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Machinability evaluation of machinable ceramics with fuzzy theory[①]

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Abstract: The property parameters and machining output parameters were selected for machinability evaluation of machinable ceramics. Based on fuzzy evaluation theory, two-stage fuzzy evaluation approach was applied to consider these parameters. Two-stage fuzzy comprehensive evaluation model was proposed to evaluate machinability of machinable ceramic materials. Ce-ZrO_2/$CePO_4$ composites were fabricated and machined for evaluation of machinable ceramics. Material removal rates and specific normal grinding forces were measured. The parameters concerned with machinability were selected as alternative set. Five grades were chosen for the machinability evaluation of machnable ceramics. Machinability grades of machinable ceramics were determined through fuzzy operation. Ductile marks are observed on Ce-ZrO_2/$CePO_4$ machined surface. Five prepared Ce-ZrO_2/$CePO_4$ composites are classified as three machinability grades according to the fuzzy comprehensive evaluation results. The machinability grades of Ce-ZrO_2/$CePO_4$ composites are concerned with $CePO_4$ content.

Key words: Ce-ZrO_2/$CePO_4$; ceramics; machinable ceramics; machinability; fuzzy theory

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1 INTRODUCTION

By controlling microstructural modifications, weak interfaces on the microstructural scale can be introduced into ceramics[1-5]. Material removals are finished due to the formation and linking of cracks at the weak interfaces between two phases. Machinable ceramics, which can be machined with conventional metal-cutting tools such as high-speed steel and tungsten carbide, show insensitivity to strength degradation from machining operations[3]. The fabrication of machinable ceramics provides an essential way to solve the machining problems of advanced ceramics. Oxide ceramics containing rare earth phosphates[5-10], such as Ce-ZrO_2/$CePO_4$, and mullite/$LaPO_4$, are machinable. There exist weak interfaces between phosphates and oxides[5, 7].

More attentions have been paid to material design, fabrication and property studies of machinable ceramics. However, machinability of material is an important factor for evaluation and design of ceramics. The optimum machining technologies can be determined according to the machinability of ceramics. And in order to obtain better machinability of ceramics, the rational property parameters might be designed before fabrication of materials. So, the chemical composition and preparation processes can be intentionally designed to meet the needs for ceramics machining. Therefore, through the research of machinability, we might design compatible advanced ceramics, which simultaneously meet the needs of both applications and machining operations[11]. Usual criteria for machinability assessment of machinable ceramics include material removal rate, tool life, brittleness index, etc. Mostly, machinability of machinable ceramics is evaluated considering any one of the above criteria[12, 13]. Recently, fuzzy evaluation approach was applied to study the machinability of ceramics[7, 11]. And the property parameters of materials were selected as alternative set. In this study, two-stage fuzzy evaluation model was used to analyze the machinability of machinable ceramics, in which both property parameters and machining output parameters were considered simultaneously. Machinabilities of five fabricated Ce-ZrO_2/$CePO_4$ composites were evaluated as the example.

2 EXPERIEMNTAL

Two-phase composites consisting of $CePO_4$ and Ce-ZrO_2 were fabricated. Powders were ball-milled in an aqueous slurry for 7 h, dried, uniaxially dry-pressed at 100 MPa, cold iso-statically pressed at 200 MPa, then sintered for 2 h in air. The hardness was measured using Vickers indentations. The fracture toughness was measured using

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single edge notched beams loaded in three-point bending. Elastic modulus was estimated from rule of mixtures for two-phase materials.

Samples were drilled with water coolant at a fixed drilling load of 22.87 N and spindle rotating speed of 3 700 r/min. The diameter of tungsten-cobalt carbide drill bits was 1.5 mm. The material removal rates were calculated as the material removal volume per unit time. Surface grinding tests were conducted on horizontal spindle precision grinder. A resin-bonded diamond wheel had grit size of 270/325 and content of 100%. Grinding tests were done in the down mode at a peripheral cutting velocity of 22.6 m/s, workpiece velocity of 5.5 m/min and grinding depth of 50 μm. Grinding coolant was water-soluble synthetics. Normal grinding forces were measured using a piezoelectric platform dynamometer. The machined surfaces of ceramics were observed with SEM.

