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A Comprehensive Evaluation Model for Assessments of Grinding Machining Quality

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Abstract: Grinding machining quality contains machining precision and grinding surface integrality. The factors influencing grinding machining quality have fuzzy characteristics. For example, the magnitude and measure methods of grinding surface roughness have fuzzy uncertainties. The grades of the machining quality are vague, and there is no definite boundary between "good" and "bad" machining quality. Analytical Hierarchy Process (AHP) combined with the fuzzy comprehensive evaluation technique is used to evaluate the grade condition of the quality in this paper. Considering the fuzziness of the factors, a two-stage fuzzy comprehensive evaluation model is proposed to evaluate the grinding machining quality. In light of different reliable degrees of different kinds of fuzzy operator models, the weighted average method is used. The membership degrees of the evaluation factors are determined by experts' knowledge and experiences. The factor weights are calculated via the AHP method. Certain synthetic importance of each stage evaluation is presented through weighted sum of the relative important degree. Examples of conventional external grinding machining illustrate the effectiveness of the proposed model.

Introduction

In general cases, a grinding machining is a final working procedure. From this point of view, the grinding machining plays a vital role in machining fields. Grinding machining quality contains machining precision and grinding surface integrality [1]. There are many factors influencing the grinding quality such as conditions of machining tools, grinding tools, operating techniques and grinding allowances. Each of these factors contains many other sub-factors. For example, the condition of the machining tool is determined by the factors such as the clearance between the wheel principal axis and bearing, electromotor vibration, grinding fluids, etc. In some senses, these factors have more or less uncertainties. Analytical Hierarchy Process (AHP) combined with the fuzzy comprehensive evaluation technique [2~6] is used to determine grades of machining quality. The evaluation system will have the ability to give reasonable evaluation results, provide useful information for decision makers and offer useful instruction for further machining with various quality grades. A two-stage fuzzy comprehensive evaluation model is finally proposed to evaluate the grinding machining quality. In light of different reliable degrees of different kinds of fuzzy operator models, the weighted average method is used in the two-stage fuzzy comprehensive evaluation model. The determination of weights is of very importance in the fuzzy comprehensive evaluation. The AHP [7, 8] is used to determine the weights, quantify the relationships between the factors. In order to do this, the weight might be more reasonable. The AHP method is introduced to calculate the factor weights. Certain comprehensive importance is presented according to weight sum of the relative importance where above-factor importance is regarded as weight.

Based on the proposed method, a grinding machining quality evaluation system is established. The paper is focus on the following four major issues: developing the fuzzy comprehensive evaluation model; selecting the fuzzy operator model; calculating the factor weights with the AHP method; and demonstrating the application of the proposed method using the case studies of the general external grinding machining.

Fuzzy comprehensive evaluation model

A factor set

There are many factors influencing grinding machining quality. In order to evaluate exactly grinding quality, it is necessary for evaluating quality system to partition two hierarchies. For factor set $U=\{u_1,u_2,\cdots,u_m\}$ with u_i $(i=1,2,\cdots,m)$ being i th factor of the first hierarchy, u_i is determined by n th factor of the second hierarchy as $u_i=(u_{i1},u_{i2},\cdots,u_{in})$ $(i=1,2,\cdots,m)$.

An assessment set

The assessment set is composed up of possible evaluation results. Therefore, we propose a qualitative assessment scale of five partitions. Five qualitative partitions, i.e., excellent, good, fair, poor, and bad, are defined for each basic attribute of the grinding quality, which is expressed as $V=\{v_1,v_2,v_3,v_4,v_5\}$.

Fuzzy relationship matrix is determined by experts' knowledge and experience. The graded marks are then balanced and integrated. Finally, each membership degree of the factor set is hierarchically calculated for each element of the assessment set.

First stage fuzzy comprehensive evaluation

Each hierarchy of factor set is determined by many factors of next hierarchy. Thus, multi-factors comprehensive evaluation should carry through from the lower hierarchy. The grinding quality assessment is processed as a two-stage fuzzy comprehensive evaluation system with two hierarchies. For single factor u_{ij} of the first hierarchy, membership degree of k th element in the assessment set is r_{ijk} ($i=1,2,\cdots,m$; $j=1,2,\cdots,n$; $k=1,2,\cdots,p$).

