). In statistics, a central composite design is an experimental design, useful in response surface methodology, for building a second order quadratic model for the response variable without needing to use a complete three-level factorial experiment. After the designed experiment is performed, linear regression is used, sometimes iteratively, to obtain results. Coded variables are often used when constructing this design.

For an optimization of cutting conditions or a prediction of cutting force in micro end-milling experiments numerous tests are required. In order to effectively accomplish researches based on experimental data, it is necessary to reduce the number of tests. In this paper, the central composite design method was used as the experimental design.

2.3. Response surface design

If there are relatively few design variables (30 or less) and the cost of analyzing a single design is high, the response surface approximate optimization method may prove to be the most efficient approach to optimization. Also, if a number of designs was previously analyzed and the corresponding response values were known, these methods may be an ideal way to perform optimization employing already obtained results and with just a few additional analysis calls. The basic idea of response surface approximate optimization is to create explicit approximation functions for the objective and constraints, and then use these when performing the optimization. The approximation functions are typically in the form of low-order polynomials (linear or quadratic) fit by least squares regression analysis. Once approximations have been constructed, they may be used as cheap function evaluators, replacing the underlying computationally expensive analysis tools. Practical engineering analysis is often encumbered with noisy behavior of responses. While noise in data from laboratory experiments is a generally accepted fact, the presence of noise in numerical simulations seems much less recognized.

However, some degree of numerical noise, associated with, for instance, round-off errors, incomplete convergence of iterative processes, and/or discretization itself, is inevitable. In direct gradient-based optimization methods, noisy responses may cause the search algorithm to get caught in a spurious local optimum. In contrast, response surface, approximate optimization is much more robust towards noise and thus enjoys higher success rates. It is important to notice, that the method's robustness only results when using more design points than the actual minimum required to perform a least squares fit of the response model coefficients. Response surface approximate optimization will deliver an optimum solution faster than the direct gradient-based methods in terms of number of performed analyses for the majority of problems. The trade-off is that the optimum is identified with less accuracy. The response surface approximate optimization process may be additionally sped up through implementation of parallel/distributed computing schemes, which can be accomplished in an efficient manner. Moreover, response surface models provide the designer with a global view of the design space, as these are typically mid-range to global approximations rather than local ones. This view includes useful insight into the relative significance and correlation of the individual design parameters. Finally, response surfaces are constructed based on response values only, and thus it is not necessary to compute design sensitivities. This is attractive in cases where these sensitivities are either costly or difficult to obtain. This is one reason because a response surface, approximate optimization process was widely used in various fields of engineering (Osborne, et al., 1997; Koyamada, et al., 2004; Tang, et al., 2010; Natarajan, et al., 2011).

3. EXPERIMENTAL WORKS

3.1. Micro machining system and measuring machine

For experimental works of the micro end-milling process, a micro machining stage was established as shown in Figure 2, which has 3-axis of degree of freedom (X-, Y-, Z-axis) and can be controlled in sub-micro unit. The specification is depicted in Table 1.

The control resolution of micro machining stage corresponds to 0.1μm and each axis can be controlled in a sub-micro unit. A high speed spindle was used in experimental works. This spindle consists of air-bearings, AC Motor and an inverter allows rotating until 100,000 rpm.
The air-bearing means that the spindle cannot generate sufficient torque when tool diameter is relatively large; however the air-bearing allows rotating in high speed and micro end-milling processes that do not need large torque for cutting when using micro end-mills less than 1mm in tool diameter. Moreover, the air-bearing system can relieve tool vibration or chatter.

Figure 2 Micro machining system

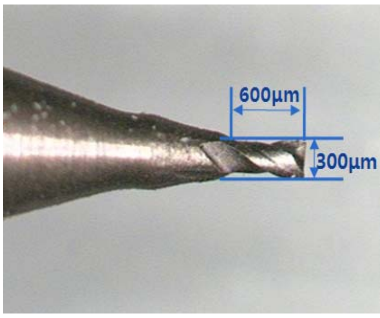


Figure 3 Micro end-mill

Figure 4 Non-contacting optical profiler

Table 1 Specification of micro machining system

Traveling Range	X, Y, Z-axis : 600×600×200mm
Resolution	X, Y, Z-axis : 0.1 μm
Accuracy	X, Y-axis : 10 μm, Z-axis : 5μm
Repeat-ability	X, Y, Z-axis : 0.2 μm
Max. Velocity	X, Y-axis : 200mm/s, Z-axis : 100mm/s
Rotational Speed	Max. 100,000rpm
Spindle Run-out	Max. 0.6 μm
Static Radial Load	Min. 6 kgf
Workpiece Weight	Max. 45 kgf
Lubrication	Dry Cutting