3 EVALUATION METHODOLOGY

Machinability means machining difficulty for certain material. Usually, machinability is estimated with two-type parameters, material property parameters and machining output parameters[11, 14, 15]. During machining processes, removal of materials is closely concerned with the deformation and fracture of material, which can be reflected by property parameters, including elastic modulus E, hardness H_v, fracture toughness K_{IC}, etc. Machining output parameters are defined as variables measured in or after machining operations, such as material removal rate, cutting force and tool life.

There exists uncertainty in linguistic notions about machinability, such as "easy to machine" and "very easy to machine". The characteristic of machinability assessments lies in the lack of precise boundaries. The machinability of material is a comprehensive factor, which could not be accurately described with single parameter. So, one system covering some parameters is needed to evaluate the machinability. Fuzzy theory is particularly appropriate to deal with the uncertain linguistic notions. Many parameters can be taken into account together through fuzzy multi-criteria decision-making method[16]. Relations between parameter and parameter are considered without missing of any information. The machinability of machinable ceramics can be completely reflected by two-stage fuzzy comprehensive evaluation method, which contains the following steps.

1) Let $U=\{u_1, u_2, \cdots, u_n\}$ be a set of available alternatives

The machinability of machinable ceramics is regarded as evaluated objective. The mechanical property parameters and machining output parameters are selected to constitute alternative set U. To avoid too many alternatives on one set, we divide set U into two subsets U_1 and U_2. Then, $U=\{U_1, U_2\}$, where U_1 denotes the subset of alternatives containing mechanical property parameters, U_2 denotes the subset of alternatives containing machining output parameters. Let $V=\{v_1, v_2, \cdots, v_m\}$ be a set of evaluation criteria, usually conflicting, by which the performance of an alternative is evaluated. The machinabilities are classified as some grades represented by fuzzy terms using linguistic variables, such as "easy" and "medium".

2) First-stage fuzzy comprehensive evaluation

Fuzzy matrices $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$ are constituted through evaluation of each alternative on subsets U_1 and U_2, respectively. Set of weights, represented as one vector $\boldsymbol{A}$, is assigned. For a given material with alternative subset U_1 and U_2, the fuzzy operations are

$$\boldsymbol{B}_1=\boldsymbol{A}_1 \circ \boldsymbol{R}_1;\ \boldsymbol{B}_2=\boldsymbol{A}_2 \circ \boldsymbol{R}_2 \tag{1}$$

where "$\circ$" is fuzzy operator. The weighted average fuzzy model[16] is chosen for considering all alternatives in terms of the assigned weights, so the fuzzy operation model in Eqn.(1) becomes $M(\bullet, \oplus)$, where "$\bullet$" denotes ordinary real multiplication, "$\oplus$" denotes bounded sum. Vector $\boldsymbol{B}_1$ represents result evaluated with mechanical property parameters, and vector $\boldsymbol{B}_2$ represents result evaluated with machining output parameters. $\boldsymbol{A}_1$ is corresponding to U_1, and $\boldsymbol{A}_2$ to U_2.

3) Second-stage fuzzy comprehensive evaluation

For alternative set U, two first-stage evaluation results constitute fuzzy matrix $\boldsymbol{R}$. Then, final evaluation result is

$$\boldsymbol{B}=(b_1, b_2, \cdots, b_n)=\boldsymbol{A}\circ\boldsymbol{R} = \boldsymbol{A}\circ\begin{bmatrix}\boldsymbol{B}_1\\ \boldsymbol{B}_2\end{bmatrix}=\boldsymbol{A}\circ\begin{bmatrix}\boldsymbol{A}_1\circ\boldsymbol{R}_1\\ \boldsymbol{A}_2\circ\boldsymbol{R}_2\end{bmatrix} \tag{2}$$

As for the maximum element $b_{j,\max}$ on vector $\boldsymbol{B}$, there will be corresponded to one grade. Then, the machinability grade of machinable ceramic material is determined.