The evaluation matrix of the second hierarchy for the single factor is defined as

$$\tilde{R}_i^1=\begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1p} \\ r_{i21} & r_{i22} & \cdots & r_{i2p} \\ \vdots & \vdots & \cdots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inp} \end{bmatrix}$$

According to the fuzzy transformation theory [5], fuzzy decision-making of the second hierarchy about the first stage can be determined as

$$\tilde{D}_i^1=\tilde{A}_i^1\circ\tilde{R}_i^1=(a_{i1},a_{i2},\cdots,a_{in})\circ\begin{bmatrix} r_{i11} & r_{i12} & \cdots & r_{i1p} \\ r_{i21} & r_{i22} & \cdots & r_{i2p} \\ \vdots & \vdots & \cdots & \vdots \\ r_{in1} & r_{in2} & \cdots & r_{inp} \end{bmatrix}=(d_{i1},d_{i2},\cdots,d_{ip})$$

where $\tilde{A}_i^1$ is weight set of n factors of the second hierarchy influencing ith factor of the first hierarchy, $\circ$ is the fuzzy operator. The weighted average model $(\bullet,\oplus)$ [5] is used, i.e.

$$d_{ik}=\min\left[1,\sum_{j=1}^{m}a_{ij}r_{ijk}\right]\quad(k=1,2,\cdots,p).$$

Thus, the first stage fuzzy evaluation matrix is

$$\tilde{D}^1 = \tilde{A}^1 \circ \tilde{R}^1 = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1p} \\ d_{21} & d_{22} & \cdots & d_{2p} \\ \vdots & \vdots & \cdots & \vdots \\ d_{n1} & d_{n2} & \cdots & d_{np} \end{bmatrix}$$

Second stage fuzzy comprehensive evaluation

The second stage fuzzy evaluation matrix is

$$\tilde{R} = \tilde{D}^1 = \begin{bmatrix} \tilde{D}_1^1 \\ \tilde{D}_2^1 \\ \vdots \\ \tilde{D}_m^1 \end{bmatrix} = \begin{bmatrix} \tilde{A}_1^1 \circ \tilde{R}_1^1 \\ \tilde{A}_2^1 \circ \tilde{R}_2^1 \\ \vdots \\ \tilde{A}_m^1 \circ \tilde{R}_m^1 \end{bmatrix}$$

Therefore, the second stage fuzzy decision-making for the grinding quality can be determined as

$$\tilde{D} = \tilde{A} \circ \tilde{R}$$

where $\tilde{A}$ is weight set of factors influencing the grinding machining quality.

According to evaluating results of the above fuzzy comprehensive evaluation $\tilde{D}$, the grade distribution of the grinding quality might be clearly described.

Determination of the fuzzy operator

Four kinds of operator models [5] are often used in the fuzzy comprehensive evaluation. Their definitions are listed in Table 1. To consider all factors and retain all the information of the single evaluating factor, the weighted average model $(\bullet,\oplus)$ is used as the operator model in this study.

Table 1
Definitions of the fuzzy operator models

Model	Expression of operator	Definition of operator
$(\wedge,\vee)$	$b_j = \bigvee_{i=1}^{n}(a_i \wedge r_{ij})\ (j=1,2,\cdots,m)$	$\alpha \wedge \beta = \min(\alpha,\beta)$
$(\bullet,\vee)$	$b_j = \bigvee_{i=1}^{n}(a_i r_{ij})\ (j=1,2,\cdots,m)$	$\alpha \vee \beta = \max(\alpha,\beta)$
$(\wedge,\oplus)$	$b_j = \oplus\sum_{i=1}^{n}(a_i \wedge r_{ij})\ (j=1,2,\cdots,m)$	$\alpha \oplus \beta = \min(1,\alpha+\beta)$
$(\bullet,\oplus)$	$b_j = \min\left[1,\sum_{i=1}^{n} a_i r_{ij}\right]\ (j=1,2,\cdots,m)$	

Analytic hierarchy process (AHP) to determine factor weights

The procedure using AHP to determine factor weights is as follows:

(1) Step 1: Build a hierarchy of the criteria that influences behaviors of the problem. It has been shown that 7 is an optimum number of elements that can be compared with any reasonable assurance of consistency [7, 8]. Thus, we must have at most seven elements in each cluster in each level of the hierarchy.

