# Computer-Aided Design and Analysis of a Custom-Engineered Form Milling Cutter

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## ABSTRACT

Custom-Engineered (Special) cutting tools are required for machining complex surfaces or for some specific application. Accurate geometry and design of custom-engineered form milling (CEFM) cutter is needed for its analysis before actual usage. Traditionally, the cutter models are usually defined using two-dimensional conventional nomenclature. This paper presents a precise geometric design model of a brazed insert-based CEFM cutter in terms of three-dimensional (3D) parameters. The proposed model, developed in terms of surface patches employs a methodology that defines the CEFM cutter in terms of 3D rotational angles. Further, an interface is developed to render the proposed 3D CEFM cutter directly in a commercial CAD modeling environment to validate the methodology. The modeled cutter is analyzed using finite element analysis (FEA) tool to study the effects on cutting insert under transient dynamic load conditions during the machining process to verify its design.

**Keywords:** custom-engineered form milling cutter, finite element analysis.
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## 1 INTRODUCTION

In machining special (complex, free-form) surfaces, existing technology basically depends on 3-axis/5-axis CNC machine tools using ball end milling (or similar) cutters. The existing technology of using ball-end mills to generate varied profiles has it own disadvantages. Custom-engineered special cutting tools are required not only to machine complex surfaces but also as special toolings for mass manufacturing. Replacing a number of tools with just one, not only provides savings in many aspects but also lead to quality enhancement, time saving, cost effectiveness, etc. In machining industry, a custom-engineered form milling (CEFM) cutter plays an important role to obtain the desired shape of a component. Precise simulation of the machining operations is possible only with the accurate models of the cutting tools used in the machining processes. The analysis of the geometry and cutting profiles of the tool along with the cutting forces acting on the cutter plays an important part in the design of the cutter and ensure the quality of the manufacturing [1-2]. Traditionally, even the geometry of customized cutting tools is defined using two-dimensional (2D) projective geometry approach [3-6], which is tough to visualize and comprehend. Some work has been done by the authors [7-8] that helps to define the geometry of a cutting tool in terms of biparametric surface patches [9]. Using similar approach, one may design a CEFM cutter by developing the comprehensive three-dimensional (3D) surface based definitions of the cutter. The proposed 3D models of the CEFM cutter can further be used for the Finite Element based engineering analysis, stress analysis, simulation of the cutting process, manufacturing of the cutter, etc.

Till date, very few custom-engineered cutting tools have drawn the attention of research fraternity. S. P. Radzevich has proposed a novel design of cylindrical hob for machining of precision involute gears [10]. The work in the direction of geometric solution for the roller nest mill cutter is done by Kuo and Wu [6]. Hsieh and Tsai [11] have presented the geometric modeling of toroid-cone shaped cutter along with the design of the grinder to generate it. Recently, Radzevich has suggested a novel method for mathematical modeling of an optimized form-cutting tool for machining a given sculptured surface [12]. Wang et al. [13] have shown the development of geometry of a form milling cutter to precisely obtain the complex freeform surfaces.

In the present work, an accurate geometry design model for a brazed insert-based CEFM cutter is developed in terms of biparametric surface patches using the concept of surface modeling. The approach adopted in this work in contrast to the former / conventional modeling efforts, is more realistic, since the proposed model defines the CEFM cutter in terms of three-dimensional rotational angles rather than the conventional two dimensional angles. To validate the methodology, an interface is developed to directly export the CEFM cutter definition in any commercial CAD package. The design of the cutter is further verified through the finite element analysis in Ansys while studying the effects of transient dynamic loading on the cutter inserts during machining.

Section 2 of the manuscript describes in detail the surface modeling of various geometric features of the CEFM cutter. Section 3 instantiates the implementation and validation of the proposed methodology, while Section 4 describes the geometric design verification of the cutter model by performing finite element analysis (FEA). Finally, Section 5 presents the concluding remarks.