4 RESULTS AND DISCUSSION

4.1 Surface and parameters

The transgranular and intergranular fractures of grains were observed on machined surfaces. Take Ce-ZrO_2/50% $CePO_4$ for example, the SEM micrographs of ground surface is shown in Fig. 1. Some grains are in cleavage fracture mode indicated by arrows A. The layered microstructures indicate that these grains are $CePO_4$. There exists transgranular fracture of $CePO_4$ grains during machining processes of Ce-ZrO_2/$CePO_4$. Arrows B shows integrated grains without breakage, which suggests intergranular fracture between ZrO_2 and $CePO_4$ grains. When composite are exerted with loads, fracture will occur along weak boundaries between ZrO_2 and $CePO_4$ grains. Similar phenomena can be observed on other composites machining surfaces. Moreover, ductile deformation of Ce-ZrO_2/$CePO_4$ material can be observed in Fig. 1 indicated by arrow C. Fig. 2 shows a lower magnification SEM image of Ce-ZrO_2/15% $CePO_4$ surface drilled with metal cutting tools. Obviously ductile machining marks, similar to metal drilled surfaces, can be observed in Fig. 2.

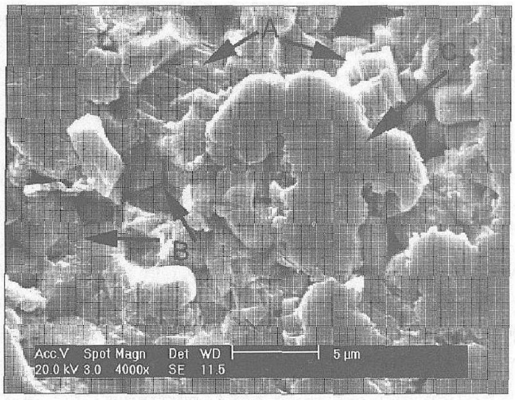

Fig. 1 Ground surface of Ce-ZrO_2/50% $CePO_4$

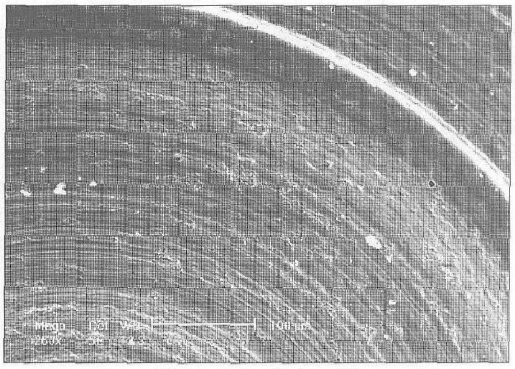

Fig. 2 Drilled marks of Ce-ZrO_2/15% $CePO_4$

The properties of composites, material removal rates Q and specific normal grinding forces F_n are listed in Table 1. The Ce-ZrO_2/$CePO_4$ composites were prepared with different $CePO_4$ content α and sintering temperature t. If only single parameter in Table 1 is selected to evaluate machinability, it is impossible to have correct and complete estimation. By fuzzy method, all parameters in Table 1 can be taken into account together to have a comprehensive evaluation result.

4.2 Evaluations

The set of alternatives is composed of H_v, K_{IC}, E, Q and F_n. Then, we have $U = \{u_1, u_2, u_3, u_4, u_5\} = \{H_v, K_{IC}, E, Q, F_n\}$, $U_1 = \{u_1, u_2, u_3\} = \{H_v, K_{IC}, E\}$, $U_2 = \{u_4, u_5\} = \{Q, F_n\}$. The set of evaluation criteria is $V = \{v_1, v_2, v_3, v_4, v_5\} = \{$very easy, easy, medium, difficult, very difficult$\}$. Suppose effects of each parameter on machinability are similar, and suppose effects of two type parameters on machinability are similar. Therefore, the weighting coefficient vectors in Eqn. (2) are assigned as $\boldsymbol{A}_1 = (0.334, 0.333, 0.333)$, $\boldsymbol{A}_2 = (0.5, 0.5)$, $\boldsymbol{A} = (0.5, 0.5)$. Suppose material property values and machining output parameter values meet normal distribution. The fuzzy normal distribution is selected as the membership function:

$$\mu(x) = -\exp\left[-\left(\frac{x - c_i}{\sigma}\right)^2\right] \tag{3}$$

where σ and c_i are constants corresponding to v_i. Here, constants are determined on basis of the value range in Table 1. Five evaluated grades of machinability are corresponding to five values in c_i. With the increase of H_v, K_{IC}, E, and F_n values, the machinable ceramics become difficult to machine. Higher Q value means the easiness of material removal. According to the influences of those parameters on material removal, the constant values for every parameter are as follows. H_v: $\sigma = 2$, $c_1 = 3$, $c_2 = 5$, $c_3 = 7$, $c_4 = 9$, $c_5 = 11$; K_{IC}: $\sigma = 2$, $c_1 = 0$, $c_2 = 3$, $c_3 = 6$, $c_4 = 9$, $c_5 = 12$; E: $\sigma = 10$, $c_1 = 150$, $c_2 = 160$, $c_3 = 170$, $c_4 = 180$, $c_5 = 190$; Q: $\sigma = 0.1$, $c_1 = 0.4$, $c_2 = 0.3$, $c_3 = 0.2$, $c_4 = 0.1$, $c_5 = 0$; F_n: $\sigma = 5$, $c_1 = 35$, $c_2 = 40$, $c_3 = 45$, $c_4 = 50$, $c_5 = 55$.

When taking Ce-ZrO_2/50% $CePO_4$ (1 450 ℃) for example, let every parameter value in Table 1 be the value of x in Eqn. (3), repeatedly substituting σ and c_i $(i = 1, 2, \cdots, 5)$ values for every pa-

Table 1 Property and machining parameters

$CePO_4$ content/%	Sintering temperature/℃	H_v/MPa	K_{IC}/(MPa·m$^{1/2}$)	E/GPa	Q/(mm^3·s^{-1})	F_n/(N·mm^{-1})
50	1 450	4 970	5.4	167	0.397	37.08
50	1 550	6 930	7.8	167	0.343	39.83
25	1 450	7 270	7.8	183	0.081	48.35
25	1 550	8 780	10.6	183	0.061	41.47
15	1 550	8 930	10.9	190	0.003	57.1

Table 2 Evaluation results of machinable ceramics

Machinable ceramics	b_1	b_2	b_3	b_4	b_5	Machinability grade
Ce-ZrO_2/50% $CePO_4$(1 450 ℃)	0.533	0.584	0.389	0.040	0.001	Easy
Ce-ZrO_2/50% $CePO_4$(1 550 ℃)	0.292	0.626	0.511	0.209	0.006	Easy
Ce-ZrO_2/25% $CePO_4$(1 450 ℃)	0.002	0.065	0.489	0.813	0.282	Difficult
Ce-ZrO_2/25% $CePO_4$(1 550 ℃)	0.047	0.236	0.295	0.633	0.425	Difficult
Ce-ZrO_2/15% $CePO_4$(1 550 ℃)	0	0.004	0.075	0.426	0.806	Very difficult

rameters into Eqn.(3), the evaluated result of every alternative can be calculated. Evaluated results of alternatives on subset U_1 constitute fuzzy matrix $\boldsymbol{R}_1$, and evaluated results of alternatives on subset U_2 constitute matrix $\boldsymbol{R}_2$. Thus, we have

$$\boldsymbol{R}_1=\begin{vmatrix} 0.38 & 1.00 & 0.36 & 0.02 & 0 \\ 0 & 0.24 & 0.91 & 0.04 & 0 \\ 0.06 & 0.61 & 0.91 & 0.18 & 0.01 \end{vmatrix};$$

$$\boldsymbol{R}_2=\begin{vmatrix} 1.00 & 0.39 & 0.02 & 0 & 0 \\ 0.84 & 0.71 & 0.08 & 0 & 0 \end{vmatrix} \tag{4}$$

Substituting $\boldsymbol{A}$, $\boldsymbol{A}_1$, $\boldsymbol{A}_2$, $\boldsymbol{R}_1$ and $\boldsymbol{R}_2$ into Eqn.(2), the comprehensive evaluation result $\boldsymbol{B}$ of Ce-ZrO_2/50% $CePO_4$ (1 450 ℃) materials is $\boldsymbol{B}$ = (0.533, 0.584, 0.389, 0.040, 0.001). In the same way, we have the comprehensive evaluation results of other composites listed in Table 2.