In fact the micro machining system is supported by independently controlled four isolators in order to avoid vibrations. More information about the micro machining system is depicted in Table 1. In experimental works two end-mills were mainly used. The end-mills of 1mm diameter were used for roughing and the end-mills of 0.3mm diameter were used as shown Figure 3. For measuring machining errors on the machined surfaces, a non-contact optical profiler was used as shown in Figure 4 and the specification is depicted in Table 2.

Table 2 Specification of non-contacting optical profiler

Measurement Capability	tree-dimensional, non-contact, surface, profile, measurements
Objectives	2.5× ; 10× ; 50×
Measurement Array	user-selectable, maximum array 736×480
FOV	1× ; 2×
Vertical Measurement Range	0.1nm to 1nm
Vertical Resolution	<1Å Ra
RMS Repeatability	0.01nm
Scan Speed	up to 7.2um.sec
Field of View (mm×mm)	2.5×1.9 ; 1.2×0.9 ; 0.6×0.4 ; 0.3×0.2 ; 0.13×0.1 ; 0.06×0.05

3.2. Experimental conditions and methods

To consider radial depth of cut and axial depth of cut as experimental factors are determined, several poles were made before actual cutting processes and reference surfaces were fabricated on the side of these poles as shown Figure 5.

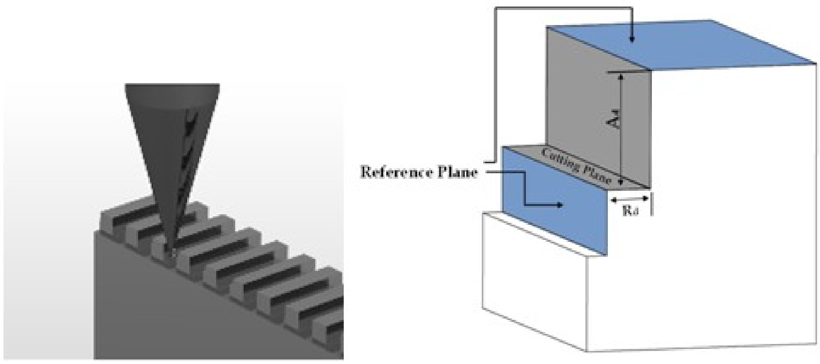


Figure 5 Pre-cutting specimen and reference surface

When cutting the reference surfaces, the most suitable feedrate and depth of cut were chosen in order to minimize the machining errors because the reference surface would become an origin for measuring machining errors. Table 3 shows experimental conditions of cutting processes and Table 4 shows chosen radial depth of cut Rd and axial depth of cut Ad in to order to apply central composite design method and response surface approximation.

Table 3 Cutting experiment conditions(1)

Micro Cutting Shape	Side Cutting
Feedrate (mm/min)	200
Tool	Φ0.3 2 Flute Flat End-mill
Workpiece	STAVAX
Cutting Speed	40,000(RPM)
Cutting Mode	Up Milling

Table 4 Cutting experiment conditions(2)

Ad / Rd		X_1				
		200	225	250	275	300
X_2	10			*		
	30		*		*	
	50	*		*		*
	70		*		*	
	90			*		

4. DISCUSSION

For obtaining 9 points of tests as shown in Table 4, 9 tests were carried out under given conditions and machined profiles were measured on the machined surfaces by using the non-contact optical profiler. Figure 6, 7 and 8 show one of this measured results. Figure 6 shows dimensional interactive display, Figure 7 shows -64.26μm of the height at X=0.82μm and Y=275μm when Ad=275μm and Rd=70μm and Figure 8 shows side cutting profile when Ad=275μm and Rd=70μm. For each of 9 tests the same measuring processes were accomplished and calculation processes were conducted in order to determine the values of Werr for 9 test points.

To determine response surface approximate function there are 5 methods; (1) linear, (2) linear interaction, (3) linear quadratic, (4) full quadratic and (5) forward stepwise regression. Among them the linear quadratic approximation could minimize the errors of approximate function so that the absolute values of studentized residual data should remain under 3.

