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On the geometric and stress modeling of taper ball end mills

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ABSTRACT

Taper ball end mills (TBEM) are widely used in 5-axis machining of complex parts such as impellers. Structural models are needed for calculating cutter load capacity and deflection and optimizing tool designs. Developing analytical structural models is difficult due to the geometric complexity. This paper establishes a novel 3D parametric model for as-ground TBEMs. Using this parameterized geometric model, the structure is analyzed to calculate bending stress and cutter deflection. The analytical model results were found to be in good agreement with Finite Element simulation results and experimental data from the literature.

1. Introduction

Complex parts such as impellers are often machined on 5-axis machines from disk-type forgings with Taper Ball End Mills (TBEM). Designing or choosing TBEM cutters which can withstand the large and variable cutting forces to produce the required finished part is challenging because of their geometric complexity. Poor selection of cutter and process parameters may result in unexpected tool breakages and part damages. Too conservative a choice of process parameters may result in extremely long cycle times.

To improve process robustness and reduce cycle time, 5-axis machining processes are often optimized using machining models [1]. Force-based optimization, often utilized, requires knowledge of the cutter load capacity. Furthermore, tool deflection is to be known to input tool compensation for machining with low-rigidity tools. Structural models for TBEMs with the full flute structure are needed to calculate the cutter load capacity and deflection under various loads. Integrating FEA with NC tool path generation in multi-axis milling models is not trivial. Moreover, each NC step may involve a different axial depth of cut and cutting force requiring a new loading and boundary condition setup in FEA. Analytical structural models are therefore a necessity.

The available literature deals with either square end mills or TBEMs without flute twist. Kops and Vo [2] studied the deflection of square end mills and proposed using a cylinder of equivalent diameter ~80% of the fluted end mill. Nemes et al. [3] incorporated this approach to estimate cutter survival rates for TBEMs without flute twist. More recently, Kivanc and Budak analyzed the dynamic stability of square end mills by solving the dynamic Euler–Bernoulli equations in a piecewise manner [4].

None of the cited literature deals with TBEMs with twisted flutes and flute surfaces that match typical as-ground cutters. This paper presents a strategy to fill this gap by modeling the flute structure with a 6-parameter self-similar motif with the cutting edge on a unit-radius circle. The flute surfaces are obtained by patterning this motif for the number of flutes, scaling to the actual diameter, and rotationally transforming the cross section for a prescribed lead length or helix angle. With the 3D geometric model established, the tool deflection and load capacity are modeled using the quasi-static Euler–Bernoulli beam theory when the number of flutes is greater than 2.

2. TBEM model development

Flutes of TBEMs are often generated by grinding on multi-axis CNC tool grinders with the aid of cutter grinding simulation. The kinematics of the grinding process and the wheel geometry determine the flute geometry of TBEMs [5,6]. The algebra of the resulting surfaces is not tractable from a structural analysis standpoint. It is more conducive if the surfaces are derived by traversing through the rotational axis of the cutter.

To that end, the geometry of a unit-radius cutter cross section is developed first. The cross-section is propogated through the cutter axis to obtain all the flute surfaces parametrically. Optimal parameters can be obtained to fit the geometry of any TBEM. The motif or template for one flute in the self-similar flute cross-section in the *UV* coordinate system for a right-handed tool is shown in Fig. 1

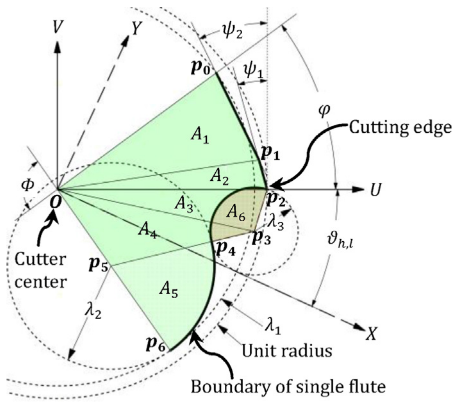

Fig. 1. Motif for the self-similar flute cross-section for a RH tool.

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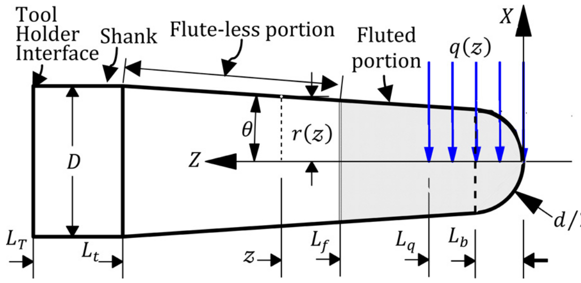

Fig. 2. Schematic of TBEM showing various symbols.

defined by the shape within points (O, $\boldsymbol{p_0}$ to $\boldsymbol{p_6}$). The points for a left handed flute can be obtained by a mirror reflection about the *U*-axis.