(2) Step 2: Calculate vectors of priorities between levels. In this step, three parts are contained. Firstly, construct a pairwise comparison matrix. n activities are assumed to be considered by a group of interested people, and the groups' goals are assumed as: to provide judgments on the relative importance of these activities, to ensure that judgments are quantified to an extent that also permits a quantitative interpretation of the judgments among all activities.

Secondly, evaluate the vectors of priorities and overall priority vector. The method of calculating the eigenvalue is usually used by AHP to evaluate vectors of priorities of parameters. The vector of priorities of the parameters in the lower level in the hierarchy is first calculated and then it progresses to get the overall priority vector.

Finally, evaluate the consistency. The consistency ratio (CR) is used to estimate the consistency of the judgments of the participants. The CR is defined as

$$CR = CI/RI$$

where CI is called the consistency index which is defined as

$$CI = \frac{\lambda_{max} - n}{n-1}$$

with λ_{max} being the maximum eigenvalue of the pairwise comparison matrix and n being the number of activities in the matrix.

(3) Step 3: After the consistency of the judgments is assured, the best design alternative can be selected according to the evaluated overall priority vector obtained from the second part of Step 2.

Example

The test conditions in a general external grinding in certain a machine shop are illustrated in Table 2.

Table 2
The test conditions

Index	Parameter
Grinder	Ordinary external cylindrical grinder
The type of grinding wheel	WA70LV, $\phi 228\times 23$
Specimen materials	S45C, HRC45
Grinding methods	$v_s = 25\,\mathrm{m/s}$, Constant-pressure feed grinding
Wheel dressing condition	Single-point diamond dresser, feed velocity, cutting depth $h = 0.0125\mathrm{mm}$, $t_d = 0.012\,\mathrm{mm/pass}$
Cooling fashion	Common supply method, pressure of supply fluid 15×10^4Pa, supply quantity 20 l/min