## 2 SURFACE MODELING OF CEFM CUTTER

A CEFM cutter is a peripheral cutter whose cutting edges are shaped so as to generate a special profile on the surfaces machined. The exact contour of the cutting edge of a form mill is reproduced on the surface of the work piece. This CEFM cutter can be used to machine various hard and soft metals, leathers, woods, etc. to reproduce the desired surface profile. There exists a variety of customized form milling cutters. In this work, we have taken one for the illustration. We have proposed a generic definition of a CEFM cutter. From this work, various tools of a family of customized form milling cutters can be generated. In the case of insert type cutter, the cutting teeth of the solid type cutter are replaced with the inserts. Here, the body of the cutter is made of one piece of material and the insert teeth of a different material. All the inserts of form milling cutter are similar in geometry. In this section, for the purpose of modeling, a unified insert tooth is considered and modeled in detail. Later, this insert is placed in the proper position and orientation on the periphery of the cutter body as many times as the number of inserts to complete the model.

The geometry of CEFM cutter projected on two-dimensional orthographic planes is shown in Fig. 1. $D_1$, $D_2$, d, $D_r$, and $D_i$ are diameter of hub1, diameter of hub2, bore diameter, root circle diameter of insert seat, and outer circle diameter of insert seat respectively. R is the radii of fillet. Keyway in the hub1 is specified by variables a and b i.e. the width and depth of the keyway respectively. For the convenience of modeling, the form of a CEFM cutter is considered to make up of three groups of surfaces, forming,

- Insert body.
- Insert seat.
- Core cutter body.

The geometry of a single insert body consists of a few planar surface patches and a NURBS sweep surface. The planar surface patches are formed by transforming suitable unbounded two-dimensional planes with their centre initially coinciding with a local coordinate system $C_2$. The insert seat geometry depends on the insert profile and consists of planar surface patches and a NURBS sweep surface. The core cutter body consists of surface patches that are either planar or cylindrical in geometry.

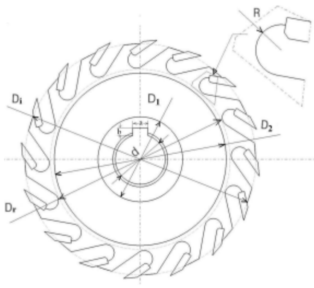

Fig. 1: Two-dimensional projected geometry of a CEFM cutter.

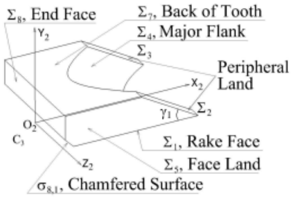


Fig. 2: Modeling of an insert in local coordinate system $C_2$.

## 2.1 Design of a Unified Insert Tooth

The geometric design of a unified insert tooth is shown in Fig. 2. The insert tooth is designed to consists of nine surface patches (eight functional surfaces and one chamfered surface), labeled as $\Sigma_1$ to $\Sigma_8$ and $\sigma_{8,1}$ respectively. For the convenience of modeling the insert surfaces, the insert is placed in a local right-hand Cartesian frame of reference $C_2\ \{O_2 : X_2, Y_2, Z_2\}$ with $X_2$-axis along the rake face, $Y_2$-axis along the end face and $Z_2$-axis along the intersection of these two surfaces. All the above surface patches except the surface patch $\Sigma_4$ are planar surfaces and are defined by transforming suitable unbounded two-dimensional planes with their centre initially coinciding with the origin in $C_2$ to their final orientation. Surface $\Sigma_4$ is developed by linearly sweeping a curve, modeled as a non-uniform rational B-spline (NURBS).

The rotational angle $\gamma_1$ is the angle through which the $Z_2X_2$ plane is rotated about $Z_2$ axis in the clockwise direction, followed by translation by an amount $l_1 \cos \gamma_1 + l_2$ along $X_2$ axis to form the peripheral land $(\Sigma_2 \& \Sigma_3)$. Here, $l_1$ and $l_2$ are the lengths of the peripheral land and back of tooth of the insert respectively.

