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THE DESIGN MODEL OF MICRO END-MILLS MADE BY USING THE FINITE ELEMENT METHOD

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Summary

The green processing technology has been brought to the focus of attention around the world. The development and application of green cutting depend on the machine and cutting tool technology progress, in so far as the development of cutting tool technology has quite a big influence. The study was focused on the simulation analysis model for micro milling SKD61 tool steel developed by the finite element method. First, because the impact of the effective rake angle on the oblique cutting model is equivalent to that of the rake angle on the orthogonal cut model, the complex tool geometry of an end-mill will be simplified to the orthogonal cutting model. Using the Taguchi method, the FEM simulation of orthogonal cutting operation was performed under different cutting speeds, cutting depths, effective rake angles and relief angles were modified. The cutting force, tool maximum temperature, tool maximum temperature and tip distance, and the contact length of tool and chip are the major performance indexes of micro milling process. Finally, the multiple cutting performance characteristic resulting from the grey relational analysis reveals that the influencing priority ranks for micro end-mills made of SKD61 tool steel are cutting speed, effective rake angle, relief angle, and cutting depth. The FEM model is suitable for simulating the cutting performance of micro cutting process, and can also be used as a design base for micro end-mills.

Key words: *micro end-mill, finite element analysis, grey relation analysis*

1. INTRODUCTION

Along with the development of semi-conductor and micro-system technologies, a large number of computers and consumer electronics products will be demanded for performances of high capacity and more functions. The requirements of parts will therefore have the tendency towards ultra-precision and miniaturization. Accordingly, the development and preference of micro-mould will be the main stream in the future. The conventional miniature products and new micro component devices are widely used. The new products will be reduced in their weight as far as possible, e.g. mobile phone and shell of notebook, to satisfy the demand for light, thin, and short products.

Therefore, aluminium alloys, magnesium alloys and titanium alloys and other light alloys are more widely used in die-casting and the mould material is mostly based on the SKD61 mould steels. Micro-milling can be employed for the production of micro components and has the processing flexibility with respect to different workpiece dimensions, shape, features and variety of materials. Yet, the micro-milling of steel is the key method of selection for the manufacture of micro-dies made of hardened mould steels. For micro-die surface finish, high accuracy and minimal burr size become essential product attributes. To satisfy these performance requirements, the selection of optimum cutting conditions is very important.

Researches into conventional cutting are involved in the investigation into the cutting process by using an experimental cutting method. Although results obtained by experimental cutting methods used to study the cutting process are close to real cuttinmg data, the experimental method has disadvantages in that it is time-consuming and very costly. Due to the emphasis on efficiency and applicability, this method is even more unsuitable nowadays. Therefore, faster, simpler and more applicable experimental methods must be developed to substitute the conventional cutting research methods.

In the past few years, many researchers have studied micro-milling and have used the finite element method to analyze the cutting process. Filiz et al. [1] investigated the micro-machinability of copper 101 by using tungsten carbide micro end-mills. Aramcharoen et al. [2, 3] investigated the dimensional effect and tool geometry in the micro-milling of tool steel. Two-flute micro flat end-mills of ultra-fine tungsten carbide micro-grain structure were used in the micro-milling of ANSI H13 tool steel. The diameter of the micro flat end-mills was 900μm. The cutting parameters include cutting feed, spindle speed, depth of cut, and the ratio of undeformed chip thickness to the tool edge radius. Ceretti et al. [4] applied DEFORM 2D to simulate a plane strain cutting process. Simulation parameters such as cutting speed, rake angles and cutting depth have been investigated. Finally, the influence of the chip flow, cutting forces, temperatures and tool wear on the cutting tool has been analyzed. Guo and Yen [5] proposed to use the FEM software for the simulation of mechanisms of discontinuous chip formation in hard machining. Qian and Hossan [6] presented the AdvantEdge software applied for the simulation of turning hardened tool steels with cubic boron nitride inserts. In the simulations, properties representative of AISI 52100 bearing steel, AISI H13 hot work tool steel, AISI D2 cold work steel, and AISI 4340 low alloy steel were assumed for the workpiece. Although a large number of investigations have been performed to analyze the cutting process [7, 8, 9, 10], few can be found about the multiple performance characteristic of micro-milling. Solving this problem and establishing a simple and effective solution remains an important issue.