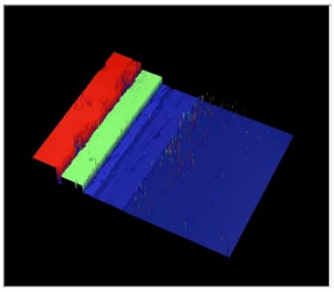


Figure 6 Dimensional interactive display

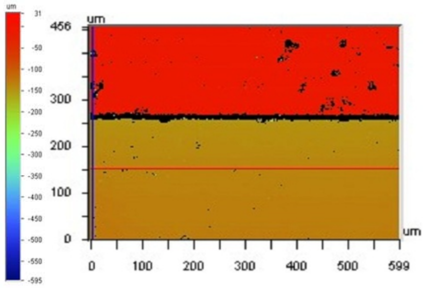


Figure 7 Surface data (Ad=275μm, Rd=70μm)

Figure 8 Side cutting profile (Ad=275μm, Rd=70μm)

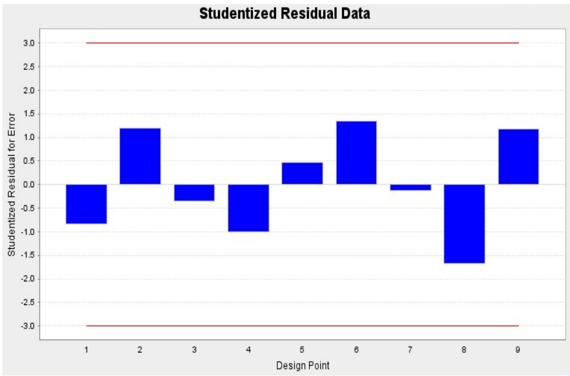


Figure 9 Analysis of variance standard residual

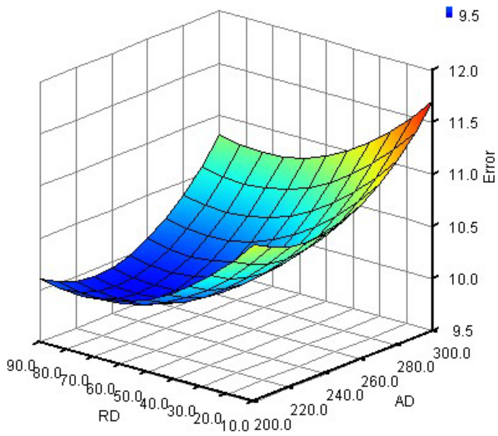


Figure 10 Response surface profile

This function is depicted below:

$$W_{err} = 0.00017\,X_1^{\,2} + 0.00023\,X_2^{\,2} - 0.0863\,X_1 - 0.0342\,X_2 + 21.13 \qquad (2)$$

where X_1 = Rd and X_2 = Ad. This function was used to create response surface and Table 5 and 6 show optimum process conditions using response surface approximation.

The values of axial depth of cut Ad were chosen in the 200~300 μm range and the values of radial depth of cut Rd were chosen in the 10~90 μm range. After determining optimized micro end-milling conditions with the values chosen, Ad = 227, Rd = 74 and Werr = 10.1 were obtained as optimal conditions.

Table 5 Optimum process condition(1)

Name	Type	Lower Bound	Value	Upper Bound
Ad	IDVar	200.000	227.1052	300.0000
Rd	IDVar	10.00000	74.13036	90.00000

Table 6 Optimum process condition(2)

Name	Type	Target Value	Worst Value	DVar/Response Value	Objective Value
Error	IResp	minimize	10.30	10.06648	10.06648

5. CONCLUSION

In order to obtain optimal cutting conditions for micro end-milling, axial depth of cut Ad and radial depth of cut Rd were taken into account as design factors among cutting conditions such as spindle RPM, feedrate, axial depth of cut and radial depth of cut by using a 3-axis micro machining system. Choosing width of machining errors as a criterion for machining quality, an approximate model was established by using "Response Surface Design", a relationship between design factors and response values was realized and cutting conditions of micro end-milling processes were optimized by using an optimization program called VisualDOC. Nine tests were thoroughly conducted at design points determined by using central composite design method. The values of axial depth of cut Ad were chosen in the 200~300 μm range and the values of radial depth of cut Rd were chosen in the 10~90 μm range. After determining optimized micro end-milling conditions with the values chosen, Ad = 227, Rd = 74 and the response value Werr = 10.1 were obtained as optimal conditions.

6. ACKNOWLEDGEMENT

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