## 2.2 Design of an Insert Seat

An insert seat is a cavity created in the cutter body to place the insert. Surface patches $\Sigma_1$ to $\Sigma_9$ form the insert seat that houses the insert of the CEFM cutter. Fig. 3(a) shows the geometry design of the insert seat. Surfaces $\Sigma_1 - \Sigma_3$ & $\Sigma_5 - \Sigma_7$ are modeled as linear sweep surfaces, surfaces $\Sigma_8 - \Sigma_9$ are planar surfaces, while surface $\Sigma_4$ is modeled by parallel sweeping a NURBS curve. Linear sweep surfaces are formed when a composite curve in $X_1Y_1$ plane is swept with a linear sweeping rule. The composite section curve profile $(V_0 - V_6)$ in $X_1Y_1$ plane is shown in Fig. 3(b). This composite curve is swept to generate the insert seat surfaces. Segments $V_0V_1V_2$ of the composite curve is a circular arc of radius $R$ with centre of the arc at vertex $c_1$ and corresponds to the fillet of an insert seat, while segments $V_2V_3$, $V_3V_4$, $V_4V_5$ and $V_5V_6$ are straight lines in two-dimensional projective plane and correspond to the four land widths, namely end face, face, land and back of insert seat.

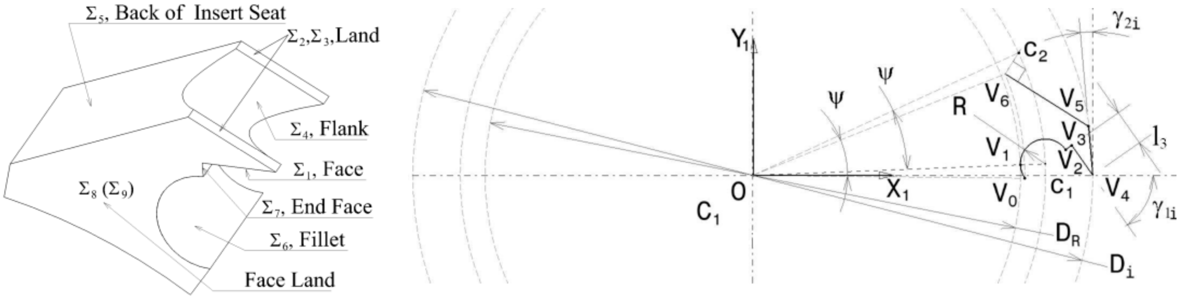


Fig. 3: Insert seat: (a) surface patches, (b) composite sectional curve.

To model the cross-sectional profile in two-dimensional plane, the input parameters are (i) length of the face $(l_3)$, (ii) 3D angles obtained to form face $(\gamma_{1i})$, and land $(\gamma_{2i})$ about $Z_1$ axis, (iii) radius of fillet $(R)$, (iv) outer diameter of insert seat $(D_i)$ and root circle diameter of insert seat $(D_R)$ and (v) number of flutes $(N)$.

The cross-sectional profile of an insert seat consists of one parametric circular edge and four parametric linear edges, namely, $p_1(s)$ to $p_5(s)$. Curve $p_1(s)$ is a circular arc of radius $R$ and $p_2(s), p_3(s), p_4(s)$ and $p_5(s)$ are straight lines in two-dimensional space. The generic definition of the sectional profile in $X_1Y_1$ plane in terms of parameter s may be represented by,

$$p_i(s) = \begin{bmatrix} f_{i1}(s) & f_{i2}(s) & 0 & 1 \end{bmatrix} \quad (2.1)$$

The surface patches $\Sigma_1 - \Sigma_3$ and $\Sigma_5 - \Sigma_7$ are linear sweep surfaces and are parametrically formed as

$$p(s,t) = p(s).[T_s], \quad (2.2)$$

$$\text{where } T_s = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & \frac{W}{2}(1-2t) & 1 \end{bmatrix}, \text{ with } 0 \le t \le 1$$

In the above equation, W is the width of the insert seat / insert.