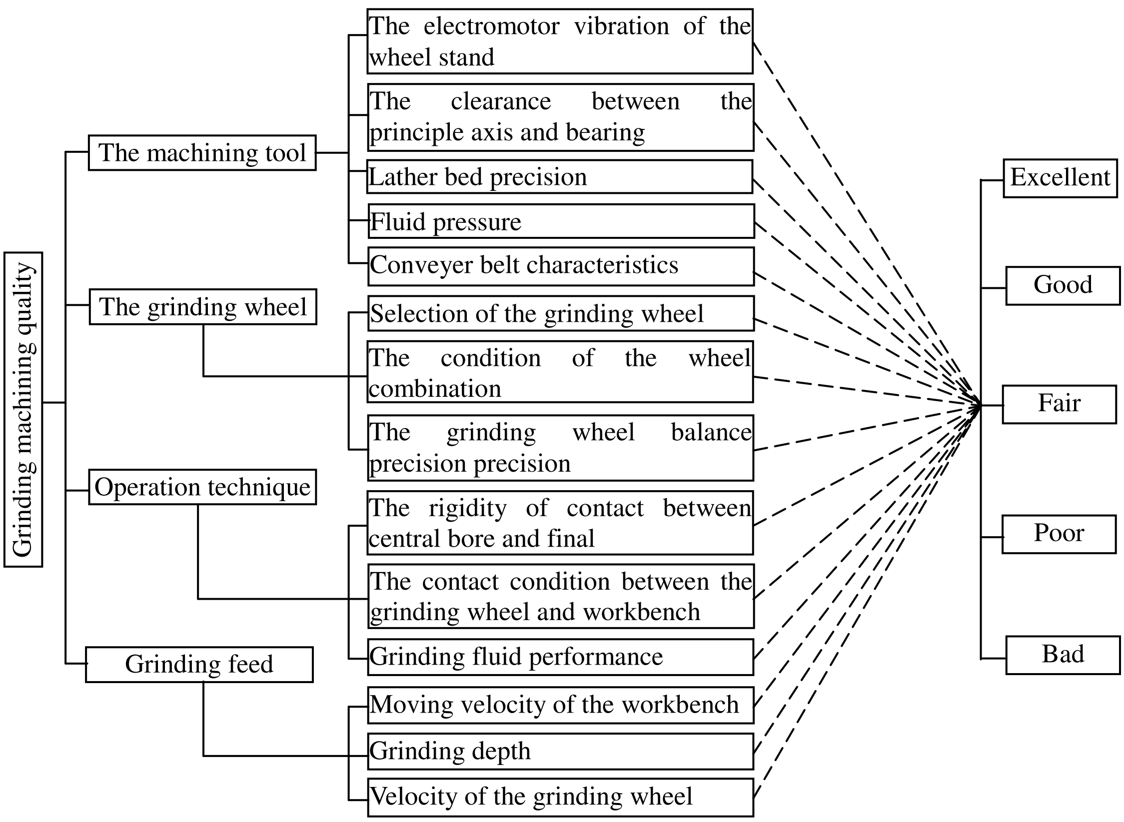

Fig. 1 The hierachy factor structure of the machining quality for the external grinding.

The mainly influencing factors for the machining quality in the external grinding [1] are illustrated in Fig. 1.

For the first stage fuzzy comprehensive evaluation, the machining tool is mainly determined by factors of electromotor vibration in the wheel stand, the clearance between principle axis and bearing, lather bed precision, fluid pressure and the conveyer belt characteristics. According to this sequence, these factors are denoted as the notations of C_1, C_2, C_3, C_4, C_5. Utilizing the AHP method, the pairwise comparison matrix, relative weights, the maximum eigenvalue $\lambda_{\max}$ and the consistency ratio CR for the machining tool factors are obtained in Table 3.

Table 3
The relative weights influencing the machining tool factors

Influencing the machining tool factors	C_1	C_2	C_3	C_4	C_5	Relative weights	$\lambda_{\max}$	CR
C_1	1	2	3	5	7	0.4298		
C_2	1/2	1	5	3	5	0.3045		
C_3	1/3	1/5	1	3	3	0.1332	5.3289	0.0734 <0.10
C_4	1/5	1/3	1/3	1	3	0.0858		
C_5	1/7	1/5	1/3	1/3	1	0.0467		

Thus, the factor weight set of influencing the machining tool can be regarded as

$$\tilde{A}_1^1 = [0.4298 \quad 0.3045 \quad 0.1332 \quad 0.0858 \quad 0.0467]$$

Similarly, the factor weight set of influencing the grinding wheel, operation technique, grinding allowance, and grinding machining quality can be regarded as

$$\tilde{A}_2^1 = [0.6370 \quad 0.1047 \quad 0.2583] \qquad \tilde{A}_3^1 = [0.4286 \quad 0.4286 \quad 0.1429]$$

$$\tilde{A}_4^1 = [0.4058 \quad 0.1140 \quad 0.4806] \qquad \tilde{A} = [0.3934 \quad 0.4258 \quad 0.0899 \quad 0.0910]$$

As described before, the quality in each case is defined by five partitions, i.e., excellent, good, fair, poor, and bad. The memberships of these partitions (quality levels) are used to establish a fuzzy evaluation matrix $\tilde{R}_i^1 \ (i = 1,2,\cdots,4)$. The mainly factors influencing the machining tool are divided into five parts, which are evaluated in the light of five quality levels by the many experts, then the evaluating matrix $\tilde{R}_1^1$ is obtained. Similarly, the evaluating matrix $\tilde{R}_2^1$, $\tilde{R}_3^1$, $\tilde{R}_4^1$ can be obtained respectively.