In this study, a simulation analysis model for the micro milling of SKD61 mould steel has been developed by the finite element package software DEFORM. The process of chip formation can be understood by simulating it. Orthogonal Arrays are used for the experiment scheme of micro milling simulation. The influence of various parameters, such as cutting speed, cutting depth, effective rake angles, and relief angles, has been investigated. The cutting force, tool maximum temperature, tool maximum temperature and tip distance, and the contact length of tool and chip are the major performance indexes of micro milling process. This is the issue of multiple quality characteristics. The grey relation grade is concerned with the conversion from multiple quality characteristics to a single performance index by applying the grey relation analysis. The optimal processing parameters are evaluated by the Taguchi parameter design method.

2. ANALYSIS METHOD

2.1. Effective rake angle [11]

In order to determine the effective rake angle α_e for any tool with inclination, it is necessary to identify the direction the chip takes as it crosses the tool face. This is most effectively specified by the angle η_c between the chip-flow direction and the normal to the cutting edge in the plane of the tool face shown in Figure 1. Stabler [12] has shown that the effective rake angle α_e can be determined when the angle η_c is known:

$$\sin\alpha_e = \sin\eta_c \sin i + \cos\eta_c \cos\iota \sin\alpha_n \tag{1}$$

It is evident from Figure 2 that equation (2) will be satisfied for any arbitrary chip-flow direction η_c

$$\cos\eta_c = \frac{b_c}{b/\cos i} \tag{2}$$

where b_c is the width of the chip; b is the width of the workpiece. Thus the chip flow direction η_c may be determined simply from measurements of the width of chips and workpieces.

Stabler [12] indicated that the angle η_c was approximately equal to the inclination angle i for a variety of tool and workpiece materials, rake angles and speeds. From equation (2) it is evident that the chip width bc will be the same as the workpiece width b, when η_c is equal to i. Thus, it simply means that the chip will take a direction relative to the cutting edge such that there is no change in width as the metal crosses the cutting edge. If the side flow is neglected, $b_c=b$ is not only a good approximation in orthogonal cutting. It also represents the first approximation for a tool having inclination. When equation (1) is simplified by equation (2) when b_c is equal to b, equation (3) is obtained.

$$\sin\alpha_e = \sin^2 i + \cos^2 i \sin\alpha_n \tag{3}$$

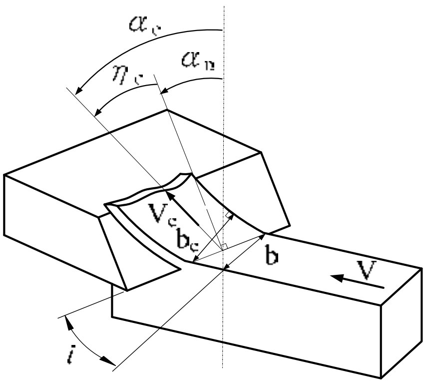

Fig. 1 Oblique cut with inclination angle

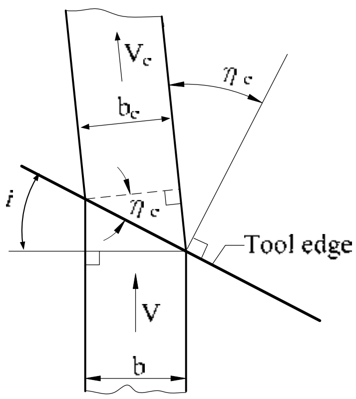

Fig. 2 Plan view of oblique cutting tool

2.2. Grey relational analysis

The grey relational analysis initially generates data pre-processing to normalize the raw data. Here, the experimental result is linearly normalized in the range between 0 and 1, which is also called grey-relational generating [13]. Then, it has a characteristic of the "lower-the-better" if the target value of original sequence is infinite. The original sequence can be normalized as follows:

$$x_i^*(k) = \frac{\max x_i^0(k) - x_i^0(k)}{\max x_i^0(k) - \min x_i^0(k)} \tag{4}$$

where i=1,…,m; k=1,…,n. m is the number of experimental data items and n is the number of parameters, with m=9 and n=2 in this study. $x_i^0(k)$ denotes the original sequence, $x_i^*(k)$ denotes the sequence after the data pre-processing, $\max x_i^0(k)$ denotes the largest value of $x_i^0(k)$, $\min x_i^0(k)$ denotes the smallest value of $x_i^0(k)$, and x_0 is the desired value.