### 2.3 Design of Core Cutter Body

The surface patches that join all the insert seats and completes the body of form milling cutter forms the core cutter body. They are twelve in number, labeled as $\Sigma_{50},\ldots,\Sigma_{61}$. Besides, there are two transitional (chamfered) surfaces, labeled as $\sigma_{50,52}$ and $\sigma_{51,52}$. They are shown explicitly in Fig. 4. These surface patches are either planar or cylindrical in geometry. Cylindrical surface patches are modeled as surface of revolution.

Transitional surface (chamfer) $\sigma_{50,52}$ is modeled as a surface of revolution and chamfer $\sigma_{51,52}$ can be modeled as the reflection of the chamfer $\sigma_{50,52}$. A straight edge of unit width on $Y_0Z_0$ plane and inclined at 45° (for 45° chamfer) is revolved about $Z_0$ axis to form $\sigma_{50,52}$. The coordinates of the ends of this straight edge are $(0, \frac{d}{2}, (\frac{W}{2} - 0.707))$ and $(0, (\frac{d}{2} + 0.707), \frac{W}{2})$. When this edge is rotated about the cutter ($Z$) axis, it forms $\sigma_{50,52}$, expressed by

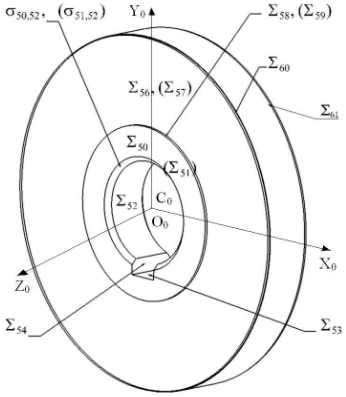


Fig. 4: Surface patches of core cutter body.

$$p_{50,52}(u,\theta) = [\ -(\frac{d}{2}+0.707u)\sin\theta \quad (\frac{d}{2}+0.707u)\cos\theta \quad \{\frac{W}{2}-0.707(1-u)\} \quad 1\ ] \tag{2.3}$$

where $0 \le u \le 1$ and $0 \le \theta \le 2\pi$ with the chamfer $\sigma_{50,52}$ non existent when $\theta \in (\frac{\pi}{4}-\sin^{-1}(\frac{a}{d}), \frac{\pi}{4}+\sin^{-1}(\frac{a}{d}))$ due to formation of keyway.

## 3 IMPLEMENTATION

The geometric parameters needed to completely describe one specific CEFM cutter based on the proposed generic definition are shown in Tab. 1(a) and 1(b). To model a complex cutter conveniently, an interactive tool design interface has been developed. The tool design interface helps render the proposed geometry of the cutter in a commercial CAD environment to validate the methodology as well as down-stream technological applications.

| *Dimensional Parameters* | *Value (mm)* | *Dimensional Parameters* | *Value (mm)* |
|---|---|---|---|
| Outer diameter of insert seat $(D_i)$ | 94.0 | Length of peripheral land $(l_1)$ | 5.0 |
| Root circle diameter of insert seat $(D_R)$ | 74.0 | Length of back of tooth insert $(l_2)$ | 6.0 |
| Outer diameter of hub2 $(D_2)$ | 70.0 | Length of face of insert seat $(l_3)$ | 5.0 |
| Outer diameter of hub1 $(D_1)$ | 35.0 | Width of the insert seat / insert $(W)$ | 10.0 |
| Bore diameter $(d)$ | 20.0 | Width of the cutter body $(W_b)$ | 9.0 |
| Number of inserts $(N)$ | 16 | Width's of peripheral land $\Sigma_2$ & $\Sigma_3$ | 1.0 |
| Fillet radius $(R)$ | 3.5 | | |

Tab. 1(a): Geometric parameters of CEFM cutter.

| *Rotational Angles* | *Value (degrees)* |
|---|---|
| $\gamma_1$ | -30 |
| $\gamma_{1i}$ | -55 |
| $\gamma_{2i}$ | 5 |

Tab. 1(b): Geometric parameters of CEFM cutter.

