Experimental Verification of Ball End-milling Condition Decision Support System Applying Hierarchical and Non-hierarchical Clustering Methods

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Abstract:
Unskilled engineers have difficulty determining the appropriate end-mills and end-milling conditions for materials and shapes designed by CAD, even though end-mills are specifically designed for various purposes such as milling at high speed and milling of difficult-to-cut materials. Ball end-mills are usually the most suitable for die and mold milling since they can be easily adapted to workpieces with complicated shapes. We previously reported an end-milling condition decision support system (“catalog mining system”) that applies data-mining methods from square end-mill tool shape parameters listed in a cutting tool catalog. Our aim was to extract new knowledge by applying data-mining techniques to a tool catalog. We used both hierarchical and non-hierarchical clustering methods and principal component regression. We focused on the shape element of catalog data and visually clustered ball end-mills from the viewpoint of tool shape, which here meant the ratio of dimensions, by using the k-means method. Expressions for calculating end-milling conditions were derived using the response surface method. We have now conducted end-milling experiments using ball end-mills and compared the calculated values with the catalog ones to validate end-milling conditions derived from catalog-mining system.

Keywords: Data mining, Ball end-milling, Hierarchical and non-hierarchical clustering, Response surface method, JIS SKD61

1. Introduction
Recent improvements in CAM systems make it easier for even unskilled engineers to generate NC programs, in which the end-milling conditions are determined by engineers. Expert engineers use their implicit knowledge to make these determinations. Unskilled engineers have difficulty determining the appropriate end-mills and end-milling conditions for materials and shapes designed using CAD, even though end-mills are specifically designed for various purposes such as high-speed milling and milling of difficult-to-cut materials.

Ball end-mills are usually the most suitable and for die and mold milling since they can be easily adapted to workpieces with various complicated shapes. They are also suitable for multi-axis control machining with collision-free tool path [1]. However, because ball end-mills are commonly used for adjustable surface processing of mold, there are many unanswered questions; for example, how does wear mode affect tool life, existence range of down and up cut. Therefore, decisions about ball end-milling conditions are more difficult than those about square end-milling ones.

While research has been reported for the ball end-mill processing mechanisms, tool path generation, ball end-mill design, wear prediction, and roughness prediction [2 - 5], few has been reported for a system that gives systematic and comprehensive solutions for use in determining ball end-milling conditions. We previously proposed an end-milling condition decision support system (“catalog mining system”) that applies data-mining methods from square end-mill tool shape parameters listed in a cutting tool catalog [6 - 7] and demonstrated its effectiveness for unskilled engineers determining end-milling conditions. Using it would speed up production and help reduce manufacturing costs.

We have now applied our catalog-mining system to ball end-mill catalog data and constructed a ball
end-milling decision support system. The flow of the catalog mining process we used for is shown in Fig. 1. Important factors for use in determining end-milling conditions were extracted from tool shape parameters as predictor variables. End-milling condition decision equations were derived from the response surface method by using predictor variables (ball end-mill shape parameters) and criterion variables (ball end-milling conditions). The end-milling conditions recommended in a square end-mill catalog take the efficiency of milling into consideration. Generally speaking, square end-mills are used for rough processing and ball end-mills are used for finish processing.

We investigated whether using the milling conditions recommended in a ball end-mill catalog lead to higher milling efficiency and/or better surface finish quality. Our aims is to use our catalog-mining system to extract implicitly defined ball end-milling tendencies for use in deriving ball end-milling conditions decision equations and to validate effectiveness of ball end-milling conditions derived from catalog mining systems by conducting several die steel (JIS SKD61) cutting experiments.

2. Catalog mining process

2.1 Target data and attribute extraction using K-means method

We extracted knowledge from target data using hierarchical and non-hierarchical clustering methods [6 -7]. The tools of interest were cemented carbide ball end-mills listed in the 2010-2011 of a major tool maker A in Japan. Schematic models of two representative ballmaker’s predictor variables are shown in Fig. 2. The catalog data was used to define spindle speed $S$ [rpm], table feed $Pf$ [mm/min], normal depth of cut $An$ [mm] and pick feed $Pf$ [mm]. These conditions were defined as criterion variables.

The work materials selected were carbon steel, alloy steel, and quenched steel. Three variables ($L/le$, $le/D$, and $Ds/D$) were used to visualize the shape of the ball end-mill. By fixing the values of these three variables, we determined the external form of the end-mill. Since engineers generally use a ball end-mill's nose section for die machining. Therefore, the ball end-mill nose section has an intimate involvement in processing. We defined a variable equivalent, $le$ [mm], for representing the shape of ball end-mill nose section shape. Equivalent $le$ is calculated using Eq. (3).