When the "higher-the-better" is a characteristic of the original sequence, the original sequence should be normalized as follows:

$$x_i^*(k)=\frac{x_i^0(k)-\min x_i^0(k)}{\max x_i^0(k)-\min x_i^0(k)} \tag{5}$$

In grey relational analysis, the measure of relevancy between two systems or two sequences is defined as the grey relational grade. When only one sequence, $x_0(k)$, is available as the reference sequence and all other sequences serve as comparison sequences, it is called a local grey relation measurement. After data pre-processing is carried out, the grey relation coefficient $\zeta_i(k)$ for the k performance characteristics in the i experiment can be expressed as follows:

$$\zeta_i(k)=\frac{\Delta_{\min}+\zeta\Delta_{\max}}{\Delta_{oi}(k)+\zeta\Delta_{\max}} \tag{6}$$

where Δ_{oi} is the deviation sequence of the reference sequence and the comparability sequence.

$$\Delta_{oi}(k)=\left\|x_0^*(k)-x_i^*(k)\right\| \tag{7}$$

$$\Delta_{\min}=\min_{\forall j\in i}\min_{\forall k}\left\|x_0^*(k)-x_i^*(k)\right\| \tag{8}$$

$$\Delta_{\max}=\max_{\forall j\in i}\max_{\forall k}\left\|x_0^*(k)-x_i^*(k)\right\| \tag{9}$$

$x_0^*(k)$ denotes the reference sequence and $x_i^*(k)$ denotes the comparability sequence. ζ is the distinguishing coefficient, $\zeta\in[0,1]$. ζ is set as 0.5 in this study.

The grey relational grade is the weighted sum of grey relational coefficients. It is defined as follows:

$$\gamma_i=\sum_{k=1}^{n}\beta_k\zeta_i(k) \quad \sum_{k=1}^{n}\beta_k=1 \tag{10}$$

where β_k represents the weighting value of the kth performance characteristic. The grey relational grade γ_i represents the level of correlation between the reference sequence and the comparability sequence.

3. THE CUSTOMIZED FEM MODEL

3.1. Process definition

The helical cutter edge of micro end-mill is divided into an infinite number of single cutting edges, and it will be the orthogonal cutting model for finite element analysis. The simulation analysis model for micro milling SKD61 mould steel has been developed by the finite element package software DEFORM. The cutting process is modelled as orthogonal with the plane strain deformation shown in Figure 3. The step increment is defined so to cut 0.0001 mm in 2000 steps. The parameters of the workpiece and the tool are listed in Table 1. The workpiece and the tool are characterized by non-uniform mesh distributions, as show in Figure 4. Very small elements are required in the contact area between the tool and the workpiece because of very large temperature gradients that will develop in this region and because of the need to minimize the loss of volume during the simulation.

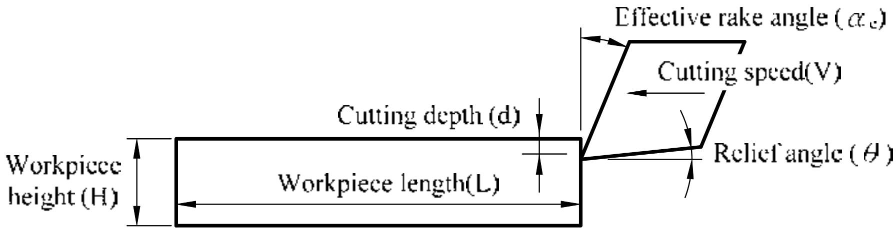

Fig. 3 Schematic of orthogonal cutting conditions for simulations

Table 1 Features of the defined objects

Parameter	Workpiece	Tool
Model for the object	Plastic	Rigid
Geometry	Length =1mm Height =0.15m	Effective rake angle $=\alpha_e$ Relief angle=θ Tool Tip Radius=0.001mm
Material	SKD 61 (ANSI H13)	WC
Number of elements	10000	6000
Thermal Properties: Specific Heat Capacity Thermal Conductivity Young's modulus Poisson's ratio	 460(J/kg-°C) 28.7 (W/m-K) 210 (GPa) 0.3	 650(GPa) 0.25
Constant Friction	m=0.5	m=0.5
Initial Temperature	20°C	20°C

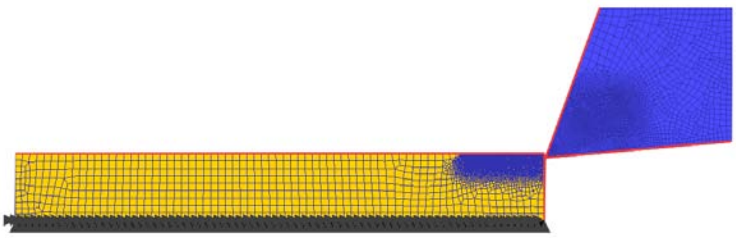

Fig. 4 Finite element model of orthogonal cutting.