The tool axis is aligned with the *Z*-axis (Fig. 2). Given the number of flutes *n*, the angle Φ is fixed. Starting from the cutting edge, the motif consists of 2 line segments for the clearance faces and 2 tangential arcs for the rake face and the blend area, respectively. With the tool axis at Point $\boldsymbol{O}$, the cutting edge is located on the unit-radius circle at Point $\boldsymbol{p_2}$ lying on the *U*-axis. The geometry of the motif needs to satisfy: (1) the tool clearance ends at Point $\boldsymbol{p_0}$ on a circle of radius λ_1 centered at Point $\boldsymbol{O}$, (2) the circular rake face of radius λ_3 centered at $\boldsymbol{p_3}$ tangentially meets the blend circle of radius λ_2 centered at Point $\boldsymbol{p_5}$, (3) this blend circle is tangential with the circle in (1). With these constraints, the coordinates ($\boldsymbol{p_i} = \{u_i, v_i\}$) of various points ($\boldsymbol{p_0}$ to $\boldsymbol{p_6}$) for the single flute can be expressed as follows (Eq. (1)):

$$\begin{aligned}
\boldsymbol{p_0} &= \{u_0, v_0\} = \{\lambda_1 \cos\varphi, \lambda_1 \sin\varphi\} \\
\boldsymbol{p_1} &= \{u_1, v_1\} = \boldsymbol{p_1}(\lambda_1, \varphi, \psi_1, \psi_2) \\
\boldsymbol{p_2} &= \{u_2, v_2\} = \{1, 0\} \\
\boldsymbol{p_3} &= \{u_3, v_3\} = \boldsymbol{p_3}(\Phi, \varphi, \lambda_1, \lambda_2) \\
\boldsymbol{p_4} &= \{u_4, v_4\} = \boldsymbol{p_4}(\Phi, \varphi, \lambda_1, \lambda_2, \lambda_3) \\
\boldsymbol{p_5} &= \{u_5, v_5\} = (\lambda_1 - \lambda_2\{\cos(\varphi - \Phi), \sin(\varphi - \Phi)\} \\
\boldsymbol{p_6} &= \{u_6, v_6\} = \{\lambda_1\cos(\varphi - \Phi), \lambda_1\sin(\varphi - \Phi)\}
\end{aligned} \tag{1}$$

While the expressions for the coordinates for points $\boldsymbol{p_0}, \boldsymbol{p_2}, \boldsymbol{p_5}$ and $\boldsymbol{p_6}$ are derived in a straightforward fashion, the remaining points are derived from the constraints imposed. Specifying the point $\boldsymbol{p_1} = \{u_1, v_1\}$ is equivalent to specifying the angles ψ_1 and ψ_2 and vice versa. Expressions for the 4 remaining unknowns (u_3, v_3, u_4, v_4) to solve the points $\boldsymbol{p_3}$ and $\boldsymbol{p_4}$ are given in Eq. (2).

$$\begin{aligned}
&(u_4 - u_5)^2 + (v_4 - v_5)^2 = \lambda_2^2 \\
&(u_4 - u_3)^2 + (v_4 - v_3)^2 = \lambda_3^2 \\
&(u_2 - u_3)^2 + (v_2 - v_3)^2 = \lambda_3^2 \\
&(u_4 - u_5)/(v_4 - v_5) = (u_4 - u_3)/(v_4 - v_3)
\end{aligned} \tag{2}$$

The Area-Moment of Inertia (area-MOI) components J_m^{xx} and J_m^{yy} of the motif can then be calculated. Then, $n - 1$ copies of the motif are made in a rotational pattern to form the unit-radius cross section. The boundary of the unit-radius cross section can be expressed as a vector function $\boldsymbol{P}(\xi) : 0 \leq \xi \leq L_{uf} \to \{u(\xi), v(\xi)\}$ by threading through all the arcs and lines, L_{uf} being the perimeter.