As shown in Fig. 3, the apical part of a ball end-mill has a hemispherical shape. We defined the blade length of this hemispherical part as variable $Ls$ [mm]. First, we magnified the hemispherical part as shown Fig. 3 and focused on the circle, which has a radius of $D/2$. We defined the blade length as the length of the sinusoidal wave. We defined the length of the sinusoidal wave as variable $Ls$, which is calculated using the curvilinear integral in the range $0 < x < \pi$. As shown in Fig. 3, the sinusoidal wave is defined as $f(x) = \sin x$. The length of the wave, $Ls$, is defined as the elliptic integral of the second kind:

$$Ls = 2\int_0^{\pi/2} \sqrt{1 + \{f'(x)\}^2} \, dx = 2\sqrt{1 + a^2} \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 x} \, dx$$

(1)

where $k^2 = a^2/(1+a^2)$ is the eccentricity. For a ball end-mill, the blade edge line is continuous at $x = \pi$. From Fig. 3, helix angle $\theta$ is defined as $\tan \theta = f'(x)|_{x=\pi} = -a$, where $a^2 = \tan^2 \theta$. To correct the error between the calculated $L$ and the measured value, we determined the appropriate correction factor which contained outside diameter $D$. As a result, $le$ is calculated using

$$le = z \left[ 0.5D \sqrt{1 + a^2} \int_0^{\pi/2} \sqrt{1 - k^2 \sin^2 x} \, dx + 0.0074D \right].$$

(2)

Figure 4 shows the three-dimension cluster distribution map obtained using the K-means method. Clusters 2 and
3 consisted of small-diameter ball end-mills (0.1 ≦ D ≦ 1.0) which in turn consisted of narrow-path ball end-mills. Cluster 1 consisted of small-diameter end-mills and rod-shaped ball end-mills (1.0 < D ≦ 20). The larger the L/le and Ds/D, the smaller the outside diameter. The larger the le/D, the higher the number of rod-shaped ball end-mills.

2.2 Predictor variable selection of representative shape

We applied variable cluster analysis and principal component regression (PCR) to each cluster classified by the K-means method from the viewpoint of the ball end-mill shape [6 - 7]. The catalog-recommended ball end-milling conditions were divided into two main processing methods in accordance with inclination angle: α ≦ 15° or α > 15°. Therefore, each cluster was divided into two attributes on the basis of the value of α.

Figure 5 shows the results of variable cluster analysis, and Fig. 6 shows those of PCR on each cluster for α ≦ 15° and α > 15°. From Fig. 5, we can interpret the correlation in each predictor variable by focusing on the left clusters, which are demarcated with a dashed line ("cutting line"). For Clusters 2 and 3, which consisted of small-diameter end-mills and narrow-path end-mills, the same tendency was extracted from each tree diagram. Because z had a constant value of 2 for Clusters 2 and 3, we eliminated z.
from the predictor variables. The variables were divided into three high-correlation clusters: \((D, l', l, \theta), (L, Ds)\), and \((HRC, PRICE)\). For Clusters 2 and 3, the simple correlation coefficient among \((D, l', l, \theta)\) was 0.80 and 0.98, between \((L, Ds)\) was 0.80 and 1.00, and between \((HRC, PRICE)\) was 0.48 and 0.42. For Cluster 1, which consisted of narrow-path end-mills and rod-shaped end-mills, the variables were also divided into three high-correlation clusters in accordance with \((D, l, Ds, PRICE, l', L), (z, HRC)\), and \((\theta)\). Because the catalog recommended \(S\) for Cluster 3 is a constant value of 40,000 rpm, a regression coefficient for \(S\) cannot be calculated.

From Fig. 6 under \(\alpha \leq 15^\circ\) and \(\alpha > 15^\circ\) of Clusters 2 and 3, we found that all criterion variables had positive relationships \((C_p = 0.02 - 0.40)\) among \(L\) and \(Ds\). That is, for the small-diameter end-mills, the larger the end-mill, the higher the ball end-milling conditions. The values of \(Pf\) had a negative relationship \((C_p = -0.4)\) among \(L\) and \(Ds\). The tendencies for Cluster 3 were stronger than those for Cluster 2. There was no difference in tendency between \(\alpha \leq 15^\circ\) and \(\alpha > 15^\circ\). For Cluster 1 for both \(\alpha \leq 15^\circ\) and \(\alpha > 15^\circ\), \(Pf\) and \(An\) had a positive relationship among \(D, l, Ds, PRICE, l', L\), and \(z\), which are related to end-mill shape and size, while \(F\) had a negative relationship among those variables.