3.2 Chip damage criteria

The Cockroft and Latham damage criteria [14] have been used. The damage was evaluated according to the following equation:

$$\int_0^{\varepsilon_f} \sigma_{\max} d\bar{\varepsilon} \geq C \tag{11}$$

where C is the critical damage value obtained by a uniaxial tensile test, ε_f is the strain at the breaking condition, $\bar{\varepsilon}$ is the effective strain and σ_{max} is the maximum stress. The criteria predict the material damage when the critical value C is exceeded. To optimize the material fracture in cutting operations, a combined criterion has been used. The Cockroft and Latham criterion has been combined with a criterion based on the effective stress. Two critical values have been defined, C and σ_{max}. The damage is evaluated for each element of the workpiece. The element deletion occurs when both damage values are satisfied.

4. EXPERIMENTAL DESIGN

First, orthogonal arrays are used in the experiment scheme of micro milling simulation. A simulation analysis model for micro milling SKD61 mould steel has been developed by the finite element package software DEFORM. In this paper, the micro end-mill experimental design is presented as the basis for the diameter of 0.2mm. The factors influencing the cutting performance are cutting speed (A), cutting depth (B), effective rake angles (C) and relief angles (D). In this study, the fore factors are regarded as regulable. The simulation parameters and their levels are listed in Table 2. The freedom of a simulation parameter is the level of the parameter minus one. Here the total freedoms are 8 so that the L9 orthogonal array is utilized for the experiment plan. The interaction among the simulation parameters has been neglected in this experimental arrangement. The configuration of simulation parameters according to the L9 orthogonal array is listed in Table 3. Finally, the cutting force, tool maximum temperature, tool maximum temperature and tip distance, and the contact length of tool and chip are the major performance indexes of micro milling process.

Table 2 The simulation parameters and their levels

Symbol	Simulation parameter	Level 1	Level 2	Level 3
A	Cutting speed (mm/s)	167.55	188.50	209.44
B	Cutting depth (mm)	0.01	0.02	0.03
C	Effective rake angle (°)	20.00	25.00	30.00
D	Relief angle (°)	7.00	10.00	13.00

Table 3 Experimental layout and results

No.	Experimental layout				Experimental results			
	A	B	C	D	Cutting force	Tool maximum temperature	Tool maximum temperature and tip distance	The contact length of tool and chip
	(mm/s)	(mm)	(°)	(°)	(N)	(°)	(mm)	(mm)
1	167.55	0.01	20.00	7.00	15.40	29.3	0.0023	0.0139
2	167.55	0.02	25.00	10.00	25.31	36.1	0.0023	0.0243
3	167.55	0.03	30.00	13.00	32.10	43.0	0.0025	0.0321
4	188.50	0.01	25.00	13.00	13.77	32.1	0.0015	0.0120
5	188.50	0.02	30.00	7.00	21.56	38.1	0.0026	0.0210
6	188.50	0.03	20.00	10.00	40.96	39.2	0.0026	0.0444
7	209.44	0.01	30.00	10.00	12.05	33.8	0.0016	0.0106
8	209.44	0.02	20.00	13.00	29.25	38.1	0.0020	0.0294
9	209.44	0.03	25.00	7.00	37.33	42.3	0.0021	0.0382

5. RESULTS AND ANALYSIS

In the study, multiple performance characteristics have been analyzed by grey relation. The procedure for the design of cutting parameters of micro end-mills is described as follows:

1. Normalization of simulation results.
2. Analysis of grey relation coefficient.
3. Calculated grey relation grade.
4. Analysis of Variation (ANOVA).
5. Determination of optimal level of cutting parameters.

5.1. Experimental results

As a rule, the longer the tool life is, the cutting force and the tool maximum temperature should be minimal and the tool maximum temperature and tip distance and the contact length of the tool and chip should be maximal. First, by equations (4) and (5), the simulation results in Table 3 have been normalized for a better comparison. The normalized results are also presented in Table 4. If the values of results after normalization are higher, the performance characteristics should be better.