As for Ce-ZrO_2/50% $CePO_4$ (1 450 ℃), the maximum element on set $\boldsymbol{B}$ is b_2 = 0.584, which corresponds to v_2= "easy" on set V. Thus, its machinability grade is "easy to machine" among five materials. From Table 2, five Ce-ZrO_2/$CePO_4$ composites are classified as three machinability grades, "easy to machine", "difficult to machine" and "very difficult to machine". The machinabilities of Ce-ZrO_2/$CePO_4$ composites increase with the increase of $CePO_4$ content.

From the experimental results of specific material removal rates Q listed in Table 1, we can estimate the machinability of five composites with single parameter criterion. Values of specific material removal rates can be classified as three grades. Among five composites, Ce-ZrO_2/15% $CePO_4$ has the lowest value of removal rates, two Ce-ZrO_2/25% $CePO_4$ ceramics have medium values of removal rates, and higher removal rates belong to two Ce-ZrO_2/50% $CePO_4$ ceramics. The evaluation results with fuzzy approach are consistent with the comparison of single parameter in machining experiments.

REFERENCES

[1] Lawn B R, Padture N P, Cai H, et al. Making ceramics ductile [J]. Science, 1994, 263(25): 1114-1116.
[2] Holand W, Rheinberger V, Schweiger M. Control of nucleation in glass ceramics [J]. Phil Trans R Soc Lond A, 2003, 361(1804): 575-589.
[3] Padture N P, Evans C J, Xu H H K, et al. Enhanced machinability of silicon carbide via microstructural design [J]. J Am Ceram Soc, 1995, 78(1): 215-217.
[4] Rawn C J, Barsoum M W, Raghy T E, et al. Structure of Ti_4AlN_3 —a layered $M_{n+1}AX_n$ nitride [J]. Materials Research Bulletin, 2000, 35(11): 1785-1796.
[5] Davis J B, Marshall D B, Housley R M, et al. Machinable ceramics containing rare-earth phosphates [J]. J Am Ceram Soc, 1998, 81(8): 2169-2175.
[6] Wang L J, Liu J C, Wang K L, et al. Investigation on ductile property of $CePO_4$ ceramic [J]. Journal of Rare Earths, 2003, 21(6): 645-647.
[7] Yu A B, Zhong L J, Liu J C, et al. Machinability evaluation of Ce-ZrO_2/$CePO_4$ ceramics [J]. Key Engineering Materials, 2004, 259-260: 259-263.
[8] Wang R G, Pan W, Chen J, et al. Microstructure and mechanical properties of machinable Al_2O_3/$LaPO_4$ composites by hot pressing [J]. Ceramics International, 2003, 29(1): 83-89.
[9] Davis J B, Marshall D B, Morgan P E D. Monazite-containing oxide/oxide composites [J]. J Eur Ceram Soc, 2000, 20(5): 583-587.
[10] Wu M, Daimon K, Matsubara T, et al. Thermal and mechanical properties of sintered machinable $LaPO_4$-ZrO_2 composites [J]. Mat Res Bull, 2002, 37(6): 1107-1115.
[11] Yu A B, Zhong L J, Tian X L. Grindability evaluation of advanced ceramics [J]. Materials Science Forum, 2004, 471-472: 132-135.
[12] Boccaccini A R. Machinablity and brittleness of glass-ceramics [J]. J Mater Process Technol, 1997, 65(1-3): 302-304.
[13] Baik D S, No K S, Chun J S, et al. A comparative evaluation method of machinability for mica-base glass-ceramics [J]. J Mater Sci, 1995, 30(7): 1801-1806.
[14] ZHOU Zhe-hua. Metal Cutting Principle [M]. Shanghai: Shanghai Scientific & Technical Press, 1993. (in Chinese)
[15] Enache S, Strajescu E, Opran C, et al. Mathematical model for the establishment of the materials machinability [J]. Annals of the CIRP, 1995, 44(1): 79-82.
[16] Chen Y Y, Liu Y F, Wang P Z. Models of multifactorial evaluations [J]. Fuzzy Mathematics, 1983 (1): 61-70. (in Chinese)

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