To form the 3D representation of the TBEM, the radius $r(z)$ (Fig. 2) for the scaling and the lag angle function $\vartheta_{h,l}(z)$ (Fig. 1) specifying the orientation of the flute cross section along *z* axis are needed. To allow an arbitrary global orientation of the tool, the cutting edge of the first flute (point $\boldsymbol{p_2}$, Fig. 1) is located at angle ϑ° from the *X-axis* at *z* = 0. The radius $r(z)$ can be expressed as follows (Eq. (3)):

$$r(z) = \begin{cases} \sqrt{(d - z)z}, & \text{if } 0 \leq z \leq L_b \\ \sec\theta(d - (d - 2z)\sin\theta)/2, & \text{if } L_b \leq z \leq L_t, \\ D/2, & \text{if } L_t \leq z \leq L_T \end{cases} \tag{3}$$

With L_b and L_t defined as:

$$\begin{aligned}
L_b &= d(1 - \sin\theta)/2 \\
L_t &= \sin\theta(-d + D\cos\theta + d\sin\theta + \sin\theta)/2
\end{aligned}$$

The lag function ϑ_h for a cutter with a constant helix angle μ can be proven to be Eq. (4):

$$\vartheta_h = \vartheta^\circ + H\tan\mu \int_0^z \frac{d\chi}{r(\chi)} \tag{4}$$

Here the variable *H* specifies left (−1) or right (+1) hand of the flutes. The lag function for the ball and tapered flute portions of the cutter are given by Eq. (5).

$$\begin{aligned}
\vartheta_{h,ball} &= \vartheta^\circ + 2H\tan\mu\tan^{-1}\sqrt{Z/(d - z)} \\
\vartheta_{h,flute} &= \vartheta^\circ + H\tan\mu(\pi/2 - \theta) + H\tan\mu(\cot\theta\log(d - d\sin\theta \\
&\quad + 2z\sin\theta/d\cos^2\theta))
\end{aligned} \tag{5}$$

For cutters with a constant lead *l*, the lag function is given by Eq. (6).

$$\vartheta_l = \vartheta^\circ + \frac{2H\pi z}{l} \tag{6}$$

Thus with $\boldsymbol{P}(\xi)$, $r(z)$, and $\vartheta_{h,l}(z)$, the complete 3D tool surface can be constructed parametrically. The 6 parameters $(\varphi, \psi_1, \psi_2, \lambda_1, \lambda_2, \lambda_3)$ for a given TBEM can be obtained by superimposing the as-ground form with its parametric representation in a solid modeling environment such as UG NX®. The starting values, especially for φ, ψ_1 and ψ_2, can be readily obtained from the cross-sections of the as-ground tool. Adjustment of the parameters may be needed so that the traces at various cross sections match each other closely.

With the preceding formulation, an as-ground TBEM model from a tool grinding software [6] was compared with its parametric representation (parameters in Table 1) and is shown in Fig. 3. The solid tool in green was constructed with the analytical model and is shown superimposed with the as-ground cutter model in red. The agreement is close as seen for three cross sections at different *z*.

Table 1
Parameters of the test cutter.

Parameter	Value	Parameter	Value	Parameter	Value
θ (°)	2.0	H	+1	ψ_2 (°)	25.77
μ (°)	30, 0	ψ_1(°)	12.0	φ (°)	25.19
λ_1	0.93	λ_2	0.56	λ_3	0.36
L_f (mm)	44.45	d (mm)	3.05	J_f^{yy} [a]	0.37
L_q (mm)	10	E (GPa)	700	A_f [a]	2.05
L_T (mm)	50.8	D (mm)	6.35	L_t (mm)[a]	48.77
$q(z)$ (N/mm)	13.0	n	3	ν	0.22

[a] Calculated.

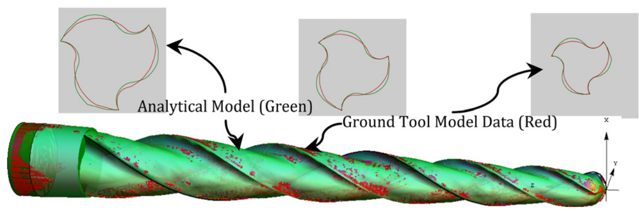

Fig. 3. Comparison of the ground tool and the analytical model.

3. Structural analysis of TBEMs

It is quite common to select cutters with 4 or more flutes for machining of superalloy impellers. The mathematical representation of a TBEM using Eqs. (1)–(5) affords a very simple methodology for stress and deflection analysis when $n > 2$ because of the rotational invariance of the area-MOI. The center $\boldsymbol{O}$ becomes a principal point and all pairs of perpendicular axes become principal axes [7]. The same is true when the cross-section is a full circle. The area-MOI components of the unit radius cross section for the fluted portion (*f*) and the solid