To compare with original sequences (ideal sequences/(1,1,1)), simulation results should be converted to grey relational coefficients by equation (6) so that the quantities are between 0.3333 and 1. These grey relational coefficients are shown in Table 5. The grey relational coefficients are substituted in equation (10) for the determination of the grey relation grade. The grey relations of multiple performances characteristics are shown in Table 5. The results demonstrate that the grey relation grade of the first group is maximal (0.7096). That means its multiple performance characteristic is the best result in 9 groups.

The response table for the grey relational grade can be analyzed and results are given in Table 6. From this table, cutting parameters of the optimal combination for multiple performance characteristics are A2B1C1D1.

5.2. Variance analysis

The goal of variance analysis is to comprehend the influence of cutting parameters on multiple performance characteristics by means of a statistical method. The results are demonstrated in Table 7. The first and foremost is the cutting speed (A) which will affect the multiple performance characteristics significantly. It is followed by effective rake angle (C), relief angle (D) and cutting depth (B).

Table 4 The sequences of experimental results after normalization

No.	Cutting force	Tool maximum temperature	Tool maximum temperature and tip distance	The contact length of tool and chip
1	0.8841	1.0000	0.7534	0.0988
2	0.5412	0.5033	0.7446	0.4054
3	0.3065	0.0000	0.9599	0.6356
4	0.9404	0.7959	0.0000	0.0411
5	0.6709	0.3572	1.0000	0.3062
6	0.0000	0.2761	0.9947	1.0000

No.	Cutting force	Tool maximum temperature	Tool maximum temperature and tip distance	The contact length of tool and chip
7	1.0000	0.6736	0.0962	0.0000
8	0.4049	0.3572	0.5101	0.5558
9	0.1254	0.0501	0.5927	0.8170

Table 5 The calculated grey relational coefficient and grey relational grade for 9 cases

No.	Cutting force	Tool maximum temperature	Tool maximum temperature and tip distance	The contact length of tool and chip	Grey relational grade	Rank
1	0.8118	1.0000	0.6697	0.3568	0.7096	1
2	0.5215	0.5016	0.6619	0.4568	0.5355	7
3	0.4189	0.3333	0.9257	0.5785	0.5641	6
4	0.8936	0.7101	0.3333	0.3427	0.5699	5
5	0.6031	0.4375	1.0000	0.4188	0.6149	3
6	0.3333	0.4085	0.9895	1.0000	0.6828	2
7	1.0000	0.6050	0.3562	0.3333	0.5736	4
8	0.4566	0.4375	0.5051	0.5296	0.4822	9
9	0.3638	0.3449	0.5511	0.7321	0.4980	8

Table 6 Response table for the grey relational grade

Symbol	Simulation parameter	Level 1	Level 2	Level 3	Max-Min
A	Cutting speed (mm/s)	0.6030	0.6225	0.5179	0.1046
B	Cutting depth (mm)	0.6177	0.5442	0.5816	0.0735
C	Effective rake angle (°)	0.6249	0.5344	0.5842	0.0905
D	Relief angle (°)	0.6075	0.5973	0.5387	0.0688
Total mean value of the grey relational grade =0.5812					

Table 7 Results of the analysis of variance

Symbol	Simulation parameter	Degree of freedom	Sum of square	Mean square	Contribution (%)
A	Cutting speed (mm/s)	2	0.0186	0.0093	39.307
B	Cutting depth (mm)	2	0.0081	0.0041	17.178
C	Effective rake angle (°)	2	0.0123	0.0062	26.043
D	Relief angle (°)	2	0.0083	0.0041	17.472
Total		8	1.8130		100.000

6. CONCLUSIONS

In this study, a simulation analysis model for micro milling SKD61 mould steel has been developed by the finite element package software DEFORM. The process of chip formation can be realized by simulating the described model. And the performance of cutters can also be predicted by that model. In this study, Orthogonal Arrays have been applied to the experiment scheme of micro milling simulation. For the issue of multiple quality characteristics, the optimal processing parameters are evaluated by the Taguchi parameter design method and grey relation analysis. The results can be summarized in the following points.

1. The analysis results of variance show that the effect of cutting speed is significant for multiple performance characteristics and its contribution reaches 39.307%. Hence, the cutting speed is an important factor.
2. The analysis results of variance reveal that the effect of effective rake angle is the next significant factor for multiple performance characteristics and its contribution reaches 26.043%. Hence, the effective rake angle is a principal factor for the design micro end-mills.
3. The FEM model is suitable for simulating the cutting performance of micro cutting process, and also can be used as a design base for micro end-mills.

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