Among the rod-shape ball end-mills in Cluster 1, there were ones with four cutting teeth \((z = 4)\) that are usually used for finishing process. The \(Pf\)'s of these tools is thus made lower than that of other end-mills to obtain a smooth finished surface. Given the hemispherical shape of a ball end-mill tip, cutting speed \(V\) [m/min] geometrically depends on \(a\). The larger the value of \(a\), the greater the radius of the ball end-mill, which affects the processing area. Therefore, the catalog-recommended \(S\) for small-diameter end-mills is higher than for rod-shaped end-mills. We compared the correlation coefficient with the criterion variables between high-predicator variables of the correlation based on these figures and reduced predictor variables which have low correlation with criterion variables.

### 2.3 Derivation of ball-end-milling condition decision equations

We derived ball-end-milling condition-decision equations using the three variables that were determined to be significant in the prediction and the response surface method, a practical optimization method. In particular, we derived ternary second-order polynomial response surface equations.

Kageyama and Yu [8] used hierarchical clustering in their proposed "hierarchized response surface method (H-RSM)" for improving approximation accuracy for the multi-peak problem. We used both hierarchical and non-hierarchical clustering to select significant variables and extract attributes effectively. These techniques can also be used to solve the multi-peak problem and make a prediction model easier to use. As an example, the ball end-milling condition decision equations for Cluster 1 for \(\alpha \leq 15^\circ\) and \(\alpha > 15^\circ\) are shown.

\[
\begin{align*}
\text{① } \alpha & \leq 15^\circ \\
A_v(R_w^2.69) &= 3.82 + 0.001Dz + 0.0019D\theta + 0.0018D^2 - 0.502^2 \times +0.0021D^2 \times 5.6 \\
Pf(R_w^2.77) &= 7.72 + 0.011Dz + 0.054D\theta + 0.001D\theta \times +0.062D^2 - 1.052^2 + 0.0038D^2 \times 11 \\
S(R_w^2.90) &= -6257D + 860HRC + 544\theta - 15HRC - 5HRC - 0.063D + 0.00065D^2 + 0.10D\theta + 0.0018D^2 - 0.21 \\
\text{② } \alpha > 15^\circ \\
A_v(R_w^2.54) &= -0.019D + 0.011Dz + 0.0019D\theta - 0.02D \times +0.00065D^2 + 0.10D\theta + 0.0018D^2 - 0.21 \\
Pf(R_w^2.65) &= -3.82 - 0.063D + 0.047Dz + 0.0063D\theta + 0.0032D^2 + 0.66D\theta + 0.0015D^2 + 5.41 \\
S(R_w^2.84) &= -4988D + 1562HRC + 2074\theta - 36HRC - 53D\theta + 25HRC + 187D^2 - 9HRC^2 - 22329 \\
F(R_w^2.67) &= -437D + 251HRC + 276\theta + 3HRC - 4HRC + 8D^2 - 2HRC^2 - 0.21 \times 4045 \\
\end{align*}
\]

To evaluate the accuracy of a prediction model, we have to compare the residual per unit freedom. The adjusted R-squared, \(R^2_{adj}\) is generally used for evaluating accuracy [9]. We used the T-test of regression coefficient to determine the significant of each coefficient. On the basis of the results of T-test, the model was optimized by adding or deleting coefficients through stepwise elimination. Significant variables used in each equation are \(D, z, \theta\), and \(HRC\). These variables are also significant in the square end-milling condition decision [6 - 7]. Unlike for square end-mills, \(\theta\) is not typically considered to determine ball end-milling conditions because the nose section, which is used for milling, is smaller than the radius.

### 2.4 Validity of derived end-milling condition equations

Catalog-recommended end-milling conditions are generally considered to be the absolute criteria for determining appropriate conditions. However, engineers often have to adjust the recommended conditions in consideration of machine tool functionality and stiffness during milling, workpiece shape, clumping, milling cost, delivery date, and chip emission treatability. Therefore, appropriate end-milling conditions have a wide range of uses. In general, end-milling conditions have to be decreased to 60% of the catalog-recommended conditions if those conditions are too fast for stable milling. Similarly, the end-milling conditions can be increased to 140% of the catalog-recommended conditions if the new conditions can be used to obtain higher efficiency in accordance with the purpose of processing and surface dignity of workpiece, machine tool stiffness.
The horizontal axis in Fig. 7 shows the values estimated by catalog mining, and the vertical axis shows the catalog-recommended values for $\alpha \leq 15^\circ$. The black open circles show the invalid ball end-milling conditions derived from the end-milling condition decision equations. The valid end-milling condition ratios for $A_n$, $P_f$, $S$, and $F$ were 60, 70, 90, and 60%, respectively, with the exception of the black open circles ratio. This tendency was the same for $\alpha > 15^\circ$. From these results, the proposed ball end-mill conditions support system can be used for die machining. Even unskilled engineers can quickly derive the ball end-milling conditions just by substituting end-mill tool shape parameters into the end-milling conditions decision equations (3) - (6).