The tool design interface has been developed in Microsoft Visual C++ using Dot Net 3.5 technology for Windows XP / Win 2003 operating systems. The users enter the 3D geometric parameters proposed in the work in a custom-GUI of the interface, and the output of the CEFM cutter model is generated in the IGES 5.3 format. The IGES format of the cutter model is then rendered in CATIA V5 CAD modeling environment (as shown in Fig. 5) and validates the geometric design of the cutter.

## 4 DESIGN VALIDATION THROUGH FINITE ELEMENT ANALYSIS

Finite element based engineering analysis (FEA) was applied on the CEFM cutter model created using the proposed methodology. The CEFM cutter model is exported for Structural Transient Dynamic Analysis in ANSYS 10. The material used here for the insert, cutter body and the work piece are cemented carbide (WC), gray cast iron and low-carbon-free-cutting steel (LCFCS) respectively. The CEFM cutter is meshed using solid45 (brick 8node) element. This 3-D brick element is defined by eight nodes having three degrees of freedom at each node, translations in the nodal x, y, and z directions. The meshed model shown in Fig. 6(a) is built as a general orthogonal cutting model. The tool was modeled with a fine mesh at the insert with less refinement at insert seat and the core cutter body was modeled coarsely. For the accuracy of simulation, the cutting force data taken in the work are based on the results of orthogonal cutting tests conducted by Childs et al. [14]. During these cutting tests, the cutting conditions are spindle speed of 100 rpm, feed rate as 50 mm/min and a radial depth of cut at 6 mm. For our simulation, major load has been applied on a single insert in radial and tangential directions.

For the transient dynamic analysis, only time factor has been considered, vibrations and other dynamic factors are neglected. The transient dynamic analysis is carried out for a total time domain of 0.05 sec (for cutter angle rotation of 30˚), with a time interval of 0.01 sec. For dynamic case, maximum deformation of 0.187e-05 m, maximum nodal stress intensity of 5886 Pa and maximum elemental total strain intensity of 0.539e-07 occurs at time 0.01 sec and are shown in Figs. 6(b)-6(d). The values as per the result analysis are much below the critical values and hence validate the design of both insert and the cutter.

Fig. 5: Rendering of a CEFM cutter in CATIA V5 CAD software.

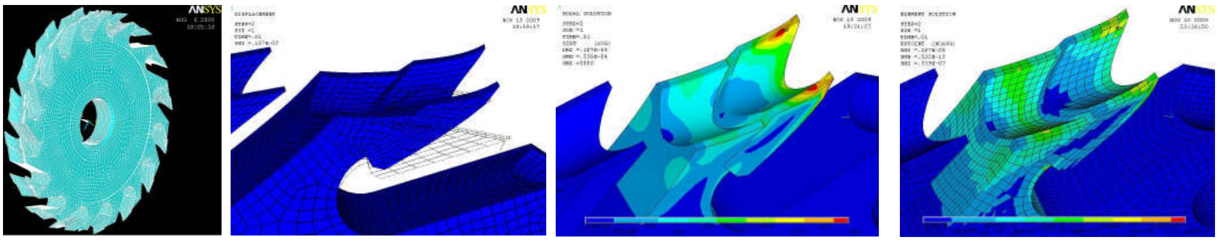

Fig. 6: CEFM cutter: (a) finite element mesh, (b) deformed mesh, (c) nodal solution: stress intensity, and (d) elemental solution: total strain intensity.

## 5 CONCLUSIONS

The method described in this paper offers a simple and intuitive way of generating exact CEFM cutter surface models for use in machining process simulations. Once an accurate biparametric surface model of the cutting tool is evolved the design can be validated and used for numerous downstream applications. Further, a user-friendly menu-driven tool design interface is developed to directly export the definition of the cutter in an existing commercial CAD package. Finite element analysis of the 3D CEFM cutter model verifies the design of the cutter. The future work includes expanding the modeler to support different types of customized cutters like custom-made drilling tools, gear cutters, custom-made form tools, etc. Currently, such tools are designed on the basis of the user specified parameters that are based on two dimensional projective geometry approaches. With the establishment of this approach, tools can be conveniently designed and redesigned on the basis of 3D geometric parameters.

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