$$\tilde{R}_1^1 = \begin{bmatrix} 0.4 & 0.7 & 0.9 & 0.5 & 0.2 \\ 0.2 & 0.4 & 0.8 & 0.9 & 0.7 \\ 0.9 & 0.7 & 0.6 & 0.3 & 0.2 \\ 0.5 & 0.7 & 1.0 & 0.4 & 0.3 \\ 0.9 & 0.7 & 0.6 & 0.3 & 0.1 \end{bmatrix} \qquad \tilde{R}_2^1 = \begin{bmatrix} 0.4 & 0.6 & 1.0 & 0.5 & 0.2 \\ 0.5 & 0.8 & 0.9 & 0.4 & 0.3 \\ 0.4 & 0.7 & 1.0 & 0.3 & 0.1 \end{bmatrix}$$

$$\tilde{R}_3^1 = \begin{bmatrix} 0.8 & 0.9 & 0.7 & 0.5 & 0.3 \\ 0.9 & 0.8 & 0.7 & 0.4 & 0.2 \\ 0.5 & 0.7 & 0.8 & 0.3 & 0.1 \end{bmatrix} \qquad \tilde{R}_4^1 = \begin{bmatrix} 0.5 & 0.8 & 1.0 & 0.6 & 0.4 \\ 0.7 & 1.0 & 0.8 & 0.5 & 0.3 \\ 0.5 & 0.7 & 0.8 & 0.6 & 0.2 \end{bmatrix}$$

The first stage fuzzy comprehensive evaluation is expressed as

$$\tilde{D}_1^1 = \tilde{A}_1^1 \circ \tilde{R}_1^1 = [0.4376 \quad 0.6087 \quad 0.8242 \quad 0.5772 \quad 0.3562]$$

$$\tilde{D}_2^1 = \tilde{A}_2^1 \circ \tilde{R}_2^1 = [0.4105 \quad 0.6468 \quad 0.9895 \quad 0.4379 \quad 0.1846]$$

$$\tilde{D}_3^1 = \tilde{A}_3^1 \circ \tilde{R}_3^1 = [0.8001 \quad 0.8287 \quad 0.7429 \quad 0.4286 \quad 0.2286]$$

$$\tilde{D}_4^1 = \tilde{A}_4^1 \circ \tilde{R}_4^1 = [0.5230 \quad 0.7751 \quad 0.8815 \quad 0.5888 \quad 0.2926]$$

The second stage fuzzy comprehensive evaluation matrix is

$$\tilde{D} = \tilde{A} \circ \tilde{R} = \tilde{A} \circ \begin{bmatrix} \tilde{A}_1^1 \circ \tilde{R}_1^1 \\ \tilde{A}_2^1 \circ \tilde{R}_2^1 \\ \tilde{A}_3^1 \circ \tilde{R}_3^1 \\ \tilde{A}_4^1 \circ \tilde{R}_4^1 \end{bmatrix} = \begin{bmatrix} 0.4665 & 0.6599 & 0.8926 & 0.5056 & 0.0953 \end{bmatrix}$$

After normalization of the matrix $\tilde{D}$, we can obtain

$$\tilde{D} = \begin{bmatrix} 0.17 & 0.24 & 0.32 & 0.18 & 0.09 \end{bmatrix}$$

According to evaluating results of the above fuzzy comprehensive evaluation $\tilde{D}$, we can find that the excellent quality accounts for 17%, the good quality accounts for 24%, the fair quality accounts for 32%, the poor quality accounts for 18% and the bad quality accounts for 9%. Therefore, it can be concluded that the grinding quality is fair at this condition.

Conclusions

The fuzzy comprehensive evaluation method for grinding quality assessment is proposed in this paper. According to the evaluation results, we can obtain intuitive and comprehensive understanding for grinding quality. The useful information might be provided for further adjustment of machining parameters. The factor weights of each hierarchy were calculated using AHP in the each stage of the fuzzy comprehensive evaluation. The weights may be easily expressed in a quantitative form, which makes them coincide with the actual grinding machining situations. The rationality of the weights is verified through the judgment matrix about whether their consistency is satisfactory or not. Therefore, the reliability and accuracy of the evaluation results can be improved. The operator model of the comprehensive evaluation adopted is the weighted average model, which fully considers each of factors. Compared with other models, this model can make better use of the characteristics of the weight normalization and overall useful information. The example of the conventional external grinding machining illustrates that the proposed model is effective. Another important advantage of this fuzzy comprehensive evaluation system is its easiness to be programmed. The evaluating procedure has already been programmed in Matlab 6.5.

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Advances in Abrasive Technology VIII

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A Comprehensive Evaluation Model for Assessments of Grinding Machining Quality

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