3. Case study

3.1 End-milling conditions and cutting tools used in experiments

We conducted cutting experiments using a rod-shaped cemented carbide ball end-mill (outside diameter $D = 8$ [mm], helix angle $\theta = 30^\circ$, number of flutes $z = 2$, TiAlN coating), a Cluster 1 end-mill, in order to investigate the validity of the catalog-recommended conditions and of those obtained from the end-milling condition decision equations. The workpiece was hardened JIS SKD61 (HRC 53), which is generally used for die molds. The conditions are shown in Table 1. The material removable rate ($MRR$) [mm$^3$/min] was defined as $MRR = A_n \cdot P_f \cdot F / 1000$. It was used as an indicative factor for evaluating the effect of combining the various end-milling conditions. The $MRR$ should be high because the catalog-recommended conditions were set under the assumption of rough processing. For $\alpha > 15^\circ$, the differences in $F$ between the catalog conditions and mined conditions tended to be less than those for the other conditions, as shown in Fig. 7 (b). As end-milling condition setting tendency extracted from difference between catalog conditions and mining conditions, for the case of $\alpha > 15^\circ$, $MRR$ was set to be 60% lower because of higher $S$ and $F$ with remaining constant depth of cut $A_n$ and $P_f$. This tendency was also found in the mined conditions. The $MRR$ from the mined conditions was 25% lower than that from catalog conditions. Because mined conditions are present in the range as shown in Fig. 7, they are suitable for practical use.

3.2 Experimental set up

We conducted contour line processing with inclination angle $\alpha = 10$, 15, or 30° using a five-axis machining center (main spindle taper size BT-40, maximum spindle speed 20,000 rpm). Using the boundary value of the inclination angle listed in the catalog ($\alpha=15^\circ$), we conducted milling using end-milling conditions for $\alpha \leq 15^\circ$ and $\alpha > 15^\circ$. The coolant was dry air. We did experiments commuting a net cutting time of 15 min into the cutting distance. A cutting time of 15
Table 1: Ball end-milling conditions.

<table>
<thead>
<tr>
<th>Catalog condition</th>
<th>Mined condition</th>
<th>Mining/Catalog ratio</th>
<th>Catalog condition</th>
<th>Mined condition</th>
<th>Mining/Catalog ratio</th>
</tr>
</thead>
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<td>V B ≥ 15°</td>
<td></td>
<td>V B ≥ 15°</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>13000</td>
<td>0.97</td>
<td>S</td>
<td>1500</td>
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<tr>
<td>F</td>
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<td>35000</td>
<td>0.97</td>
<td>F</td>
<td>13000</td>
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<tr>
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<td>1.00</td>
<td>d0</td>
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</tr>
<tr>
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<td>0.90</td>
<td>1.13</td>
<td>PF</td>
<td>0.80</td>
</tr>
<tr>
<td>MRR</td>
<td>0.92</td>
<td>0.99</td>
<td>1.07</td>
<td>MRR</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Figure 8: Flank face and wear length of ball end-mill.

Figure 8 shows the flank face and wear length (V B [mm]) of the ball end-mill. We estimated the tool life with respect to tool flank wear length V B (0.2 mm). Figure 8 shows that tool wear progressed steadily with cutting time up to 15 min. Under both the catalog conditions and mined conditions, V B did not reach 0.2 mm within 15 min except for milling with α = 30°. This results shows that mined conditions with a higher MRR are practical.

If the nose section of ball end-mill is used in the milling, the net cutting speed at the nose section is the same as table feed F. Because F under α = 30° conditions had tended to be set lower, as shown in Table 1, flank wear occurred around the nose section. Under α = 15° mined conditions, V B did not reach 0.2 mm for either α ≤ 15° and α > 15°. Practical ball end-milling conditions can be quickly derived from equations (3) - (10) by simply substituting the end-mill parameters without searching for the catalog conditions. In particular, the F derived from catalog-mining can be used as an indicative value of how much the end-milling conditions can be increased on the basis of the catalog conditions. In short, end-milling conditions derived from our catalog-mining system are useful for engineers as "criterial" end-milling conditions.

4. Conclusion

We have shown that catalog mining based on hierarchical and non-hierarchical clustering can be used as part of a decision methodology for determining ball end-milling conditions. We derived end-milling condition decision equations using the response surface method and hierarchical and non-hierarchical clustering methods. We found that catalog mining can be used to derive guideline cutting conditions for unskilled engineers. Even though the cutting conditions can be obtained from tool catalog data, the milling may still be unstable. Using mined conditions derived from tool catalog data can avoid such problems.

References